Thermal Modeling And Laser Beam Shaping For Microvias Drilling In High Density Packaging

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THERMAL MODELING AND LASER BEAM SHAPING FOR MICROVIAS DRILLING IN HIGH DENSITY PACKAGING

by

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A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Mechanical, Materials and Aerospace Engineering
in the College of Engineering and Computer Science and
the College of Optics and Photonics / CREOL&FPCE
at the University of Central Florida
Orlando, Florida

Summer Term
2008

Major Professor: Aravinda Kar
ABSTRACT

Laser drilling of microvias for organic packaging applications is studied in present research. Thermal model is essential to understand the laser-materials interactions and to control laser drilling of blind micro holes through polymeric dielectrics in multilayer electronic substrates. In order to understand the profile of the drilling front irradiated with different laser beam profiles, a transient heat conduction model including vaporization parameters is constructed. The absorption length in the dielectric is also considered in this model. Therefore, the volumetric heating source criteria are applied in the model and the equations are solved analytically. The microvia drilling speed, temperature distribution in the dielectric and the thickness of the residue along the microvia walls and at the bottom of the microvia are studied for different laser irradiation conditions. An overheated metastable state of material is found to exist inside the workpiece. The overheating parameters are calculated for various laser drilling parameters and are used to predict the onset of thermal damage and to minimize the residue.

As soon as a small cavity is formed during the drilling process, the concave curvature of the drilling front acts as a concave lens that diverges the incident laser beam. This self-defocusing effect can greatly reduce the drilling speed. This effect makes the refractive index of the substrate at different wavelengths an important parameter for laser drilling. A numerical thermal model is built to study the effect of self-defocusing for laser microvias drilling in multilayer electronic substrates with Nd:YAG and CO₂ lasers. The laser ablation thresholds was calculated with this model for the CO₂ and Nd:YAG lasers respectively. Due to the expulsion of materials because of high internal pressures in the case of Nd:YAG laser microvia drilling, the ablation
threshold may be far below the calculated value.

A particular laser beam shape, such as pitch fork, was found to drill better holes than the Gaussian beam in terms of residue and tapering angle. Laser beam shaping technique is used to produce the desired pitchfork beam. Laser beam shaping allows redistribution of laser power and phase across the cross-section of the beam for drilling perfectly cylindrical holes. An optical system, which is comprised of three lenses, is designed to transform a Gaussian beam into a pitchfork beam. The first two lenses are the phase elements through which a Gaussian laser beam is transformed into a super Gaussian beam. The ray tracing technique of geometrical optics is used to design these phase elements. The third lens is the transform element which produces a pitchfork profile at the focal plane due to the diffraction effect. A pinhole scanning power meter is used to measure the laser beam profile at the focal plane to verify the existence of the pitchfork beam.

To account for diffraction effect, the above mentioned laser beam shaping system was optimized by iterative method using Adaptive Additive algorithm. Fresnel diffraction is used in the iterative calculation. The optimization was target to reduce the energy contained in the first order diffraction ring and to increase the depth of focus for the system. Two diffractive optical elements were designed. The result of the optimization was found dependent on the relation between the diameter of the designed beam shape and the airy disk diameter. If the diameter of the designed beam is larger, the optimization can generate better result.

Drilling experiment is performed with a Q-switched CO₂ laser at wavelength of 9.3 μm.
Comparison among the drilling results from Gaussian beam, Bessel beam and Pitchfork beam shows that the pitchfork beam can produce microvias with less tapering angle and less residue at the bottom of the via. Laser parameters were evaluated experimentally to study their influences on the via quality. Laser drilling process was optimized based on the evaluation to give high quality of the via and high throughput rate.

Nd:YAG laser at wavelengths of 1.06 μm and 532 nm were also used in this research to do microvias drilling. Experimental result is compared with the model. Experimental results show the formation of convex surfaces during laser irradiation. These surfaces eventually rupture and the material is removed explosively due to high internal pressures. Due to the short wavelength, high power, high efficiency and high repetition rate, these lasers exhibit large potentials for microvias drilling.
ACKNOWLEDGMENTS

I would like to thank all the people who have contributed and supported to finish the research at College of Optics and Photonics and Department of Mechanical, Materials and Aerospace Engineering, University of Central Florida. First of all my heartfelt appreciation goes to my advisor, Prof. Aravinda Kar, for his guidance, encouragements, and support throughout my doctoral studies. His helpful suggestions and countless discussions have made this work possible. I am also grateful to Dr. Islam Salama, Dr. Yonggang Li and Dr. Nathaniel Quick for their support, contribution and encouragement to the success of this research work.

I would like to thank my committee members, Prof. Alain Kassab, Prof. Antonio Minardi, Prof. Louis C. Chow and Prof. Martin C. Richardson for their time and helpful comments on my dissertation. Appreciation also goes to all LAMP group members for their assistance, discussions and inspirations. Finally, I would like to express my gratitude to my family and friends for their love, understanding and support.
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$A$</td>
<td>Absorptivity</td>
</tr>
<tr>
<td>$A_p$</td>
<td>Area of the pinhole</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat capacity</td>
</tr>
<tr>
<td>$d$</td>
<td>The thickness of the polymer layer</td>
</tr>
<tr>
<td>$d_{Cu}$</td>
<td>Thickness of the copper layer</td>
</tr>
<tr>
<td>$d_{pol}$</td>
<td>Thickness of thermal penetration</td>
</tr>
<tr>
<td>$D$</td>
<td>Distance between the input and output lenses</td>
</tr>
<tr>
<td>$D^*$</td>
<td>Microvia depth</td>
</tr>
<tr>
<td>$D_b$</td>
<td>Diameters at the bottom of the via</td>
</tr>
<tr>
<td>$D_r$</td>
<td>Laser energy deposition depth</td>
</tr>
<tr>
<td>$D_t$</td>
<td>Diameter at the top of the via</td>
</tr>
<tr>
<td>$E$</td>
<td>Elastic modulus</td>
</tr>
<tr>
<td>$E_v$</td>
<td>Specific ablation heat</td>
</tr>
<tr>
<td>$f$</td>
<td>Focal length</td>
</tr>
<tr>
<td>$g$</td>
<td>Volume heat source</td>
</tr>
<tr>
<td>$h$</td>
<td>Heat transfer coefficient</td>
</tr>
<tr>
<td>$I_0$</td>
<td>Laser irradiance at the center of the beam</td>
</tr>
<tr>
<td>$I_a$</td>
<td>Laser irradiance absorbed by the copper surface</td>
</tr>
<tr>
<td>$I_e$</td>
<td>Laser irradiance entering the polymer</td>
</tr>
<tr>
<td>$I_i$</td>
<td>Incident laser irradiance</td>
</tr>
<tr>
<td>$I_{ip}$</td>
<td>The laser irradiance propagating downward</td>
</tr>
<tr>
<td>$I_{op}$</td>
<td>Irradiance of the laser beam coming out of the polymer</td>
</tr>
<tr>
<td>$I_{out}$</td>
<td>Output super Gaussian beam irradiance</td>
</tr>
</tbody>
</table>
$I_r$ Irradiance of the reflected beam

$I_{rp}$ The laser irradiance propagating upward

$k$ Thermal conductivity

$k_{Cu}$ Thermal conductivity of the copper layer

$\mathbf{i}$ Laser propagation path vector

$l_v$ Absorption depth

$L$ Axial distance

$L_v$ Heat latent of vaporization

$n_a$ Refractive index of the air

$n_p$ Refractive index of the polymer

$N_F$ Fresnel number

$P$ Average laser power

$Pe$ Peclet number

$P_{\text{eff}}$ Effective recoil pressure

$r$ Radial distance

$r_0$ Radius of the incident laser beam

$r_{\|}$ Reflection coefficients for parallel-polarized lights

$r_\perp$ Reflection coefficients for perpendicular-polarized lights

$R$ Radial distance on the output plane

$R_{\|}$ Reflectance for parallel-polarized lights

$R_\perp$ Reflectance for perpendicular -polarized lights

$R_0$ Output super Gaussian beam radius

$R_{cu}$ Reflectance of copper

$R_p$ Reflectance of the polymer

$R_{\text{th}}$ Thermal resistance
\( s \)  Drilling front depth
\( St \)  Stefan number
\( t \)  Time
\( t_1 \)  Thicknesses of the input lens
\( t_2 \)  Thicknesses of the output lens
\( t_3 \)  Thickness of the focusing lens
\( t_{on} \)  Pulse-on time
\( t_p \)  Period of the laser pulses
\( t_{qs} \)  Time to reach quasi-steady state
\( t_v \)  Time to absorb the specific ablation heat
\( T \)  Temperature
\( T_0 \)  Ambient temperature
\( T_a \)  Actual temperature
\( T_d \)  Thermal decomposition temperature
\( T_f \)  Front surface temperature
\( T_g \)  Glass transition temperature
\( T_p \)  Transmittance of the polymer
\( T_r \)  Rear surface temperature
\( T_v \)  Vaporization temperature
\( u_r \)  Characteristic velocity of the molten polymer
\( U \)  Diffraction field amplitude
\( U_0 \)  Amplitude of the super Gaussian beam
\( V \)  Velocity of the vaporization front
\( V_{eff} \)  Effective vapor velocity
\( V_h \)  Volumetric heating number
\( w_0 \)  Beam waist
\(w_{0u}\) \hspace{2cm} Beam waist at the focal spot
\(w_r\) \hspace{2cm} Radius of the reflected beam
\(z\) \hspace{2cm} Axial distance
\(z_{wa}\) \hspace{2cm} Distance between the focal plane and the substrate
\(Z\) \hspace{2cm} Distance between the aperture and the diffraction plane

**Greek Symbols**

\(\alpha\) \hspace{2cm} Thermal diffusivity
\(\alpha_e\) \hspace{2cm} Thermal expansion coefficient
\(\delta\) \hspace{2cm} Thickness of the liquid layer
\(\varepsilon\) \hspace{2cm} Error function
\(\varepsilon_m\) \hspace{2cm} Emissivity
\(\phi\) \hspace{2cm} Optical phase delay
\(\Phi\) \hspace{2cm} Phase function from the diffractive optical element
\(\Phi_p\) \hspace{2cm} Laser pulse shape function
\(\lambda\) \hspace{2cm} Laser wavelength in the vacuum
\(\lambda_m\) \hspace{2cm} Laser wavelength in the medium
\(\mu\) \hspace{2cm} Absorption coefficient
\(\nu\) \hspace{2cm} Poisson ratio
\(\rho\) \hspace{2cm} Density
\(\rho_1\) \hspace{2cm} Aperture size of the focusing lens
\(\sigma\) \hspace{2cm} Stefan-Boltzmann constant
\(\sigma_{zz}\) \hspace{2cm} Axial stress
\(\tau\) \hspace{2cm} Thermal diffusion time
<table>
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<tr>
<td>$\tau_v$</td>
<td>Laser vaporization experiment time</td>
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CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

1.1 Motivation

As electronic products have become smaller, faster and more portable, the demand for microvia-formation technology has increased dramatically. A multilayer substrate in electronic packaging generally consists of an insulative polymer layer and a thin conductive copper sheet for interconnects. Lasers are usually employed to produce microvias for interconnects. Although excimer lasers can produce clean holes in most polymers with good resolution, they are not popular for commercial application due to their high cost and low throughput capability. CO\(_2\) lasers of wavelength 9.3 \(\mu\)m are prevalent in most microvia drilling industries because of its high absorptivity in the polymer, low cost and high throughput. However, because of diffraction limit due to relatively long wavelength (9.3 \(\mu\)m), the CO\(_2\) lasers cannot be focused to a very small diameter with precise resolution. The strong reflection of CO\(_2\) lasers by the copper layer changes the heating mechanism as the thickness of the polymer layer above the copper layer decreases during the drilling process. The polymer layer absorbs less heat as its thickness decreases and thus the initial rapid heating by the high irradiance laser beam changes to slow heating near the end of the drilling process. The slow heating of the polymer produces a carbonaceous black deposit, which is known as the residue, is formed at the bottom of the hole.

Nd:YAG lasers in microvias drilling are often frequency tripled or quadrupled. The fundamental frequency (1.06 \(\mu\)m) and 2\(^{nd}\) harmonic (532 nm) are rarely used, because of the low
absorptivity in the polymer material. However, Nd:YAG lasers have potential advantages over CO₂ lasers. The shorter wavelength (1.06 μm) of Nd:YAG lasers enables focusing to smaller beam diameters than CO₂ lasers and, therefore, Nd:YAG lasers are more readily adaptable for smaller diameter via drilling than the CO₂ lasers. Also the reflectivity of copper at the Nd:YAG laser wavelength is not as high as for CO₂ lasers. The copper layer will be heated during the Nd:YAG laser microvia drilling and it will provide an additional mechanism to heat the polymer layer from bottom at the polymer-copper interface. Thus a rapid heating mechanism may be maintained with a Nd:YAG laser during the entire drilling process to avoid the formation of residue at the bottom of the hole, which will allow cleaner (residue-free) microvia drilling than in the case of CO₂ lasers.

The purpose of this project is to analyze the microvias drilling process as shown in Figure 1.1 with CO₂ lasers and Nd:YAG laser to produce residue free holes with the diameters less than 67 μm.
Figure 1.1 Geometric configuration for drilling model
1.2 Literature Review

1.2.1 Background for laser microvias drilling

Lasers are extensively used to process various types of materials such as metals, semiconductors, polymers and ceramics. In microvias drilling in polymer substrate, laser have replaced the conventional drilling. Tokarev (2000) and Chen (1997) have studied the mechanism of the interaction between excimer laser and polymer material. Biernaux (1997) and Rho (2004) used CO$_2$ lasers to produce microvias in printed circuit boards. Karasaki et al. (1998) and Nakayama (2000) used CO$_2$ lasers for printed wiring board applications. A CO$_2$ laser of wavelength 9.3 $\mu$m is widely used for microvia drilling in polymeric dielectrics to produce high density, multilayer, interconnect substrates. During laser drilling not only phase transitions (e.g., solid $\rightarrow$ glassy phase $\rightarrow$ melt $\rightarrow$ vapor) occur, but also chemical degradation of the polymer can occur before reaching the vaporization point [Godovsky et al. (1992)]. To simplify the modeling approach, the chemical degradation can be treated as sublimation, because both processes absorb energy and give off gases. The surface temperature quickly stabilizes after the chemical degradation of the polymer and tends to remain constant for different laser parameters [Arnold et al. (1999)]. So the surface temperature, which is termed the thermal decomposition point, is considered to be constant in this study. Unlike most metallic materials, which have an absorption length less than 0.1 $\mu$m for the laser wavelength, polymeric materials allow deeper penetration of lasers at certain wavelengths [Hector et al. (1996)]. Usually the absorption depth $l_v$, which is given by $l_v \sim 1/\mu$ where $\mu$ is the absorption coefficient, of polymer is 10 $\mu$m [Noguchi et al. (2003)]. Phonons are created in the substrate after the laser energy is absorbed by the substrate molecules. These phonons conduct heat to various regions of the substrate. The
The characteristic length for the propagation of the thermal energy is given by the thermal influence length \( l_T \sim \alpha/V \), where \( \alpha \) is the thermal diffusivity and \( V \) is the velocity of the vaporization front [Mazhukin et al. (1995)]. The relative magnitude of these two lengths defines whether volumetric laser heating is important for a given case of laser-matter interaction. A volumetric heating \((V_h)\) number, which is a dimensionless number given by \( V_h = V/\alpha \mu \), is defined in this study to express the relative importance of these two lengths. The volumetric heating is appreciable when \( V_h \geq 1 \). This condition is satisfied for many polymeric dielectrics even for \( V \sim 0.01 \text{ m/s} \). So the drilling model must consider the laser heating and the removal of polymeric material due to volumetric heating. It has been confirmed experimentally that an analytic model based on volumetric heating is more accurate than a model based on surface heating [Li et al. (2004)].

The volumetric heating creates an overheated metastable state with the maximum temperature occurring beneath the substrate surface [Mazhukin et al. (1995); Mazhukin et al. (1995), Von Der Linde et al. (1987)], when the surface is maintained at a constant temperature, e.g., the vaporization temperature. This overheating induces phase transformation in the polymer. It also causes thermomechanical breakage of the material when the thermal stress exceeds a critical value, leading to material removal through explosion under certain laser parameters. Such an explosive material removal mechanism makes the drilling process unstable. Additionally the overheating can produce a thicker heat-affected zone (HAZ) in the polymer. The HAZ, which will be referred to as “smear residue,” is formed in the region where the temperature exceeds the thermal decomposition point [Hirogaki et al. (2001)]. Smear residue is formed along the walls of
the hole and at the bottom of the embedded copper pad in multilayer copper-polymer structures [Noguchi et al. (2003); Inaba et al. (2001)].

Despite the above disadvantages, the explosive removal of polymeric material through the volumetric heating mechanism would be energetically more efficient than the conventional laser polymer drilling which relies only upon the vaporization of the material. So the volumetric heating process needs to be studied to control the explosive removal of materials and to minimize or eliminate the formation of smear residue. The effects of volumetric heating on the quality of laser drilling depend on the thermophysical and optical properties of polymeric substrates as well as the laser beam parameters such as the irradiance and pulse duration. To improve the drilling efficiency, a short drilling time at high irradiance (\(\sim 10^5\) W/cm\(^2\)) is generally required. At high irradiances, however, the hot polymer vapor transforms into plasma [Sankaranarayanan et al. (1999); Mazhukin et al. (2004); Fan et al. (2002)], affecting the propagation of the laser beam through the plasma to the substrate. For materials having low vaporization temperatures, the plasma formation is negligible when the irradiance is not excessively high [Zhang et al. (2005)].

Most of the previous laser drilling models only considered the laser energy absorbed at the substrate surface [Kar et al. (1992), (1994) and (1996); Xie et al. (1997); Pecharapa et al. (1997)]. Dabby et al. (1972) presented a transient one-dimensional model considering the penetration of radiation into the material. Noguchi et al. (2003) applied the enthalpy method to formulate a one-dimensional volumetric heating model and solved it using a finite element technique. Mozhukin et al. (1995) analyzed the overheating process by using a one-dimensional
model. Sobol and Petrovskaya (1993) studied the HTSC (High-T<sub>c</sub> Super-Conductor) evaporation and decomposition due to volumetric heating.

### 1.2.2 Background for laser beam shaping

Laser beam shaping is the process of redistributing the irradiance and phase of the laser [Dickey et al. (2000)]. It is widely used in the laser material processing, such as pulsed laser deposition, lithography, micro machining [Kajava et al. (2006)], laser fusion, laser radar, laser scan, optical data processing [Dickey et al. (2005)]. For different laser materials processing applications, different irradiance profiles such as flat-top beam, Bessel beam and annular beam [Hoffnagle et al. (2003); Arif et al. (1998); Zeng et al. (2006)] are necessary. Several methods have been investigated for beamshaping in the near field. The most straightforward approach is through the use of apodization and truncation. However, this approach is fundamentally energy inefficient. Reflective optics, refractive optics [Hoffnagle et al. (2003); Arif et al. (1998); Zeng et al. (2006)], diffractive optics [Liu et al. (2004)], acousto-optics [Abdelaziez et al. (2005)] and liquid crystal [Shevchenko et al. (2006)] are generally employed to shape the laser beam. It can also be achieved by the introduction of some unconventional optical elements inside the laser resonators, such as diffractive optical elements, a Gaussian mirror, or internal phase plates [Yun et al. (2007)]. The most popular technique used for laser beam shaping is beam integration, which consists of mixing fractions of the input beam to smooth out the intensity spikes [Kana et al. (2006)]. The beam homogenization by means of integration is based on splitting the input beam into beamlets that overlap at the focal plane of a lens. The refractive optical system basically consists of two components as shown in Fig. 1.2. The first optical element is a divider.
which is an array of lenses splitting the input beam into beamlets. The second element is a condenser which is a lens (or mirror) that overlaps the beamlets at its focal plane.

![Diagram of a standard beam homogenizer](image)

**Figure 1.2** A standard beam homogenizer

Faceted integrating mirrors, which separate the incoming laser beam into several beamlets, are similar to refractive beam homogenization. The surface of every single facet is formed to create the desired phase distribution of each beamlet. The desired fluence distribution is achieved after propagation to the image plane, where the beamlets are superimposed [Bemges et al. (1999)]. Diffractive optics in the form of computer-generated holograms [Eismann et al. (1989); Aleksoff et al. (1991)], diffraction gratings [Veldkamp (1982)] and diffractive optical phase plates [Cordingley (1993)] have found wide application. The conversion of a Gaussian beam into a uniform beam of rectangular support has been demonstrated using computer-generated holograms [Aleksoff et al. (1988)]. The limitation for computer-generated holograms is the low diffraction efficiency. The diffractive optical phase element appears to be an ideal choice for beam shaping because of high diffraction efficiency, a coaxial transformation feature, compact configuration, and low cost of production and replication [Tan et al. (1995)].
Numerous beam-shaping techniques and systems have been developed and applied to solve the practical problem. Shealy et al (2004) use geometrical optics for design of gradient-index (GRIN) laser beam shapers with the conditions of conservation of energy and constant optical path length for all rays passing through the system. By introducing a low-index inner core into the core of index-guiding microstructure optical fibers, Lu et al (2006) shaped Gaussian laser beams into flat-top ones. Beam-splitter gratings are also used to generate top-hat profile of an excimer-laser beam [Kajava et al. (2006)]. S. Corbett et al. (2005) explored laser direct-write photolithography and ablation processes in densely patterned circuit substrates with square top-hat beam. J. Khare et al (2007) used top-hat beam for microstructural control during laser surface melting. By focusing with Axicon lens, the diffraction free Bessel beams are produced [Durnin et al. (1987), Sedukhin et al. (1998)]. Zeng et al. (2006) used axicon lenses for annular beam shaping which is used in laser trepanning drilling.

Ray tracing technique for beam shaping and diffractive optical elements are studied in this paper. The ray tracing technique is based on geometrical optics beam shaping [Dickey et al. (2000)]. In physical optics, the light is considered as an electromagnetic wave having diffraction and interference properties. However as the wavelength of the radiant energy decreases in comparison to the physical dimensions of the optical system, the effects of the wavefront become less significant. For this case, the approximation of geometrical optics is considered suitable. If the wavelength of the laser beam is large, or the dimension of the spot size is small, diffractive analysis needs to be considered. In this paper, diffraction analysis is employed for the optimization of the optical system. Algorithm such as iterative Fourier transformation algorithm
[Fienup (1980)], Gerchberg–Saxton (GS) [Gerchberg et al. (1972); Zalevsky et al. (1996)], direct binary search [Seldowitz et al. (1987)] and simulated annealing [Kirkpatrick et al. (1983); Turunen et al. (1987)] often used laser beam shaping in free space. In the present work, adaptive additive algorithm is used in the iterative method for designing diffractive optical elements. With the algorithm of repeated Fourier transformations for the near- and the far-field planes Dixit et al. (1994 and 1996) obtained a super-Gaussian beam with more than 95% of the incident energy converged into the desired region. Lin et al. (1996) developed the Gerchberg–Saxton algorithm and obtained a good 4th-power super-Gaussian fit and lower scattering loss. Liu et al. (2002) developed an improved iterative algorithm beginning with Gerchberg–Saxton approach and obtained a 12th-power super-Gaussian with 97.4% of the incident energy in the desired region. Michael et al (1998) used a modification of the Gerchberg-Saxton algorithm to design the beam shaping system with two holographic elements for converting a Gaussian beam into a uniform beam with rectangular support in the far field of the source.

1.3 Objectives

By analyzing the process of laser microvias drilling, optical systems to produce the optimized beam shape for microvias drilling is developed. Modeling work and experimental work are included in this research.

Modeling work will include the following aspects:

(a) Transient analysis of volumetric heating for laser drilling.
(b) Numerical analysis of laser microvias drilling.
(c) Laser beam shaping system by geometrical optics.
(d) Diffraction analysis of pitchfork beam shaping system.
(e) Laser beam shaping system by diffractive analysis.

Experimental work will include the following aspects:

(a) Measurements of thermophysical properties of the polymer substrate
   - Design and construction of thermophysical properties measurements system.
(b) Laser drilling microvias experiment
   - Design and construction laser drilling system
   - Measurement and analysis of the characteristics of drilled microvias in the polymer substrate.
(c) Measurements of pitchfork beam intensity profiles
   - Design and construction of laser beam shaping system.
   - Design and construction of beam profiles measurement system

Contribution to the science includes the following aspect:

The interaction between the laser and the polymer substrate is studied. The drilling mechanism, which includes volumetric heating, self-defocusing and explosion at the interface of the copper layer and polymer layer, will be testified by experiment.

Contributions to the technology include the following aspects:

(a) Residue free hole is drilled with the pitchfork beam. The process cost is greatly reduced.
(b) The absorption efficiency of the pitchfork beam is high and the drilling process can be completed within a shorter time. So the productivity of the laser drilling system can be improved.

(c) Pitchfork beam is expected to produce holes with less taper angle.
CHAPTER 2: ANALYTIC MODELING OF VOLUMETRIC HEATING FOR LASER MICROVIAS DRILLING

2.1 Introduction

Generally laser energy is considered to interact only with the substrate surface, as in metals, where the laser beam does not propagate into the substrate beyond a very small absorption depth. There are, however, many instances, particularly for ceramics and polymers, where the laser beam can penetrate into the substrate to substantial depths depending on the laser wavelength and laser-material interaction characteristics. Specifically there are polymeric dielectrics used as multilayer electronic substrates in which a laser beam of wavelength 9.3 μm can penetrate into the substrate. The laser energy interacts at the substrate surface as well as inside the substrate. This particular aspect of laser-material interactions is important in laser drilling of blind microvias in polymeric multilayer electronic substrates. A one-dimensional transient heat conduction model including vaporization parameters is constructed to analyze this behavior. The absorption coefficient of the dielectric is also considered in this model and the problem is solved analytically. The microvia drilling speed, temperature distribution in the dielectric and the thickness of the residue along the microvia walls and at the bottom of the microvia are studied for different laser irradiation conditions. An overheated metastable state of material is found to exist inside the workpiece. The overheating parameters are calculated for various laser drilling parameters and are used to predict the onset of thermal damage and to minimize the residue.
2.2 Mathematical Model with Volumetric Heating Source

The occurrence of various optothermal processes due to laser-polymer interactions is described in Figure 2.1. When a laser beam is incident on a substrate, a fraction of the laser energy penetrates into the substrate and is absorbed within a certain volume of the material resulting in volumetric heating. This will heat up the substrate first by supplying only the sensible heat up to a certain time \( t_h \). At time \( t = t_h \), the surface temperature reaches the vaporization point of the substrate. The specific ablation heat will be absorbed by the surface up to a certain time \( t_v \), i.e., during the time period \( t_h \leq t < t_v \) and overheating (i.e., temperature exceeding the vaporization point) starts inside the work piece in this time period. At time \( t = t_v \), the energy absorbed by the surface exceeds the specific ablation heat and a transient state of vaporization occurs up to a certain time \( t_{qs} \), i.e., during \( t_v \leq t < t_{qs} \). This vaporization process enables drilling of the substrate. As the drilling front moves, a quasi-steady state is established at \( t = t_{qs} \). During the quasi-steady state \( (t_{qs} \leq t < t_{on}) \) where \( t_{on} \) is the pulse-on time, the overheating inside the polymer continues. A large portion of the polymer is vaporized in this period. During the laser pulse-off time \( (t_{on} \leq t < t_p, \) where \( t_p \) is the period of the laser pulses), vaporization continues due to the excess thermal energy in the overheated region inside the substrate. Depending on the amount of the excess energy, the volumetric heating may leave residue on the side walls and at the bottom corner of holes in polymeric substrates. The residue can be removed by using more pulses with annular irradiance profile. The overheating can also cause thermochemical damage to the substrate around the surface of the hole, and generate residual thermal stresses in the substrate. Explosive material removal occurs during the drilling process if the thermal stress exceeds the yield stress of the substrate.
Figure 2.1 A schematic representation of laser-polymer interaction process
The depth of the microvias is about 30 μm. During the drilling process the thickness of the liquid layer would be a fraction of this depth. It is actually less than 0.5 μm, if the laser intensity is larger [Hirogaki et al. (2001)] than 3.69×10⁴ W/cm². The laser intensity used to drill the polymer substrate is 1.2×10⁶ W/cm² in this paper, which produces a thinner liquid phase. The Peclet number, \( Pe = \delta u_r/\alpha \), is a measure of the importance of heat convection relative to the heat conduction. Here \( \delta \) is the thickness of the liquid layer; \( u_r \) is a characteristic velocity of the molten polymer and \( \alpha \) is the thermal diffusivity of the polymer. The value of \( u_r \), which represents the radial velocity in this study, is estimated below to obtain \( Pe \).

Three driving forces may be identified for the flow of molten polymer: (i) buoyancy force due to the density difference, (ii) surface tension gradient due to the temperature dependence of surface tension and (iii) recoil pressure due to the outgoing vapor. Because of the volumetric heating and thinness of the liquid layer the temperature is expected to be uniform along the depth of the liquid layer and therefore the buoyancy force can be neglected. The surface tension gradient causes radial flow while the recoil pressure squeezes the liquid in the z-direction (Figure 1.1) to eventually cause radial flow. An effective recoil pressure, \( P_{\text{eff}} = \frac{1}{2} \rho V_{\text{eff}}^2 \), may be defined to combine the effects of these two driving forces in order to estimate \( u_r \). Here \( V_{\text{eff}} \) is an effective vapor velocity representing the sum of the actual vapor velocity and an additional velocity whose recoil pressure produces the same effect on the polymer flow as the surface tension gradient. \( \rho \) is the density of the liquid polymer. The effective recoil pressure induces shear stress in the liquid polymer, i.e., \( P_{\text{eff}} \approx \mu \frac{du_r}{dz} \), where the shear stress of Newtonian fluids has
been considered, although polymers are generally non-Newtonian fluids, in order to estimate \( u_r \). Here \( \mu \) is the viscosity of the molten polymer with typical values [Xie et al. (1997), Pecharapa et al. (1997)] \( 10^6 \) kg/(m·s). Since \( \delta \) is small, \( \frac{du_r}{dz} \) can be expressed as \( \frac{u_r}{\delta} \). So the above approximation leads to \( u_r \approx \frac{\delta}{\mu} \frac{1}{2} \rho V_{eff}^2 \).

Substituting the properties of the polymer into this expression, \( u_r = 2.5 \times 10^{10} V_{eff}^2 \). If the effective velocity is taken as the speed of sound, i.e., \( V_{eff} = 340 \) m/s, the characteristic velocity of the liquid polymer is \( u_r = 2.89 \times 10^{-5} \) m/s and the corresponding Peclet number \( Pe = 5.78 \times 10^{-5} \) which is very small. Even if the effective vapor velocity \( V_{eff} \) corresponds to Mach number 10, which is very high, the Peclet number \( Pe = 5.78 \times 10^{-4} \) is still very small. So the convection in the molten polymer can be neglected.

The mathematical model is based on the drilling geometry presented in Figure 1.1 which shows a multilayered substrate consisting of an embedded copper layer covered with polymer layers on both sides of the copper pad. During pulse-on time, the laser beam penetrates into the substrate and is absorbed by the substrate having an absorption coefficient \( \mu \). Assuming the Bouguer-Lambert law to be valid, the laser irradiance propagating downward inside the polymer can be expressed as

\[
I_w = I_i \cdot \exp(-\mu \cdot z)
\]

in a moving coordinate system with the origin of \( z \) located at the drilling front \( s(r,t) \). \( I_i \) is the incident laser irradiance.
For a Gaussian beam,

\[ I_i = (1 - R_p) \cdot I_0 \cdot \exp(-2r^2 / r_0^2) \cdot \Phi_p(t) \]  

(2.2)

where \( R_p \) is the reflectance of the polymer and \( \Phi_p(t) \) is the laser pulse shape function which is considered to be rectangular in this study. \( I_0 \) is laser irradiance at the center of the beam.

\[ I_0 = 2Pt_p / \pi r_0^2 \tau_{on} \]  

(2.3)

where \( P \) is the average laser power and \( r_0 \) is the radius of the incident laser beam.

Due to high reflectivity of copper, a small amount of the laser energy is absorbed at the copper surface and the rest is reflected. The irradiance of the reflected beam (\( I_r \)) at the copper surface can be expressed as:

\[ I_r = R_{cu} \cdot I_i \cdot \exp[-\mu(d - s(r,t))] \]  

(2.4)

where \( R_{cu} \) is the reflectance of copper. This reflected beam also deposits energy inside the polymer layer as the beam propagates upward and the corresponding irradiance (\( I_{rp} \)) is given by

\[ I_{rp} = I_r \cdot \exp[-\mu(d - s(r,t) - z)] \]  

(2.5)

The thermal model is developed by assuming homogeneous and isotropic polymer material and constant thermophysical properties. The absorbed laser energy is assumed to convert into heat instantaneously. The attenuation of the beam by plasma and the radiative heat loss are not considered in this model. The material removal is modeled as a sublimation process, solid to vapor, because of the liquid phase exists for a short duration.
Because of the short heating time prior to the surface temperature reaching the vaporization point, the vaporization is considered to begin as soon as the laser irradiation is started. Since shallow (~40 μm deep) microvias are drilled in a very short time, a one-dimensional heat conduction may be applied to analyze the distribution of thermal energy. So the governing heat transfer equation for the quasi-steady state can be written in a moving coordinate system as:

$$\frac{\partial^2 T}{\partial z^2} + \frac{g}{k} = -\frac{1}{\alpha} \frac{\partial T}{\partial t}$$ \hspace{1cm} (2.6)

for 0<z<d(s(r,t)). Here k and α are the thermal conductivity and thermal diffusivity of polymer respectively and g is the volume heat source given by

$$g = -\frac{\partial I_{sp}}{\partial z} + \frac{\partial I_{pp}}{\partial z}$$ \hspace{1cm} (2.7)

The boundary conditions are:

$$T=T_v, \quad \text{at } z=0$$ \hspace{1cm} (2.8-a)

$$-k \frac{\partial T}{\partial z} + I_a = \frac{T - T_0}{R_{th}}, \quad \text{at } z=d-s(r,t),$$ \hspace{1cm} (2.8-b)

where $T_v$ is the vaporization point. $T_0$ is the ambient temperature. $I_a$ is the laser irradiance absorbed by the copper surface given by $I_a = (1 - R_{es}) \cdot I_i \cdot \exp[-\mu(d-s(r,t))]$. $R_{th}$ is the thermal resistance of the composite medium made of the copper layer and the polymer layer beneath the copper layer. It should be noted that the polymer layer above the copper layer is being considered for microvia drilling. The value of the thermal resistance can be obtained from the following relation:

$$R_{th} = \frac{\delta_{Cu}}{k_{Cu}} + \frac{\delta_{poly}}{k}$$ \hspace{1cm} (2.9)
where $\delta_{Cu}$ and $k_{Cu}$ are the thickness and thermal conductivity of the copper layer. $\delta_{poly}$ is the thickness of thermal penetration in the underlying polymer layer.

The Stefan condition at the solid-vapor interface is [Alexiades et al. (1993)]:

$$ k \frac{\partial T}{\partial z} \left[ 1 + \left( \frac{\partial s(r,t)}{\partial r} \right)^2 \right] = \rho L_v \frac{\partial s(r,t)}{\partial t} \quad \text{at } z=s(r,t) \quad (2.10) $$

where $L_v$, $\rho$ and $C_p$ are the heat latent of vaporization, density and specific heat of the polymer, respectively.

### 2.3 Method of Solution

#### 2.3.1 Method of solution for laser pulse-on time

During the drilling process, some of the thermal energy, which is deposited in the substrate by the laser beam, is removed by the high temperature ejecta. This mechanism can create a quasi-steady state condition. However, there is a time lag to establish the quasi-steady process because the surface temperature needs to reach the vaporization point first and then the vaporization front needs to attain a constant speed from its initial static condition. This time lag is very short since the Stefan number $St = C_p (T_v - T_0) / L_v \to 0$ and, therefore, the quasi-steady approximation can be applied to the present case during the pulse-on time [Alexiades et al. (1993)]. Eqs. (2.6 – 2.10) are a set of partial differential equations which can be solved to obtain the temperature distribution and drilling front profile as below:
\[ T(r, z, t) = \frac{C_1}{\rho C_p} \cdot \frac{1}{\frac{\partial s(r, t)}{\partial t}} + C_2 \exp\left(-\frac{\partial s(r, t)}{\partial t} \right) + \frac{1}{\rho C_p} \frac{I_i}{\frac{\partial s(r, t)}{\partial t}} + \frac{1}{\rho C_p} \frac{I_p}{\frac{\partial s(r, t)}{\partial t}} + \alpha \mu \] (2.11)

where \( C_1 \) and \( C_2 \) are integral constants and are functions of \( r \) and \( t \). By substituting Eq. (2.11) into boundary conditions (2.8-a) and (2.8-b), \( C_1 \) and \( C_2 \) can be expressed as:

\[
C_2 = \frac{\alpha}{1 - \exp\left[-\frac{\partial s(r, t)}{\partial t} \right]} \cdot \frac{1}{\alpha \mu} \cdot \frac{k}{\rho C_p} \left[ \frac{1}{\frac{\partial s(r, t)}{\partial t}} + \frac{1}{\rho C_p} \frac{I_i}{\frac{\partial s(r, t)}{\partial t}} + \frac{1}{\rho C_p} \frac{I_p}{\frac{\partial s(r, t)}{\partial t}} - C_2 \right] + \frac{\alpha}{\alpha \mu} \cdot \frac{k}{\rho C_p} \left[ \frac{1}{\frac{\partial s(r, t)}{\partial t}} + \frac{1}{\rho C_p} \frac{I_i}{\frac{\partial s(r, t)}{\partial t}} + \frac{1}{\rho C_p} \frac{I_p}{\frac{\partial s(r, t)}{\partial t}} - C_2 \right].
\]

Now substituting Eq. (2.11) into the Stefan condition (2.10), a partial differential equation for \( s(r, t) \) is obtained as follows:

\[
\frac{\partial s(r, t)}{\partial t} = A_1 I_i + A_2 I_i s(r, t) + \left[ A_3 \frac{\partial s(r, t)}{\partial t} + A_4 I_i + A_5 I_i s(r, t) \right] \left( \frac{\partial s(r, t)}{\partial r} \right)^2
\] (2.12)

which can be rewritten as:

\[
\frac{\partial s(r, t)}{\partial r} = f[r, t, s(r, t)]
\] (2.13)

where

\[
A_1 = \frac{k R_{th} \mu [2 \exp(-\mu d) - 1 - \exp(-2 \mu d)] + 1 - \exp(-2 \mu d)}{\rho [C_p (T_v - T_0) + L_v]},
\]

\[
A_2 = \frac{A_1}{d},
\]

\[
A_3 = \frac{\rho C_p (T_v - T_0)}{\rho [C_p (T_v - T_0) + L_v]}
\]

and
\[ f[r,t,s(r,t)] = \left[ \frac{\partial s(r,t)}{\partial t} - A_1 I_i - A_2 I_s(r,t) \right]^{1/2} \left[ \frac{A_3 \partial s(r,t)}{\partial t} + A_1 I_i + A_2 I_s(r,t) \right]. \]

The drilling front is considered to be symmetric at \( r = 0 \), so \( \frac{\partial s(r,t)}{\partial r} = 0 \) and then Eq. (2.12) can be written as:

\[ \frac{\partial s_0(r,t)}{\partial t} = A_1 I_i + A_2 I_s(r,t), \quad \text{at } r = 0. \] (2.14)

By using the integrating factor \( \exp\left(\int_0^t -A_2 I_s \, dt\right) \), Eq. (2.14) can be solved to obtain

\[ s_0(r,t) = \frac{\int_0^t A_1 I_i \exp\left(\int_0^t -A_2 I_s \, dt\right) \, dt}{\exp\left(\int_0^t -A_2 I_s \, dt\right)}. \] (2.15)

Since a solution of \( s(r,t) \) is known at \( r = 0 \), Eq. (2.13) can now be solved by the method of successive approximation [Ince (1956)]:

\[ s_1(r,t) = s_0(r,t) + \int_0^t f[r',t,s_0(r',t)] \, dr' \]
\[ s_2(r,t) = s_0(r,t) + \int_0^t f[r',t,s_1(r',t)] \, dr' \]
\[ \vdots \]
\[ s_n(r,t) = s_0(r,t) + \int_0^t f[r',t,s_{n-1}(r',t)] \, dr' \]

As \( n \) increases indefinitely, the sequence of function \( s_n(r,t) \) tends to the exact solution of Eq. (2.13).

Results show that the iteration converges rapidly. From the calculated result, it is found that the difference between \( s_1(r,t) \) and \( s_0(r,t) \) is very small. So \( s_1(r,t) \) is taken as the approximate solution to Eq. (2.13):
\[ s(r,t) = s_0(r,t) + \int_0^t f(r',t, s_0(r',t))dr'. \]  \hspace{1cm} (2.16)

After calculating the drilling front profile \( s(r,t) \), the temperature distribution can be obtained by substituting Eq. (2.16) into Eq. (2.11)

### 2.3.2 Method of solution for laser pulse-off time

It should be noted that the drilling process continues during the pulse-off time due to the overheating inside the polymer. This process cannot be considered as a quasi-steady state because the overheating diminishes as the drilling front absorbs the specific ablation heat and this slows down the speed of the front from its initial high value, which is attained at the end of the pulse-on time, to a lower value or zero depending on the pulse-off duration. So the governing equation during the pulse-off time can be written as follows in the stationary coordinate system:

\[
\frac{\partial^2 T'}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T'}{\partial t} \hspace{1cm} (2.17)
\]

for \( 0 < z < d' \), where \( d' = d - s(r,t) \), \( T' = T - T_0 \). \( s(r,t) \) is the position of the drilling front at the end of the pulse-on time.

The boundary conditions for Eq. (2.17) are the same as above. Eq. (2.17) can be solved using Green’s function [Ozisik (1980)] for which the phase change interface is considered as a moving heat source inside the polymer and then Eq. (2.17) can be rewritten as:

\[
\frac{\partial^2 T'}{\partial z^2} - \frac{1}{k} \rho L_v \frac{d s'(t)}{dt} \delta[z - s'(t)] = \frac{1}{\alpha} \frac{\partial T'}{\partial t} \hspace{1cm} (2.18)
\]

where \( \delta(z - s'(t)) \) is the Dirac delta function.
The boundary conditions for this problem are:

\[ k \frac{\partial T'}{\partial z} = 0, \quad \text{at } z = 0 \]  
(2.19-a)

\[ -k \frac{\partial T'}{\partial z} = \frac{T'}{R_h}, \quad \text{at } z = d' \]  
(2.19-b)

The initial condition is the temperature distribution, \( F(z) \), which is given by the solution of Eq. (2.11) at the end of the pulse-on time:

\[ T' = F(z), \quad \text{at } t=0 \]  
(2.20)

Using Green’s function, the temperature distribution can be expressed as:

\[ T'(z,t) = \int_0^d G(z,t|z',\tau) \left[ \frac{\partial F(z')}{\partial s'} + \frac{\alpha}{k} \int_0^\tau G[z,t|s'(t),\tau] \cdot [\rho \frac{ds'}{dt}] d\tau \right] d\tau \]  
(2.21)

where the Green function is obtained by solving the corresponding homogeneous problem using the separation of variable,

\[ G(z,t|z',\tau) = \sum_{m=1}^\infty \exp[-\alpha \beta_m^2 (t-\tau)] \frac{1}{N(\beta_m)} \cos(\beta_m z) \cdot \cos(\beta_m z') \]  
(2.22)

\[ \frac{1}{N(\beta_m)} = 2 \cdot \frac{\beta_m^2 + 1/(kR_h)^2}{d'(\beta_m^2 + 1/(kR_h)^2) + 1/(kR_h)} . \]  
(2.23)

Here \( N(\beta_m) \) is the normalization constant and \( \beta_m \) is the eigenvalue. Different values of \( \beta_m \) are given by the solutions of the following transcendental equation:

\[ \beta \cdot \tan(\beta \cdot d') = 1/(kR_h) . \]  
(2.24)

Since the temperature of the vaporization front is fixed at the vaporization point, \( T_v \), the location of the front can be obtained by substituting expression (21) into the condition: \( T'(s,t) = T_v - T_0 \). This yields the following expression:
The integrals in Eq. (2.25) can be evaluated numerically. The position of drilling front $s(t_n)$ for different times $t_n$, $n = 1, 2, 3, \ldots$, can be solved by the bisection method [Arfken (1985)]. The time step for the numerical integration is chosen as $1/2000$ of the pulse-off time. The error in the value of $s(t_n)$ is less than 0.0011% as the time step decreases from $1/1000$ of the pulse-off time to $1/2000$ of the pulse-off time.

2.4 Results and Discussion

2.4.1 Overheating

The temperature distributions along the $z$-direction at $r = 0$ are presented in Figure 2.2 for different laser powers which correspond to different irradiances. Because of the Gaussian beam profile, the maximum laser irradiance ($I_0$) occurs at the center of the beam ($r = 0$) and this produces maximum temperature at $r = 0$ on a given plane of fixed depth. For low laser irradiances the maximum temperature occurs at the drilling front. There is a definite temperature gradient in the $z$-direction within the polymer layer. The temperature gradient, however, is very small in the copper layer because of its high thermal conductivity (~390 W/m K), which is about 1000 times higher than that of the polymer substrate. The volumetric heating becomes important at high laser irradiances. For $I_0 \leq 1$ kW/cm$^2$ the overheating inside the polymer can be neglected. For $I_0 = 1.2$ MW/cm$^2$ the maximum temperature inside the polymer is 2630 K which is much higher than the vaporization point 583 K.
Figure 2.2 Temperature distribution at different maximum laser irradiances of Gaussian beams for pulse-on time = 20 μs, period = 50 μs, and time t = 0 μs.

2.4.2 Drilling depth profile

2.4.2.1 Effect of embedded copper layer

The drilling speed is greatly reduced due to the buried copper layer. It can be seen in Figure 2.3 that after 20 μs of irradiation with a Gaussian beam of P = 3 W, pulse-on time=20 μs and period=50 μs, the drilling depth is much larger for an infinitely thick polymer substrate than for a 30 μm-thick polymer layer containing a buried copper layer. This is due to the energy loss through heat conduction and reflection of the laser beam by the copper layer.
Figure 2.3 The difference of drilling depth profile between infinite thick polymer and 30μm-thick polymer for the same Gaussian beam of P=3 W, pulse-on time=20 μs, period=50 μs, and time t=20 μs.

### 2.4.2.2 Drilling front profile for different laser beam profiles

For low laser power, the residue exists even after two pulses of laser irradiation. The amount of residue is, however, different for different combinations of the laser beam shape. The drilling depth after 2 pulses of laser irradiation is presented in Figure 2.4 for different beam shapes with the same laser power of 1 W and the same period of 50 μs. For curves A, B and C, the first irradiation is with a Gaussian beam and then the second irradiation is applied with a Gaussian beam, a full Gaussian annular beam (with the maximum irradiance being at the central circle of the annulus) and a half Gaussian annular beam (with the maximum irradiance being at the outer radius of the annulus) respectively. When both irradiations are due to a laser beam of uniform...
irradiance profile, the thickness of the residue is approximately to zero at the bottom of the hole (curve D in Figure 2.4). When the first irradiation is with a Gaussian beam, the second irradiation should be with a half Gaussian annular beam to achieve the minimum amount of residue at the bottom of the hole (curve C in Figure 2.4).

![Figure 2.4 The drilling depth after 2 pulses of laser irradiation for different beam profiles of P=1 W, pulse-on time=20 μs, and period=50 μs.](image)

To compare the drilling efficiency of these three beam profiles, the mass removal rate through vaporization is calculated as follows:

\[
\dot{m} = \int_0^s \rho \frac{\partial s(r,t)}{\partial t} \cdot 2\pi r dr,
\]

and the results are presented in Figure 2.5. For each beam profile, the mass removal rate is large
at the beginning of the drilling process and then the rate reduces with time as the drilling front approaches towards the copper layer. This is because the thickness of the polymer absorbing the laser energy is reduced and the laser energy reflected by the copper layer is increased. During the pulse-off time, the mass removal rate drops sharply to zero. The mass removal rate for a uniform beam profile is almost always higher than that for the Gaussian or the annular Gaussian beam profiles. It should be noted that the area below each curve in Figure 2.5 is the total mass removed during the drilling process. The total mass removed by the uniform laser beam profile is the largest.

Figure 2.5 The mass removing rate variation with times after laser irradiation begins for different laser beam profiles of P=3 W, pulse-on time=20 μs, and period=50 μs.
2.5 Conclusions

A thermal model with volumetric heating source is presented to analyze the microvia drilling process in polymeric substrates.

(1) Because of volumetric heating, an overheated region is formed inside the polymer for laser irradiances larger than 1 kW/cm². The maximum internal temperature of polymer increases as the laser irradiance increases.

(2) The depth of the point of maximum temperature from the drilling front first increases and then decreases as the drilling process progresses. This depth also decreases as the laser pulse-on time decreases.

(3) As the drilling front approaches the bottom of the hole the volume of the polymer that absorbs the laser energy decreases and the laser energy reflected by the copper layer increases. Consequently the drilling speed decreases. Residues are formed at the bottom of the hole. These residues may be removed using lasers of different beam profiles.
CHAPTER 3: NUMERICAL ANALYSIS FOR LASER MICROVIAS DRILLING

3.1 Introduction

Usually numerical models are used to describe the volumetric heating process. Noguchi et al. (2003) applied the enthalpy method to formulate a one-dimensional volumetric heating model and solved it using a finite element technique. Voisey and Clyne (2004) and Sezer et al. (2006) numerically simulated pulsed laser drilling of thermal barrier coatings with assist gas. Semak et al. (1999) used a finite difference method, whereas Zeng et al. (2005) presented an analytic model to calculate the temperature field during laser drilling by considering convective heat transfer due to the liquid metal flow induced by the recoil pressure of the outgoing metal vapor. The convective heat transfer is negligible in the case of polymeric materials for which the liquid layer is thin [Zhang et al. (2006)].

Self-defocusing of the laser beam is another effect that can be important in laser drilling of semi-transparent materials. As the drilling process progresses, a crater-shaped hole with a concave curvature is generally formed. The concave surface acts as a lens with negative focal length defocusing the incident laser beam. This phenomenon is termed as self-defocusing during laser drilling, which depends on the refractive index of the material. Large refractive index means high optical power of the negative lens leading to more pronounced defocusing effect. Most of the studies analyzed the role of plasma on self-focusing or self-defocusing effects during laser-
material interactions [Ashkenasi et al. (1998); Sun et al. (2004); Amrita et al. (2006)]. Strombeck and Kar (1998) studied the self-focusing effect in laser welding where convex surfaces are formed by the molten material due to the surface tension between the melt and substrate.

This research examines the self-defocusing effect arising due to the divergence of the incident laser beam by the concave drilling front as the laser beam propagates into the polymeric substrate. Volumetric laser heating is also considered in the thermal model which is solved using the finite difference method. Since the laser irradiance is very high for laser drilling, the volumetric heat source term in the energy equation generally causes numerical instability while solving the finite difference equations. To ensure computational stability, time-split MacCormack method [Anderson et al. (1984)] is used. The locations of the drilling front are tracked at each time step of the calculation.

### 3.2 Numerical Model with Self-Defocusing Effect

When a laser beam is incident on polymer substrates, a portion of the light penetrates into the material and deposits a fraction of its energy within a certain volume of the substrate. Thus the laser beam acts as a volumetric heat source. As the substrate surface temperature rises, melting and material removal due to vaporization and chemical degradation of the polymer occur creating a hole in the substrate.
3.2.1 Gaussian beam propagation

The propagation of the Gaussian laser beam in the substrate is analyzed for the drilling geometry presented in Figure 3.1 showing a multilayered substrate consisting of an embedded copper layer covered with polymer layers on both sides of the copper pad. The incident laser beam is focused towards the substrate with a lens of focal length $f_a$ creating a beam waist $w_{0a}$ at the focal spot. The distance between the focal plane and the top surface of the substrate is $z_{wa}$. As drilling progresses, the concave drilling front, which is simplified as a negative focusing lens, defocuses the laser beam producing another beam waist $w_0$ which is imaginary at the focal spot of the negative lens. If the effective focal length of the drilling front is taken as $f$ which is negative, the beam waist $w_0$ can be expressed as [Strombeck and Kar (1998)]:

$$\frac{1}{w_0^2} = \frac{1}{w_{0a}^2} \left(1 + \frac{z_{wa}}{f_a}\right)^2 + \frac{1}{f^2} \left(\frac{\pi w_{0a}}{\lambda_m}\right)^2$$  (3.1)

where $\lambda_m$ is the wavelength of the laser inside the polymer material i.e., $\lambda_m = \lambda / n_p$. $\lambda$ is the wavelength of the laser in vacuum and $n_p$ is the refractive index of the polymer.

The location of the waist, $z_w$, is given as [Strombeck and Kar (1998)]:

$$z_w = f - (z_{wa} + f) \frac{f}{(z_{wa} + f)^2 + (\pi w_{0a}^2 / \lambda_m)^2}$$  (3.2)

and the radius of the beam is given by:

$$w(z) = w_0 \left(1 + \frac{(z - z_w)^2}{z_r^2}\right)^{1/2}$$  (3.3)
Figure 3.1 Self-defocusing effect in laser drilling of semi-transparent materials.
as it propagates through the substrate. The penetrated laser beam is absorbed by the substrate with an absorption coefficient $\mu$. Assuming the Bouguer-Lambert law to be valid, the laser irradiance propagating downward inside the polymer can be expressed as

$$ I_w = I_i \exp[-\mu(\overline{l} - s)] \quad (3.4) $$

where $\overline{l}$ is the laser propagation path vector representing the path length along the direction of laser beam propagation, $s$ is the drilling depth measured in the $z$ direction and $I_i$ is the irradiance of the incident laser beam. If the divergence of the beam is not large, $\overline{l}$ is in the $z$ direction. For a Gaussian beam,

$$ I_i = (1 - R_p) \cdot I_0 \cdot \exp[-2r^2 / w^2(z)] \cdot \Phi_p(t) \quad (3.5) $$

where $R_p$ is the reflectance of the polymer, $I_0$ is the laser irradiance at the center of the beam and $\Phi_p(t)$ is the laser pulse shape function which is considered to be rectangular in this study. $R_p$ depends on the incident angle of the laser beam and the laser polarization, as shown in Figure 3.2. The Fresnel reflection coefficients $r_\parallel$ and $r_\perp$ for parallel- and perpendicular-polarized lights respectively are given by

$$ r_\parallel = \frac{n_p \cos \theta_i - n_a \cos \theta_i}{n_p \cos \theta_i + n_a \cos \theta_i} \quad \text{and} \quad r_\perp = \frac{n_a \cos \theta_i - n_p \cos \theta_i}{n_a \cos \theta_i + n_p \cos \theta_i} \quad (3.6) $$

where $\theta_i$ and $\theta_t$ are the incident and refraction angles respectively and $n_a$ and $n_p$ are refractive indices of the air and the polymer respectively.

The reflectance $R_\parallel$ and $R_\perp$ for parallel and perpendicular-polarized lights respectively are then given by $R_\parallel = |r_\parallel|^2$ and $R_\perp = |r_\perp|^2$. $R_p$ is taken as the average value of $R_\parallel$ and $R_\perp$. 
Figure 3.2 Variation of reflectivity at the drilling front with the incident angle.

The laser irradiance at the center of the beam is given by

\[ I_0 = \frac{2Pt_p}{\pi w^2(z)t_{on}} \]  

(3.7)

for a pulsed laser, where \( P \) is the average laser power and \( t_p \) and \( t_{on} \) are the pulse duration and pulse-on time respectively. Combining Eqs. (3.4), (3.5) and (3.7), \( I_{ip} \) can be expressed as:
\[ I_{rp} = \frac{2P(1-R_p)t_p}{\pi w^2(z)t_{on}} \exp\left( -\frac{2r^2}{w^2(z)} \right) \exp[-\mu(z-s)] \] (3.8)

Due to high reflectivity of the embedded copper layer in the multilayer polymer substrate (Figure 3.1), a very small amount of the laser energy is absorbed at the copper surface and the rest is reflected back into the polymer layer. The radius of the reflected beam can be expressed as:

\[ w_r(z) = w_0 \left( 1 + \frac{(d-z_w+d-z)^2}{z_w^2} \right)^{1/2} \] (3.9)

where \( d \) is the thickness of the polymer layer. The irradiance of the reflected beam at its center \( (I_{0r}) \) is given by:

\[ I_{0r} = 2(1-R_p)R_{cu} P t_p / \pi w_r^2(z)t_{on} \] (3.10)

where \( R_{cu} \) is the reflectance of copper. If the reflected beam is still Gaussian, the corresponding irradiance \( (I_{rp}) \) is given by:

\[ I_{rp} = I_{0r} \exp\left( -\frac{2r^2}{w_r^2(z)} \right) \exp[-\mu(d-s+d-z)] \] (3.11)

### 3.2.2 Thermal model

The thermal model for laser heating and heat conduction within the substrate is developed by assuming homogeneous and isotropic polymer material and constant thermophysical properties. The absorbed laser energy is assumed to convert into heat instantaneously. The attenuation of the beam by plasma [Zhang et al. (2005)] and the radiative heat loss are not considered in this model. The material removal is modeled as an ablative sublimation process, solid → vapor.
phase transition with chemical decomposition, because the liquid phase exists for a short
duration [Zhang et al. (2005)].

The enthalpy method is used to solve the phase change problem, where the enthalpy in different
regions of the substrate is utilized to ascertain the temperature field as given below:

\[
T = \begin{cases} 
  T_0 + H/C_p & \text{for } H < C_p(T_d - T_0) \\
  T_d & \text{for } C_p(T_d - T_0) \leq H \leq C_p(T_d - T_0) + E_v \\
  T_d + [H - C_p(T_d - T_0) + E_v]/C_p & \text{for } H > C_p(T_d - T_0) + E_v
\end{cases}
\] (3.12)

where \(T_d\) is the thermal decomposition temperature at which ablative material removal occurs
and \(E_v\) is the specific ablation heat. \(T_0\) is the ambient temperature.

The transient energy equation in the cylindrical coordinate system can be written as:

\[
\rho \frac{\partial H}{\partial t} = k \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + k \frac{\partial^2 T}{\partial z^2} + g
\] (3.13)

for \(0 < z < d\). Here \(k\) and \(\alpha\) are the thermal conductivity and thermal diffusivity of polymer
respectively and \(g\) is the volumetric heat source given by

\[
g = -\frac{\partial I_p}{\partial z} + \frac{\partial I_p}{\partial z}
\] (3.14)

The boundary conditions are:

\[
k \frac{\partial T}{\partial z} = 0 \quad \text{at } z = 0 \quad \text{(3.15-a)}
\]

\[-k \frac{\partial T}{\partial z} + I_a = \frac{T - T_0}{R_{th}} \quad \text{at } z = d \quad \text{(3.15-b)}
\]

\[
k \frac{\partial T}{\partial r} = 0 \quad \text{at } r = 0 \quad \text{(3.15-c)}
\]

\[
T = T_0 \quad \text{at } r = \infty \quad \text{(3.15-d)}
\]
$I_a$ is the laser irradiance absorbed by the copper surface, which is given by

$$I_a = (1 - R_{cu}) \cdot I_i \cdot \exp[-\mu(d - s(r,t))]$$

(3.16)

$R_{th}$ is the thermal resistance of the composite medium made of the copper layer and the polymer layer beneath the copper layer. It should be noted that the polymer layer above the copper layer is being considered for microvia drilling. The value of the thermal resistance can be obtained from the following relation:

$$R_{th} = \frac{d_{Cu}}{k_{Cu}} + \frac{d_p}{k}$$

(3.17)

where $d_{Cu}$ and $k_{Cu}$ are the thickness and thermal conductivity of the copper layer. $d_p$ is the thickness of thermal penetration in the underlying polymer layer.

### 3.2.3 Numerical solution

The Time-Split MacCormack Method [Anderson et al. (1984)] is used to solve the partial differential Eq. (3.13) by taking the numerical stability factor $r' = \alpha \Delta t / (\Delta r \Delta z)$ less than 0.5, where $\Delta t$, $\Delta r$ and $\Delta z$ are respectively time step and spatial steps in the $r$ and $z$ directions. A computational flow chart is presented in Figure 3.3 and various thermo-physical properties of the polymer material are listed in Table 3.1. Different laser parameters such as the wavelength, average power, beam size, pulse repetition rate and pulse width are also input parameters for numerical calculations. The substrate surface is flat before the drilling process begins and therefore, the effective focal length of the surface is taken as infinite prior to material removal. The drilling front, however, presents a concave surface to the incident laser beam after drilling begins to occur, for which the effective focal length is calculated by fitting the drilling front with
second order polynomials such as \( s(r, t) = C_1 r^2 + C_2 r + C_3 \), where \( C_1 \), \( C_2 \) and \( C_3 \) are constants

and \( f = \frac{n_p}{2C_1(n_p - n_a)} \).

Table 3.1. Thermophysical and optical properties of the polymer used for numerical computations.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>0.12 W/m K</td>
</tr>
<tr>
<td>Specific heat</td>
<td>1.62×10^3 J/kg K</td>
</tr>
<tr>
<td>Density</td>
<td>1.44×10^3 kg/m^3</td>
</tr>
<tr>
<td>Thermal decomposition point</td>
<td>539 K</td>
</tr>
<tr>
<td>Specific ablation heat</td>
<td>4.67 MJ/kg</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>11.2×10^{-5} K^{-1}</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>0.62 GPa</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.35</td>
</tr>
<tr>
<td>Refractive index (( \lambda = 9.3 \mu m ))</td>
<td>1.92</td>
</tr>
<tr>
<td>Refractive index (( \lambda = 1.06 \mu m ))</td>
<td>10.63</td>
</tr>
<tr>
<td>Reflectance (( \lambda = 9.3 \mu m ))</td>
<td>9.97%</td>
</tr>
<tr>
<td>Reflectance (( \lambda = 1.06 \mu m ))</td>
<td>68.56%</td>
</tr>
<tr>
<td>Absorption coefficient (( \lambda = 9.3 \mu m ))</td>
<td>0.103 ( \mu m^{-1} )</td>
</tr>
<tr>
<td>Absorption coefficient (( \lambda = 1.06 \mu m ))</td>
<td>0.041 ( \mu m^{-1} )</td>
</tr>
</tbody>
</table>
Figure 3.3 Flow chart for numerical computation.
The propagation of laser beam inside the material is simulated during the laser pulse-on time when the volumetric heat source \( g \) is calculated based on the absorption of the laser energy given by Eq. (3.14). The volumetric heat source is set to zero during the laser pulse-off time. The temperature field is calculated by the Time-Split MacCormack Method. If the temperature of a grid is larger than the thermal decomposition temperature \( T_d \), that grid is considered to absorb the specific ablation heat according to Eq. (3.12). The grid is eliminated from the computational domain if the enthalpy of the grid is greater than or equal to \( C_p(T_d - T_0) + E_v \), which corresponds to material removal during the drilling process. Usually the enthalpy of a grid does not come out to be exactly equal to \( C_p(T_d - T_0) + E_v \) and, therefore, the material removal (the drilling) lies somewhere between two grid points. The enthalpy is considered to vary linearly between two consecutive grid points as shown in Figure 3.4 in order to track the drilling front.

Figure 3.4 Tracking the drilling front within a grid bounded by grid points \( Z_i \) and \( Z_{i+1} \).
3.3 Results and Discussion

The computational domain of the polymer material is 60 \( \mu \text{m} \) in the \( r \) direction and 40 \( \mu \text{m} \) in the \( z \) direction. The independence of the solution on the number of grid is tested by comparing the numerical results to an analytical model [Zhang et al. (2005)] as presented in Figure 3.5, showing the axial temperature distribution in the polymer material at the center of the Gaussian beam \((r = 0)\). Various laser parameters for this testing are: 3 W average power of a CO\(_2\) laser of wavelength 9.3 \(\mu\text{m}\), 20 \(\mu\text{s}\) laser pulse-on time with a period (pulse-on time + pulse-off time) of 50 \(\mu\text{s}\). The calculation error, which is represented by the difference between the numerical result and the analytic solution is less than 0.7% when the calculation domain is divided into 200\(\times\)200 grids and the error is less than 0.2% for 500\(\times\)500 grids. The results presented in this paper are for the calculation domain divided into 600\(\times\)400 grids with calculation error less than 0.3%. The stability of the calculation is shown in Figure 3.6, indicating that the Time-Split MacCormack Method yields a stable solution even when the stability factor \( r' = \alpha \Delta t / (\Delta r \Delta z) \) is as large as 0.47.

The temperature distributions along the \( z \) direction at \( r = 0 \) are presented in Figure 3.7 for four different times after the beginning of laser irradiation. Because of the Gaussian beam profile, the maximum laser irradiance \((I_0)\) occurs at the center of the beam \((r = 0)\) and this produces maximum temperature at \( r = 0 \) on a given plane of fixed depth. The energy of the Gaussian laser beam is 0.392 mJ/pulse, beam radius is 25 \(\mu\text{m}\), pulse-on time is 430 ns, and the pulse repetition rate is 50 kHz. As the irradiation time increases, the temperature inside the polymer increases. After the thermal decomposition point is reached, the temperature will not rise because the
specific ablation heat is absorbed. Since the polymer material can greatly attenuate the laser beam propagating inside it, the temperature is the maximum at the top surface and drilling begins from top to the bottom for CO₂ lasers. In this paper, the enthalpy method is used to describe the phase change and the laser heating model is not based on the boundary condition of a fixed temperature at the drilling front. Consequently overheating of the polymer, i.e., the occurrence of maximum temperature inside the material is not seen in this case (Figure 3.7). However if the temperature is held constant at the drilling front, overheating can be observed inside the polymer substrate [Zhang et al. (2006)].

Figure 3.5 Comparison of an analytic solution with numerical results for different grid numbers, indicating the selection of grids for computational accuracy.
Figure 3.6 Comparison of numerical results for different time step, indicating the selection of the time step for computational stability.
Figure 3.7 Axial temperature distribution at different times during CO$_2$ laser drilling.
However, the drilling mechanism is different for Nd:YAG lasers of wavelength 1.06 μm. The axial temperature distribution due to Nd:YAG laser irradiation is compared to that of the CO₂ laser in Figure 3.8 at time $t = 0.1 \ t_{on}$ which is 43 ns. The laser parameters are same as those used in the case of the CO₂ laser irradiation. Since the absorption coefficient of the polymer material is 0.041 μm⁻¹ at the wavelength of the Nd:YAG laser, which is less than that (0.103 μm⁻¹) at the CO₂ laser wavelength as listed in Table 3.1, the Nd:YAG laser energy reaching the polymer-copper interface will be higher than in the case of the CO₂ laser irradiation. This causes the temperature at the copper-polymer interface to be higher for the Nd:YAG laser than for the CO₂ laser. The radial temperature distribution at the interface is presented in Figure 3.9 at time $t = 0.1 \ t_{on}$, which shows that the temperature will be higher than the thermal decomposition point within a radius of 15 μm after 43 ns of laser irradiation. The polymer may turn into vapor in this region, resulting in high pressure and high thermal stresses inside the material. If the pressure and thermal stresses are high enough, the polymer material above the copper layer will be expelled out and a hole will be formed. This type of material expulsion can improve the drilling rate because more material can be removed by the expulsion process than just by vaporizing the material only at the drilling front.
Figure 3.8 Comparison of the axial temperature distributions for Nd:YAG and CO\textsubscript{2} laser drillings at $r = 0$ and drilling time $t = 0.1$ ton.
Figure 3.9 Comparison of the radial temperature distributions for Nd:YAG and CO₂ laser drillings at the interface of the top polymer and copper layers when drilling time \( t = 0.1 \) \( t_{\text{on}} \).
The drilling front profiles formed at different times are presented in Figure 3.10 for Gaussian CO₂ lasers with pulse energy 0.392 mJ, beam radius 25 μm, pulse-on time 430 ns and repetition rate 50 kHz. The hole depth increases as the drilling time increases and the embedded copper layer can be reached after 3 pulses. More pulses can increase the hole diameter at the copper surface and thus reduce the tapering angle. The self-defocusing effect discussed in this paper can affect the drilling process significantly as seen from the results in Figure 3.11. Without the self-defocusing effect, the embedded copper layer can be reached after one laser pulse which is less than three laser pulses required with the self-defocusing effect.

The drilling is not initiated instantaneously after the laser irradiation begins. The lower the pulse energy, the longer time is needed to initiate the drilling as shown in Figure 3.12. During this time, the laser energy heats up the material to the thermal decomposition point and supply the specific ablation heat. This energy is termed as the ablation threshold energy. The ablation threshold fluence is calculated for different pulse energies in Figure 3.13. Although the drilling inception time is different in Figure 3.12, the laser energy (i.e., the product of the drilling time and the average laser power) supplied to the substrate are the same and the corresponding ablation threshold energies are the same for different pulse energies as shown in Figure 3.13. When the laser energy is accumulated in the material for being heated up to the ablation threshold energy, the absorbed energy may also be lost due to heat diffusion. The diffusion heat loss largely depends on the drilling time. Longer diffusion time means large heat loss. Since the ablation threshold energy is found to be the same
in Figure 3.13 for different nanosecond laser pulses, the diffusion heat loss is negligible in these cases as nanosecond is a small time period for the occurrence of heat diffusion.

Figure 3.10 Depth of the drilling front at different radial locations (drilling front profile) as the drilling progresses.
Figure 3.11 Self-defocusing effect on the drilling front profile.
Figure 3.12 Drilling depth at the center of the laser beam as a function of time for different CO$_2$ laser pulse energies.
Figure 3.13 Ablation threshold fluence for different CO$_2$ laser pulse energies.
The effect of laser beam shape on the drilling process is also analyzed for three types of beam shapes, uniform beam, Gaussian beam and pitchfork beam, as shown in Figure 3.14. For uniform beams, the beam shape at the focal spot is a Bessel beam [Hecht (2001)] due to diffraction. The drilling front profiles due to Bessel beam, Gaussian beam and pitchfork beam are calculated using the numerical model. The laser parameters for these three types of beam shapes are: pulse energy 0.392 mJ/pulse, beam radius 25 μm, pulse-on time 430 ns and pulse repetition rate 50 kHz. The drilling front profiles are shown in Figure 3.15 for the three beam shapes after the first pulse. For the same amount of laser energy, the pitchfork beam has the possibility of producing microvias with the smallest tapering angle. The advantage of the pitchfork beam is that it can utilize the self-defocusing or self-focusing effect to improve the effectiveness of the drilling process. The central region of the drilling front in Figure 3.15 can be regarded as a positive focusing lens for the pitchfork beam, whereas the same region will act as a negative lens for the Gaussian beam. Therefore the central portion of the pitchfork beam will be focused by the drilling front, raising its irradiance and causing rapid material removal. Thus the drilling speed is enhanced by the pitchfork beam. Drilling experiment was carried out with the pitchfork laser beam. A scanning electron microscopic cross-sectional view of the microvia drilled by a pitchfork laser beam is shown in Figure 3.16. The laser parameters for the drilling experiment were: pulse energy = 0.3 mJ, beam radius = 21 μm, pulse width = 430 ns and repetition rate = 83.3 kHz. The optics to convert an incident Gaussian beam into the pitchfork beam was so designed that the central valley and peripheral peak regions (Figure 3.14) of the beam contained 1.1% and 17.8% of the total laser energy respectively. 8 pulse trains each containing 8 pulses were used to drill one microvia. The drilling front profile calculated by the
model with the same laser parameters is also shown in Figure 3.16 as the white solid line which agrees the experimental data very well.

Figure 3.14 Different laser irradiances used in the comparison of drilling front profiles.
Figure 3.15 Comparison of drilling front profiles after one laser pulse for different beam shapes with the same pulse energy.
Figure 3.16 Drilling front profile produced with a pitchfork laser beam (pulse energy = 0.3 mJ, beam radius = 21 μm, pulse width = 430 ns, repetition rate = 83.3 kHz). Due to diffraction the central lobe of the beam only contains 18.9% of the total laser energy.
3.4 Reflection by Embedded Copper Plane and Volumetric Heating in Laser Drilling

The effects of irradiance and pulse shape on the thickness of the residue were studied by the numerical thermal model.

3.4.1 Effect of nanosecond-rectangular pulse and pitchfork beam

As discussed earlier, three mechanisms can be identified for microvia drilling, which have been designated as super-critical, critical drilling and sub-critical drilling. Figure 3.17 shows the microvia depth as a function of time for rectangular pulse shape and pitchfork beams. The drilling does not occur at the beginning up to about 60 ns because the laser energy is absorbed just to heat up the material to its thermal decomposition temperature and to supply the specific ablation heat. After this threshold regime, the material begins to vaporize and the drilling process starts. Most of the laser energy is deposited over a large depth of the polymer layer in this super-critical drilling stage, which reduces the strength of the volumetric heat source, i.e., the amount of laser energy deposited per unit volume of the polymer layer per unit time, and consequently the microvia depth increases gradually. In the critical drilling stage, however, both the incident and the reflected laser beams deposit energy within a thin (less than or equal to 9.7 μm) section of the polymer layer, which increases the strength of the volumetric heat source, and therefore the microvia depth increases rapidly. In the sub-critical drilling stage, a very thin layer of polymer is expected to remain as residue at the bottom of the microvia. The result of the model shows that the residue thickness is less than 0.1 μm for nanosecond pulsed laser in figure 3.17.
The drilling speed at various stages of the drilling process is presented in figure 3.18, showing an almost constant drilling speed at the super-critical drilling stage. When the thickness of the polymer layer decreases to the absorption depth of 9.7 μm, the critical drilling begins and the drilling speed increases sharply. Soon the sub-critical drilling mechanism sets in and the drilling speed decreases steeply. For pulse width \( \tau = 430 \text{ ns} \), the final residue is 0.1 μm. A rectangular pulse is used to obtain these results. To remove the residue, i.e., to drill microvias without any residue, the pulse shape, i.e., temporal distribution of laser energy would have to be designed. Residue removal, however, implies that the residue is formed at first and then we are seeking a solution to remove the residue, which makes the drilling process inherently ineffective. An effective drilling process should prevent the formation of the residue and thereby allow clean microvia drilling, which may be accomplished by pulse shaping as examined below.
3.4.2 Effect of nanosecond ramp-up pulse and pitchfork beam

Figure 3.19 shows the microvia depth as a function of time for ramp-up (triangular) pulse. The drilling threshold time (60 ns) for the rectangular pulse is shorter than the threshold time (160 ns) for the ramp-up pulse because the laser power increases to its final value instantaneously in the former case, whereas the laser power is small and rises slowly at the beginning in the latter case. Although the ramp-up pulse requires a long drilling time (~160 ns), much of the drilling time is consumed as the drilling threshold time. After the drilling begins, the ramp-up pulse takes less time to remove the polymer layer than the rectangular pulse. Near the end of the pulse, the drilling speed is also higher as shown in figure 3.20. The high drilling speed indicates that the energy input to the polymer layer is higher than the energy loss from the layer and, consequently, the 0.1 μm thick residue is removed more efficiently. A combination of the rectangular and ramp-up pulses as shown in figure 3.21 would be useful to reduce the drilling threshold time at the beginning of the pulse and then apply a very high laser intensity near the end of the pulse to vaporize the thin polymer layer in the sub-critical stage. This will prevent the formation of residue allowing residue-free, i.e., clean microvia drilling.
Figure 3.18 Drilling speed as a function of time for the pitchfork laser beam: rectangular pulse, pulse energy = 0.9 mJ, pulse width = 430 ns, repetition rate = 20 kHz.

Figure 3.19 Drilling depth as a function of time for the pitchfork laser beam: triangular pulse, pulse energy = 0.9 mJ, pulse width = 430 ns, repetition rate = 20 kHz.
Figure 3.20 Drilling speed as a function of time for the pitchfork laser beam: triangular pulse, pulse energy = 0.9 mJ, pulse width = 430 ns, repetition rate = 20 kHz.

Figure 3.21 A schematic representation of optimized pulse shape for laser microvia drilling.
3.4.3 Effect of microsecond rectangular pulse and pitchfork beam

Figure 3.22 shows the microvia depth as a function of time for microsecond pulsed laser with rectangular pulse width 430 μs. After the drilling threshold time (60 μs) when the drilling begins as shown in figure 3.23, the drilling speed is almost constant before the polymer layer thins down to the absorption depth of 9.7 μm. Near the end of the pulse, the drilling speed increases fairly fast and then gradually decreases to zero. This slow heating rate leads to the formation of residue at the bottom of the via. The final residue is 0.3 μm thick for pulse width 430 μs, which is thicker than the residue thickness 0.1 μm for 430 ns pulse width. This difference in the residue thickness for the two pulse regimes could be because the nanosecond pulsed laser can deposit the laser energy in the residual layer of thickness $D_r$ at a shorter time scale than the thermal diffusion time, i.e., $\tau < D_r^2 / \alpha$, and, therefore, less energy is lost to the copper plane in the case of nanosecond pulsed laser than in the case of microsecond pulsed laser.

![Figure 3.22](image_url)

Figure 3.22 Drilling depth as a function of time for the pitchfork laser beam: rectangular pulse, pulse energy = 0.9 mJ, pulse width = 430 μs, repetition rate = 20 kHz.
Figure 3.23 Drilling speed as a function of time for the pitchfork laser beam: rectangular pulse, pulse energy = 0.9 mJ, pulse width = 430 μs, repetition rate = 20 kHz.

3.5 Conclusions

A numerical thermal model is developed accounting for the self-defocusing effect to analyze the microvia drilling process in polymer substrates. Results show that self-defocusing of the laser beam by the drilling front can greatly reduce the drilling speed. So the refractive index of the material at a specific wavelength is an important parameter for laser drilling. The CO₂ laser drilling of polymer substrates is mainly due to ablation as well as vaporization. The Nd:YAG laser drilling mechanism involves thermomechanical breakage or expulsion of the material by high internal pressure. The self-focusing effect can be utilized advantageously with pitch fork beams to increase the drilling speed compared to uniform and Gaussian beam shapes.
This thermal model is also used to analyze the effects of volumetric heating and reflection by embedded copper plane for microvia drilling in multilayered polymeric substrates. Three drilling mechanisms, super-critical, critical and sub-critical drilling stages have been identified. The drilling speed increases sharply when the polymer layer thins down to the absorption depth because both the incident and reflected laser beams contribute to the volumetric heating over a small polymer volume. The residue thickness is thinner for drilling by the nanosecond pulsed laser compared to the case of microsecond pulsed laser drilling. For CO₂ laser pulse energy higher than 0.9 mJ and pulse width 430 ns, the residue thickness is less than 0.1 μm after one period, i.e., the pulse-on time plus pulse-off time. Laser pulse shaping is necessary to efficiently utilize the laser energy and to remove the residue, i.e, to drill residue-free microvias.
Organic substrates are widely used in flip chip microelectronic packaging because of its unique electronic, thermophysical and mechanical properties. A variety of polymer materials such as FR4 (Flame Retardant 4) resin, tetrafunctional phenolics, cyanate ester, polyimides and BT (Bismaleimide Triazine) are used [Lee et al. (1998)] to manufacture substrates and printed circuit boards (PCB). An emerging material for high density packaging in microelectronics applications are inorganic particle-filled epoxies. The material used in this study is 30-40 wt.% silica-filled epoxy. Closely-spaced small diameter vias are necessary for high density packaging in microelectronics industries. Lasers are used to drill microvias in build up substrates. Thermophysical properties of the polymer should be known to produce high quality microvias such as nontapered and polymer char-free holes without any heat-affected zones.

Different measurement systems are used to determine the thermal conductivity and diffusivity and solid-to-gas/vapor phase transition enthalpy. Traditionally there are three measurement techniques: 1) steady-state heating, 2) periodic heating and 3) pulsed heating [Azar (1997)] for thermal conductivity and diffusivity. The pulsed heating technique is particularly useful for measuring the thermal diffusivity of thin plates. In the steady-state heating method, the steady state is attained after a relatively long time and, therefore, the heat loss has a great influence on
the data [Azar (1996)]. Morikawa and Hashimoto (1997) have employed alternating current (AC) joule heating to induce periodic heating in order to measure the thermal diffusivity of polyethylene terephthalate and polyethylene naphthalate. The flash method developed by Parker et al. (1961) has become one of the most popular pulsed heating techniques [Vozar et al. (2003)]. The thermal diffusivity of most materials including semitransparent materials [Lazard et al. (2000)], anisotropic media [Demange (2002)] and thin films [Tang et al. (2000)] can be measured by the flash method. The flash method involves pulsed heating of the sample in order to apply a heat flux just to the sample surface instantaneously. Femtosecond lasers may achieve spatially confined and temporally very fast heating conditions for certain materials. However, the finite heat pulse duration, finite absorption depth and thermal response time of the material may affect the accuracy of measurement for thin films. Taketoshi et al. (2001) employed a complex thermoreflectance technique to measure the thermal diffusivity of submicrometer thin films.

During laser drilling of microvias in polymers, various physico-chemical phenomena such as the gas diffusion, phase transition (e.g., solid → glassy phase → melt → vapor), chemical degradation and chemical reaction may occur before reaching the thermal decomposition temperature $T_d$ [Godovsky (1992)]. These processes may occur concurrently, leading to the ablation of materials and thus provide a mechanism for laser microvia drilling. To account for the energy involved in these phenomena, “specific ablation heat,” representing the amount of heat needed to ablate a unit mass of the polymeric material at its thermal decomposition temperature, is measured in this study. The substrate surface temperature quickly stabilizes after the chemical degradation of the polymer and tends to remain constant under a quasi steady state.
condition during laser microvia drilling [Arnold (1995)]. So the surface temperature, which is
termed as the thermal decomposition point, can be considered to be constant and the
corresponding heat input may be taken as the specific ablation heat. This specific ablation heat
is similar to the term “specific ablation heat” used to define the heat input for boiling materials
at their respective boiling temperature.

Most measurements of the latent heat of vaporization are based on calorimetric method [Stephan
et al. (2004); Parillo et al. (1998)]. Recently Godts et al. (2005) discussed a simple flowmetric
method to determine the solid latent heat of vaporization. A laser heating-based simple and
general experimental setup is investigated in the present paper to measure the thermophysical
properties of 30-40 wt.% silica-filled epoxy. Higher concentration of the filler increases the
thermal conductivity in the temperature range used in this paper, because of the relatively higher
thermal conductivity of fused silica. A 10% increase of the weight fraction of the filler can result
in about 25% increase of the composite thermal conductivity [Garret and Rossenberg (1974)].
The size effect of the filled particle is not pronounced since the temperature range for the
experiment is much higher than 20 K [Garret and Rossenberg (1974)]. The thermophysical
properties measured in this study are average values for the temperature range 20 to 200°C at the
standard atmospheric pressure. Higher temperature can result higher thermal conductivities for
non-metals.
4.2 Experimental Procedure

The experimental setup to measure the thermal diffusivity and conductivity of the polymer is shown in Figure 4.1. A Nd:YAG laser at the wavelength of 1.06 μm is used to heat the sample. The optical property of the polymer material is such that the Nd:YAG laser beam propagates through the polymer sheet with an absorption coefficient of $4.1 \times 10^4$ m$^{-1}$ which is calculated by

$$\mu = -\ln\left(\frac{T_p}{1-R_p}\right) / d,$$

where $\mu$ is the absorption coefficient and $d$ is the thickness of polymer. $R_p$ and $T_p$ are reflectance and transmittance measured by CARY 500 Scan spectrophotometer. Thus the laser beam deposits its energy inside the sheet and acts as a volumetric heat source to heat up the material. The temperatures of the front and rear surfaces of the sheet are measured with an infrared optical pyrometer with the accuracy of 0.3% + 2K. As the amount of the absorbed energy increases, the polymer material becomes soft and then decomposes into gases. The temperature at which the polymer begins to decompose is referred to as the decomposition point. To determine the thermal diffusivity, the decomposition should be avoided. The temperature field in the polymer sheet attains a steady state after a short period of time due to the heat loss from the sheet to the surrounding environment. After the steady state is established, the laser irradiation is stopped and the temperature at the rear surface of the sheet is recorded as a function of time until the temperature drops to room temperature. This temporal profile of the temperature is fitted to the analytic solution of a thermal model to determine the thermal diffusivity. By estimating the heat transfer coefficient of the surrounding air [Incropera et al. (1990)], the thermal conductivity of the polymer can be obtained from the convection boundary condition at the sheet-air interface.
Figure 4.1 Experimental setup for temperature measurements to determine the thermal conductivity and thermal diffusivity of the polymer sample.

Table 4.1. Values of different thermophysical properties obtained in this study for a typical polymer build up film.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>0.18 W/m K</td>
</tr>
<tr>
<td>Thermal diffusivity</td>
<td>1.2×10^{-7} m^2/s</td>
</tr>
<tr>
<td>Specific heat</td>
<td>1.04×10^3 J/kg K</td>
</tr>
<tr>
<td>Density</td>
<td>1.44×10^3 kg/m^3</td>
</tr>
<tr>
<td>Thermal decomposition point</td>
<td>539 K</td>
</tr>
<tr>
<td>Specific ablation heat</td>
<td>4.96 MJ/kg</td>
</tr>
<tr>
<td>Reflectance</td>
<td>68.56%</td>
</tr>
<tr>
<td>Absorption coefficient at wavelength 1.06 μm</td>
<td>4.1×10^4 m^{-1}</td>
</tr>
</tbody>
</table>
The specific ablation heat is determined using an experimental setup shown in Figure 4.2. Since the specific ablation heat is considered in this study to represent the heat input to the material at the chemical degradation temperature during the laser drilling of microvias in polymers, the polymer sheet used in the measurement should be identical to the polymer sheet used as build-up substrates for a given microelectronics application. This special consideration in selecting the sample for experimental studies will allow the estimation of the specific ablation heat that can be used for modeling the actual microvia drilling process. Since the actual build up substrate consists of multilayer polymer layers and copper metallizations, laminated polymer film on a copper claded core was used as a sample in this study. The laser power incident on the front surface of the sample was measured with a power meter. A portion of the incident laser energy is reflected and the rest is absorbed by the polymer. Since the wavelength of the Nd:YAG laser was 1.06 μm, the reflectivity of the polymer \( R_p \) was measured with an infrared spectrometer and its value is listed in Table 4.1. For the specific ablation heat experiment, a laser beam of relatively high irradiance was used. The absorbed laser energy heats up the polymer to its decomposition temperature and causes ablation of the material. The specific ablation heat can be calculated by knowing the loss of mass due to ablation and the absorbed laser energy. Because of the low thermal conductivity and the small size of the laser beam, the heat loss due to conduction, convection and radiation is negligible compared to the reflected laser energy. If the heat loss is not ignored, it can be considered together with reflection in a single coefficient – absorptivity \( A \), which is described in the following section. The loss of mass is determined by weighing the sample before and after the laser ablation experiment. Since the polymer sheet is very thin and the diameter of the laser spot is very small, the loss of mass would be very small if the laser beam is irradiated to a single spot on the sample and it would be difficult to determine
such a small change in the mass. So the sample was moved with an x-y stage to induce laser irradiation over a large surface area in order to increase the loss of mass. The controller of the stage was a VXM Stepper Motor Controller with two Vexta PK266 motors. The motion of the stage was programmed with the Velmex COSMOS software. After laser ablation, a quartz crystal microbalance was used to measure the mass loss after the laser vaporization experiment. The density of the polymer was determined by measuring the mass of a polymer sheet with the microbalance and by knowing the volume of the sheet. The surface area and thickness of the sheet were 36 mm × 24 mm and 97 μm respectively. The value of the density is listed in Table 4.1.

Figure 4.2 Experimental setup for laser-induced vaporization and thermal decomposition of the polymer sample to determine a characteristic value of the specific ablation heat.
4.3 Thermal Modeling for Material Property Determination

Analytic thermal models are used to evaluate the thermophysical properties of the polymer sheet. To measure the thermal conductivity and thermal diffusivity, a one-dimensional heat conduction model is considered to be appropriate since the polymer sheet is very thin (97 μm) compared to the diameter of the laser beam (2 mm). The polymer material, such as the epoxy resin widely used as the organic high density interconnecting substrates, is considered isotropic. The thermophysical properties are also considered independent of temperature. The absorbed laser energy is assumed to be transformed into thermal energy instantaneously. If the polymer material is considered as a gray body, the emissivity is equal to the absorptivity which is found to be 0.3 based on spectrophotometric measurements on the reflectivity and transmissivity of the sample. The radiative heat loss from this grey body can be calculated from 

\[ E_\varepsilon = \varepsilon_m \sigma (T^4 - T_0^4) \]

where \( \varepsilon_m \) is the emissivity. \( \sigma \) is the Stefan-Boltzmann constant. \( T_0 \) is the surrounding (room) temperature. The temperature of the polymer \( T \) was kept at about 196°C to avoid any thermal decomposition for the conductivity determination experiments. This value of the temperature yields the radiative heat loss less than 8% of the heat conduction and heat convection.

The laser irradiance on the sample was kept low using a large diameter (2 mm) laser beam in the experiments for measuring the thermal conductivity and thermal diffusivity. Typical samples for these experiments were sheets of polymers. Low irradiance is necessary to prevent localized melting or oxidation of the sample in order to achieve just conduction heat transfer in the sample. At the same time, however, the temperature of the sample should be sufficiently high to
measure the temperatures at the front and rear surfaces accurately. Most of the laser light passes through the sample since the polymer sheet is semi-transparent. A black coating was painted on the front surface of the polymer sheet to enhance the absorption of laser energy at the front surface, which raised the temperature of the polymer sample significantly. The black coating was very thin compared to the polymer sheet and was able to absorb most of the laser energy. So the surface heating instead of volumetric heating can be used in the thermal model.

To measure the specific ablation heat, however, a certain amount of the sample needs to be vaporized, which was readily achieved using a small diameter (60 μm) laser beam and, therefore, the black coating was not used in the laser vaporization experiments. The melting of a very small amount of the materials with a scanning laser beam allows us to consider an overall energy balance instead of the differential heat conduction equation. Since it is difficult to distinguish the onsets of vaporization and thermal decomposition of the polymer material, we attempt to obtain a characteristic value for these physical phenomena so that the value of this material property can be used for analyzing the laser microvia drilling of actual polymer substrates. The experimental sample for the laser vaporization studies is, therefore, chosen to be the laminated polymer substrates with copper metallization.

4.3.1 Determination of the ratio of heat transfer coefficient (h) to thermal conductivity (k), i.e., h/k, and thermal conductivity using the steady state thermal analysis

For evaluating first the heat transfer parameter (h/k) and then the thermal conductivity, a laser beam of relatively low irradiance is used to establish a steady state temperature field in the sample. The vaporization of the polymer is avoided in the experiment in order to induce
conduction heat transfer in the sample without any phase (solid → glassy phase → liquid → vapor) change.

The governing equation for the steady state heat conduction is

\[
\frac{\partial^2 T}{\partial z^2} = 0 \tag{4.1}
\]

for \(0 < z < d\), where \(z\) and \(t\) are the axial and time variables respectively, \(d\) is the thickness of the polymer sheet. The \(z\)-axis, which is in the direction of laser beam propagation, is directed along the thickness of the sample with origin at the front surface of the sample. Here \(T\) is the excess temperature above room temperature, i.e., \(T = T_\text{a} - T_0\), where \(T_\text{a}\) and \(T_0\) are the actual temperature of the sample and room temperature respectively.

The boundary conditions for Eq. (4.1) can be written as

\[
T = T_f \quad \text{at } z = 0 \tag{4.2}
\]

and

\[
- \frac{\partial T}{\partial z} = \frac{h}{k} T \quad \text{at } z = d, \tag{4.3}
\]

where \(T_f\) is the temperature at the front surface of the sample, which is measured with an infrared optical pyrometer. \(h\) is the heat transfer coefficient of the surrounding air and \(k\) is the thermal conductivity of the polymer material.

The solution to Eq. (4.1) subject to boundary conditions (4.2) and (4.3) is

\[
T = - \frac{(h/k)T_f}{(h/k)d + 1} z + T_f \tag{4.4}
\]
Knowing $T$ at a certain value of $z$, the unknown parameter $h/k$ can be determined from Eq. (4.4) and then the thermal conductivity $k$ can be obtained for a given value of $h$ prevailing during the experiment. Although the heat transfer coefficient of surrounding air can be estimated from Ref. [Incropera et al. (1990)], the uncertainty in the value of $h$ will affect the accuracy of the measurement technique. To exclude this uncertainty, $h/k$ is treated as a single parameter and the temperature $T$ is measured at $z = d$, which is referred to as the rear surface temperature $T_r$. Substituting $T_r$ into Eq. (4.4), $h/k$ can be obtained from the following expression:

$$\frac{h}{k} = \frac{T_f - T_r}{T_r d}$$

(4.5)

Since $T_f$, $T_r$ and $d$ are measured directly, the value of $h/k$ would be accurate and will allow to determine the thermal diffusivity as discussed in the following section.

To determine the thermal conductivity, however, we need to rely on the estimated value of $h$ so that $k$ can be obtained by the following expression:

$$k = \frac{h T_r d}{T_f - T_r}$$

(4.6)

Thus the value of $k$ is expected to be less accurate than the value of the thermal diffusivity.

From Eqs. (4.4) and (4.5), the steady state temperature distribution in the sample can be rewritten as

$$T = T_f - (T_f - T_r) \frac{z}{d}$$

(4.7)
which is used as the initial condition in the following thermal model to determine the thermal diffusivity of the sample.

### 4.3.2 Determination of thermal diffusivity and specific heat capacity using the transient thermal analysis

The laser irradiation is stopped when the steady state is reached in the experiment mentioned in section 4.3.1, resulting in cooling of the sample. The temperature distribution during the cooling period is analyzed using the following transient thermal model:

\[
\frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t},
\]

where \( \alpha \) is the thermal diffusivity of the polymer. The initial condition for Eq. (4.8) is taken as the steady state temperature distribution in the sample (Eq. (4.7)) at the moment the laser irradiation is stopped.

The boundary conditions are:

\[
\frac{\partial T}{\partial z} = \frac{h}{k} T \quad \text{at} \quad z = 0,
\]

and

\[
-\frac{\partial T}{\partial z} = \frac{h}{k} T \quad \text{at} \quad z = d,
\]

where \( h/k \) is obtained in section 3.2.2.1.

The solution to the heat conduction problem given by Eqs. (4.8-4.10) is
\[ T(z, t) = \sum_{m=1}^{\infty} \frac{\exp(-\alpha \lambda_m^2 t)}{N(\lambda_m)} \cdot Z(\lambda_m, z) \cdot \int_0^d Z(\lambda_m, z) \cdot \left( T_f - (T_j - T_i) \cdot \frac{z}{d} \right) dz \]  

(4.11)

where the normalization constant is

\[ N(\lambda_m) = \frac{1}{2} \left[ (\lambda_m^2 + (h/k)^2) \cdot \left( d + \frac{h/k}{\lambda_m^2 + (h/k)^2} \right) + \frac{h/k}{\lambda_m^2} \right] \]  

(4.12)

and the eigenfunction is

\[ Z(\lambda_m, z) = \lambda_m \cdot \cos(\lambda_m z) + \frac{h/k}{\lambda_m} \cdot \sin(\lambda_m z) \]  

(4.13)

The eigenvalues \( \lambda_m \) are the roots of the following transcendental equation

\[ \tan(\lambda_m d) = \frac{\lambda_m 2h/k}{\lambda_m^2 - (h/k)^2} \]  

(4.14)

Thus the transient temperature field can be calculated using Eq. (4.11). Since the temporal change in temperature at the rear surface is recorded during the experiment, the theoretical temperature profile, \( T(d, t) \), obtained from Eq. (4.11) is fitted to the experimental temperature profile by choosing an appropriate value of the thermal diffusivity.

The specific heat capacity at constant pressure, \( C_p \), can be obtained using the expression

\[ \alpha = k l(\rho C_p) \]  

where \( \rho \) is the density measured by the method mentioned earlier.

### 4.3.3 Determination of Thermal Decomposition Point and Specific Ablation Heat Using Overall Energy Balance
To measure the thermal decomposition temperature $T_v$, the optical pyrometer is used to monitor the heating process. As the amount of the absorbed laser energy increases, the polymer material decomposes into gases. The inception of gas formation is observed visually. When the polymer sheet just begins to liberate gases, the surface temperature of the sample is recorded with the optical pyrometer as the thermal decomposition point.

To measure the specific ablation heat, the following overall energy balance equation is used:

$$P(1 - R_{\text{poly}})A\tau = \Delta m[E_v + C_p(T_d - T_0)]$$

(4.15)

where $P$ is the average power of the incident Nd:YAG laser beam, $R_p$ is the reflectance of the polymer sheet, $\tau_v$ is the laser vaporization experiment time and $\Delta m$ is the loss of mass during the experiment. $T_0$ is the surrounding (room) temperature. $E_v$ is the specific ablation heat that we want to determine. After a fraction of the incident laser energy is reflected at the front surface of the sample, the rest of the laser energy penetrates into the sample since the polymer is semitransparent. The absorption of this transmitted energy can be divided into three parts: 1) energy absorbed by the polymer when the beam propagates from the front surface to the copper layer, 2) energy absorbed by the copper layer and 3) energy absorbed by the polymer when the laser beam propagates upward to the front surface after being reflected by the copper layer. The absorptivity $A$ in Eq. (4.15) refers to the ratio of the total amount of energy absorbed by the polymer to the total energy penetrated into the sample. The value of $A$ is evaluated using the Bouguer-Lambert law as discussed below.

During laser irradiation of the sample as shown in Figure 4.3, the laser beam penetrating into the substrate is absorbed by the sample with an absorption coefficient $\mu$. 
Figure 4.3 Curved vaporization surface, $s(r)$, formed in the polymer during laser vaporization experiment with a scanning laser beam. This curved profile is taken into account in the calculation for determining the specific ablation heat.

The laser irradiance propagating downward inside the polymer can be expressed as:

$$I_{qp} = I_e \exp(-\mu \cdot z) ,$$

(4.16)

where $I_e$ is a fraction of the incident laser irradiance that enters into the polymer sheet.

For a Gaussian beam, $I_e$ is related to the incident laser irradiance by the following expression:

$$I_e = I_0 (1 - R_{poly}) \exp(-2r^2 / r_0^2) \Phi(t) ,$$

(4.17)

where $I_0$ is irradiance at the laser beam center, $r$ is the radial distance from the laser beam center, $r_0$ is the radius of the incident laser beam and $\Phi(t)$ represents the following laser pulse shape function in this study.
\[ \Phi(t) = \begin{cases} 
1 & \text{for } nt_p < t \leq nt_p + t_{on} \
0 & \text{for } nt_p + t_{on} < t \leq (n+1)t_p 
\end{cases} \quad (4.18) \]

where \( t_{on} \) is the pulse-on time and \( t_p \) is the period (pulse-on plus pulse-off time) for rectangular pulse shape. \( I_0 \) is given by

\[ I_0 = 2Pt_p / (\pi_0^2 t_{on}) , \quad (4.19) \]

for a rectangular pulse shape considered in this study.

The laser beam does not penetrate the copper layer. The irradiance of the laser beam coming out of the polymer after being reflected by the copper layer can be expressed as

\[ I_{out} = I_e R_{cu} \exp(-2\mu(d - s(r))) \quad (4.20) \]

and the laser irradiance absorbed by the copper can be expressed as

\[ I_a = I_e (1 - R_{cu}) \exp(-\mu(d - s(r))) \quad (4.21) \]

where the absorption coefficient \( \mu \) is \( 4.1 \times 10^4 \text{ m}^{-1} \). The reflectivity of the copper layer \( R_{cu} \) is 97.2\% at 1.06 \( \mu \text{m} \) wavelength. Since the laser beam moves relative to the sample in this experiment, a quasi-steady state is established with a curved surface in the polymer representing its vaporization front as shown in Figure 4.4. The profile of this vaporization front \( s(r) \) is calculated using a thermal model in Ref. [Zhang et al. (2006)]. Now the absorptivity \( A \) for Eq. (4.15) can be obtained by the following expression

\[ A = \frac{\int_0^\theta \int_0^{2\pi} (I_e - I_{out} - I_a)rd\theta \cdot dr}{\int_0^\theta \int_0^{2\pi} I_erd\theta \cdot dr} \quad (4.22) \]
Based on the above-mentioned methods, the thermophysical properties of the polymer sample are obtained as listed in Table 4.1. The thermal conductivity was found to be $0.18 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ which is an average value over the temperature range, i.e., the steady state temperature distribution that existed in the sample during experiment. Garret and Rossenberg (1974) reported a thermal conductivity of $0.3 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ at 300 K for substrates made up of Araldite MY 740, HY 906, DY 062 and 44 wt% glass filler materials. The discrepancy between these two studies may be due to the different types of polymers used. The average temperature of the sample was 196°C in this study. Knowing the thermal conductivity and the heat transfer coefficient of the surrounding air, the theoretical temperature profile $T(d,t)$ is calculated using Eq. (4.7) to fit the experimental data for a particular value of thermal diffusivity as shown in Fig. 4.4. This measured thermal diffusivity is found to be $1.2 \times 10^{-7} \text{ m}^2 \cdot \text{s}^{-1}$ which is the representative value at the mean temperature of the transient process. The specific heat capacity is then calculated to be $C_p = k/(\rho \alpha) = 1.04 \times 10^3 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$.  

4.4 Results and Discussion
While conducting the temperature measurement experiment, the laser power was varied and the temperature of the sample was recorded when the steady state was achieved for each laser power. The steady state surface temperature is presented in Figure 4.5 as a function of laser power for a given laser beam diameter (2 mm). As the laser power increases, the surface temperature will increase due to the increasing heat flux at the surface of the sample. When the surface temperature reaches 266°C, the polymer begins to liberate gases indicating the onset of thermal decomposition. Chemical reaction occurs between the polymer and the oxygen of the air during the experiment. The oxidation becomes visibly intense with burning flames at the surface temperature 505°C. Figure 4.5 shows that the polymer temperature continues to rise as the laser power increases and eventually the temperature approaches a constant value of 730°C. This
indicates that the thermal decomposition occurs over a range of temperature. The temperature range for thermal decomposition is from 266 to 730°C. Vaporization/boiling generally occur at a fixed temperature for single component materials. It is, however, expected to occur over a range of temperature for multicomponent materials such as the polymer. Since it is very difficult to distinguish between the thermal decomposition and vaporization, these two phenomena are considered to occur in the same temperature range in this study.

Figure 4.5 Steady state temperatures at the top surface of the polymer sample due to a continuous wave stationary laser beam of radius 2 mm for different laser powers.

The sample used for measuring the specific ablation heat was a laminated multilayer polymer sheet with copper layer. The surface area and the thickness of the sheet above the copper layer
were (15.9 mm × 12.6 mm) and 50 μm respectively. The sample was placed in the air and was scanned with a laser beam of average power 1.25 W at the scanning speed of 2 mm/s; 40 tracks of width 60 μm each were created on the sample surface. So the sample was irradiated with the laser beam for a duration of \( \tau = 159.4 \) s. The loss of mass was measured with a microbalance, which was found to be 1.81 mg. The specific ablation heat depends on the ratio of the energy absorbed by the polymer material to the energy penetrating into the sample, \( A \), as shown in Figure 4.6. By selecting an appropriate value of \( A \), the specific ablation heat \( E_v \) can be determined accurately. Taking \( A \) as 0.155 based on the model in Ref. [Zhang et al. (2006)], the specific ablation heat is calculated to be \( 4.96 \times 10^6 \) J/kg. For the specific ablation heat measurement, the interactions between the laser and polymer are complex which include pyrolysis and oxidation depending on the ambient around the interaction zone. The specific ablation heat provides a simplified description for the heat transfer mechanism during laser removal of polymeric materials such as laser microvia drilling. The value of this energy was determined in this study based on experiments conducted in air which may cause both pyrolysis and combustion. In other environments such as inert gases or pure oxygen the measured data can be different due to different physico-chemical phenomena. The polymeric material would be pyrolized in inert ambients, whereas complete combustion would occur in pure oxygen environments.
Figure 4.6 Specific ablation heat as a function of the ratio of the absorbed laser energy to the total amount of laser energy entered into the polymer sample.

4.5 Conclusions

A simple laser heating method is presented to measure the thermal conductivity, specific heat capacity at constant pressure, density, thermal decomposition temperature and specific ablation heat for epoxy resin sheets of high glass transition temperature filled with fused silica. A constant value of thermal diffusivity fits the theory and experimental data over a large range of temperature, indicating that the thermal diffusivity of the polymer material may be considered constant over this temperature range. The complex interactions between the laser and polymers may be represented by a single material property which is referred to as the specific ablation heat.
heat. These thermophysical properties can be used for modeling and understanding laser microvia drilling processes.
CHAPTER 5: DESIGN OF PITCHFORK BEAM SHAPING OPTICS
BASED ON RAY TRACING AND SCALAR DIFFRACTION ANALYSIS

5.1 Introduction

CO₂ lasers of wavelength 9.3 μm are usually used to produce interconnects in the polymer layers or microvias in the substrate because of low reflectivity and high absorption coefficient of the polymer. They can drill blind holes in the polymer layer without damaging the copper pad. As the thickness of the polymer layer decreases the heat conduction and the reflection of the CO₂ layer becomes important sources of energy loss. Due to volumetric heating, the volume to absorb the laser energy also decreases. The heating mechanism changes from the initial rapid heating to slow heating near the end of the drilling process. The slow heating of the polymer produces a thin layer of carbonaceous deposit, which is known as the residue, formed along the walls of the hole and at the bottom of the via especially at the periphery of the hole if a Gaussian beam is used for microvias drilling. To remove the residue, a subsequent cleaning process is needed. Even when a uniform beam is used for microvias drilling, the residue may still exist at the periphery of the via due to heat conduction in the polymer and copper layers [Zhang et al. (2005)].

To remove the residue during the drilling process, both pulse shaping and beam shaping are necessary. The transformation of a Gaussian laser beam into a pitchfork profile is studied in this paper. Here the pitchfork profile refers to the longitudinal cross-section of the laser beam at the
focal spot that has high irradiance at the edge of the beam and low irradiance at the center. Typically, the irradiance of the beam coming out of the laser resonator has a Gaussian profile. Laser beam shaping is the process of redistributing the irradiance and phase of the laser. For different laser materials processing applications, different irradiance profiles such as flat-top beam, Bessel beam and annular beam are necessary. Refractive optics, diffractive optics and acousto-optics are generally employed to shape the laser beam. Refractive optics is, however, preferred because they are easy to manufacture at a low cost.

5.2 Transformation of a Gaussian Beam into a Pitchfork Beam

A three-lens refractive optical system is designed for pitchfork beam shaping in this paper. The first two lenses A and B in figure 5.1, which are plano-concave aspheric lens and plano-convex aspheric lens respectively, act as an optical phase element. The third lens C, which is the transform element, is a commercially available aspheric focusing lens. It ensures a pitchfork profile at its focal plane owing to its effect on the optical phase of the laser beam at different transverse locations. Based on the known shape and size of lens C and the desired pitchfork profile, the shape of the super Gaussian beam is determined using the Fresnel diffraction for beam propagation. Now the input beam profile to lens A, i.e., the Gaussian beam obtained from the laser system, and the desired beam profile that must be produced by lens B, i.e., the above-mentioned super Gaussian beam, are known. Lenses A and B, and the distance between them are then designed using the ray tracing technique to satisfy the above-mentioned two conditions on the beam profiles. Thus the optical phase element (lenses A and B) are designed to transform
the input collimated Gaussian beam of the laser system to a collimated super Gaussian profile. Since the left hand side of lens A and the right hand side of lens B are plane surfaces, collimated beams do not refract at these two surfaces and, therefore, only the aspheric surfaces of these two lenses and the distance between them need to be designed.

Fast Fourier Transform (FFT) is used to analyze the effect of Fresnel diffraction on the shape of the beam as it propagates after the super Gaussian beam passes through lens C. The radial variation in the power of the pitchfork beam is measured near the focal spot using a scanning method and the experimental data are used to verify the theoretical profile of the pitchfork beam.

Figure 5.1 Geometrical configuration of the phase and transform elements of a three-lens beam shaping system to transform a Gaussian beam into a pitchfork beam.
5.2.1 Fresnel diffraction analysis for beam propagation to determine the super Gaussian beam shape for a given lens C and a given pitchfork profile

This analysis starts by assuming different profiles incident on lens C and carrying out the diffraction analysis for beam propagation to check which incident beam profile would yield the desired pitchfork beam. Different incident beam profiles such as the Gaussian, uniform and super Gaussian beam profiles were tested and only the super Gaussian beam with irradiance distribution \( I_{\text{out}} = I_0' \exp\left(-2(R/R_0)^{10}\right) \) was found to generate the required pitchfork beam near the focal plane of lens C. Here \( I_0' \) is the laser irradiance at the center of the beam, \( R \) is the radial coordinate in the transverse plane of the beam with origin at the beam center and \( R_0 \) is the beam radius. The diffraction effect needs to be considered to determine the irradiance profile owing to the small (comparable to the wavelength) size of the beam around the focal plane. Usually, the Fresnel approximation is used to calculate the diffraction field if the Fresnel number \( N_F \ll 1 \), where \( N_F = w^2 / \lambda Z \), \( w \) is the radius of the aperture (or the laser beam in this case) and \( Z \) is the distance between the aperture (lens C in this case) and the diffraction plane of interest. For the present case, the radius of the laser beam at the input surface of lens C (the left hand side of lens C in figure 1), i.e., \( w = 2 \) cm. Also \( Z = 5.08 \) cm which is the focal length of lens C since we want to analyze the diffraction pattern at the focal plane. So the Fresnel number, \( N_F = 846.7 \), i.e., \( N_F \gg 1 \), and therefore the Fresnel diffraction formula is applicable in this study.

5.2.1.1 Fresnel approximation of the diffraction field after the focusing lens C

The focusing lens C can be a plano-convex or an aspherical lens with \( f = 5.08 \) cm. The amplitude of the super Gaussian electromagnetic wave incident on the input surface of lens C,
\( U_0 \), can be written as follows:

\[
U_0(x, y) = A_0 \exp \left[ -\left( \frac{\sqrt{x^2 + y^2}}{R_0} \right)^{10} \right] \tag{5.1}
\]

As in the wave propagates through the focusing lens (lens C) in figure 1, the optical phase delay \( \phi(x, y) \) introduced by the focusing lens and the air is

\[
\phi(x, y) = knt_3 - kn_0 \frac{x^2 + y^2}{2f} . \tag{5.2}
\]

where \( t_3 \) is the thickness of the focusing lens along its optical axis and \( f \) is the focal length.

The transmittance function \( t(x,y) \) of the focusing lens can be written as:

\[
t(x, y) = \begin{cases} 
\exp(i\phi(x, y)) & \text{for } x^2 + y^2 < \rho_i^2, \\
0 & \text{for } x^2 + y^2 \geq \rho_i^2,
\end{cases} \tag{5.3}
\]

where \( \rho_i \) is the aperture size of the focusing lens. Here \( t(x,y) \) is the aperture truncation function whose effect on the focal shift and focused spot size was analyzed by Sun (1998). In this paper, the truncation effects are considered through Eq. (5.3) in the diffraction analysis.

Combining Eqs. (5.2) and (5.3) and neglecting the constant phase factor \( \exp(iknt_3) \), the diffraction field \( U(\alpha, \beta, L) \) at a distance \( L \) from the focusing lens along the optical axis can be expressed by the following Fresnel diffraction integral:

\[
U(\alpha, \beta, L) = \frac{k}{iL} \exp(ikL) \iint_A U_0(x, y)t(x, y)\exp\left\{ \frac{ik[(x-\alpha)^2 + (y-\beta)^2]}{2L} \right\}dA \tag{5.4}
\]

This integral, which can be regarded as a Fourier transform at frequencies
\( f_x = \alpha k / 2\pi L, \ f_y = \beta k / 2\pi L \), can be evaluated numerically by two-dimensional fast Fourier transform:

\[
U(\alpha, \beta, L) = \frac{k \exp(ikL)}{iL} \cdot \exp\left(\frac{ik(\alpha^2 + \beta^2)}{2L}\right) \cdot \text{FFT}\left[U_0(x, y) r(x, y) \exp\left(\frac{ik(x^2 + y^2)}{2L}\right)\right]_{dx dy} \quad (5.5)
\]

The beam maintains the pitchfork profile from \( L = 1.002f \) to \( 1.008f \) as shown in figure 5.2. The axial range is \( \Delta L = 304.8 \mu m \) over which the beam has the pitchfork shape for a focusing lens (lens C) of focal length \( f = 50.8 \text{ mm} \).

### 5.2.2 Ray tracing for designing lenses A and B to generate the super Gaussian beam

After determining the super Gaussian beam shape based on the above-mentioned diffraction analysis, ray tracing is used to design lenses A and B. The ray tracing technique is based on geometrical optics [Dickey et al. (2000)]. In physical optics, the light is considered as an electromagnetic wave having diffraction and interference properties. However as the wavelength of the radiant energy decreases in comparison to the physical dimensions of the optical system, the effects of the wavefront become less significant. For this case, the approximation of geometrical optics is considered suitable. In the present case, the minimum dimension for ray tracing is the input Gaussian beam with a radius of 2 mm which is much larger than the wavelength (9.3 \( \mu m \)) of the laser beam.
Figure 5.2 Variation of the pitchfork beam shape at different distances (z positions) from the focusing lens C.
For the ray tracing studies in this paper, the input Gaussian beam is considered as a plane wave. However, for a real Gaussian beam, the radius of curvature of the beam decreases from infinity to a finite value when it travels from its waist to the far field. If the input surface of lens A (the left hand side surface of lens A in figure 5.1) is placed at the laser beam waist, we indeed will have a plane wave at this location. The following formula can be used for the radius of curvature \( R(z) \) of the Gaussian beam wavefront [Silfvast (1996)]:

\[
R(z) = z \left[ 1 + \left( \frac{\pi w_0^2}{\lambda z} \right)^2 \right]
\]

(5.6)

where \( z \) is the longitudinal distance from the beam waist. In the present case, the beam waist \( w_0 = 2 \text{ mm} \) and the wavelength of the laser beam \( \lambda = 9.3 \text{ μm} \). If the distance between the lenses A and B is 5 cm, the radius of curvature of the laser beam at the input surface of lens B (the left hand surface of lens B in figure 5.1) would be 36.6 m which is much larger than the diameter (5.08 cm) of lens B. So the plane wave approximation is applicable in the present case.

### 5.2.2.1 Conservation of energy

Due to energy conservation, the powers of the input and output laser beams of the optical phase element shown in figure 5.1 must be equal. The energy balance can be written as:

\[
\int_{0}^{2\pi} \int_{0}^{2\pi R_0} I_i(r) r dr d\theta = \int_{0}^{2\pi} \int_{0}^{2\pi R_0} I_{out}(R) R dr d\theta
\]

(5.7)

where \( I_i \) and \( I_{out} \) are the irradiances of the input Gaussian and output super Gaussian laser beams respectively, \( r_0 \) is the radius of the input Gaussian laser beam and \( R_0 \) is the radius of the output laser beam. \( I_i(r) \) and \( I_{out}(R) \) can be written as:

\[
I_i = I_0 \cdot \exp(-2r^2/r_0^2)
\]

(5.8)
\[ I_{\text{out}} = I'_0 \cdot \exp[-2(R/R_0)^{10}] \]  

(5.9)

where \( I_0 = \frac{2P}{\pi r_0^2} \), \( P \) is the laser power, \( I'_0 \) is the central irradiance of the output laser beam.

Substituting Eqs. (5.8) and (5.9) into Eq. (5.7), the expression for \( I'_0 \) is obtained:

\[
I'_0 = I_0 \cdot \frac{1 - \exp(-2)}{\int_0^{R_0} R \cdot dR} \exp[-2(R/R_0)^{10}] R \cdot dR
\]  

(5.10)

Eq. (5.7) is an energy balance over the entire laser beam cross-section (i.e., over the radii \( r_0 \) and \( R_0 \)). The same energy balance equation can be applied to two arbitrary radii \( r \) and \( R \) (figure 5.1).

From Eqs. (5.7) and (5.10), the relationship between \( r \) and \( R \) can be found as:

\[
r = \frac{r_0^2}{2} \cdot \ln \left(1 - \frac{I'_0}{I_0} \cdot \int_0^{R_0} \exp \left[-2 \left(\frac{R}{R_0}\right)^{10}\right] R \cdot dR \right)
\]  

(5.11)

5.2.2.2 The constancy of optical path length

Based on figure 1, the optical path length of the central ray can be written as

\[ nt_1 + n_o D + nt_2 = F \]  

(5.12)

where \( F \) is the optical path length which is a positive constant, \( t_1 \) and \( t_2 \) are thicknesses of the input and output lenses (lenses A and B) respectively, \( D \) is the distance between the input and output lenses, and \( n \) and \( n_a \) are the refractive indices of the lens and the air respectively.

For an arbitrary ray, the optical path length \( F \) is

\[ n_z + n_a \sqrt{(R - r)^2 + (Z - z)^2} + n(t_1 + t_2 + D - Z) = F \]  

(5.13)
Combining Eq. (5.12) and Eq. (5.13) together, the following expression can be obtained:

\[ n_a \sqrt{(R - r)^2 + (Z - z)^2} = n(Z - z) - D(n - n_0) \]  

(5.14)

Letting \( \gamma = n_a / n \) and \( F' = (\gamma - 1)D \), Eq. (5.14) yields the following relationship between \( Z \) and \( z \):

\[ Z - z = \frac{- F' + \sqrt{F'^2 - (1 - \gamma^2)[F'^2 - \gamma^2(R - r)^2]}}{1 - \gamma^2} \]  

(5.15)

### 5.2.2.3 Snell’s law

The optical system is designed to operate with input rays parallel to the optical axis and also give the output rays parallel to the optical axis, which is shown in Figure 5.3. The slope of the lens and the refracting angle can be written as:

\[ \frac{dz}{dr} = \frac{dZ}{dR} = \tan \theta_1 = \tan \theta_2 \]  

(5.16)

\[ \tan(\theta_1 - \theta_2) = \tan(\theta_1 - \theta_2) = (R - r) / (Z - z) \]  

(5.17)

Applying Snell’s law to the equations above, the slopes of the surface of the input and output lens can be determined by

\[ \frac{dz}{dr} = \frac{dZ}{dR} = \frac{(R - r)\gamma}{\left[F'^2 - (R - r)^2 + (R - r)^2\right]} \]  

(5.18)

Substituting the expression for \( r \) from Eq. (5.11) into Eq. (5.18) and numerically integrating Eq. (5.18), the curved profile of lens B, \( Z(R) \), is determined. The curved profile of lens A, \( z(r) \), is determined from Eq. (5.15).
5.2.2.4 Design results

The constraints for optimization of the assembly and fabrication of the lens system may be applied as [Zeng et al. (2006)]:

1) The distance between the input and output lens should be a minimum.
2) The lens surface curvature $\chi$, where $\chi = \left( \frac{d^2 z}{dr^2} \right)_{\text{max}}$, should be a minimum.

To avoid any damage to the beam shaping optics, the peak laser irradiance needs to be determined. For the input Gaussian beam, the incident laser irradiance is $I_i = I_0 \cdot \exp(-2r^2/\rho_0^2)$, where $\rho_0 = 0.2 \text{ cm}$ is the radius of the incident laser beam and $I_0$ is the laser irradiance at the center of the beam. The average value of $I_0$ is 238.7 W/cm$^2$ and the peak value of $I_0$ is $5.835 \times 10^4$ W/cm$^2$. For the output super Gaussian beam, the laser irradiance is $I_{\text{out}} = I'_0 \cdot \exp(-2(R/R_0)^{30})$. The radius of the output laser beam $R_0 = 2 \text{ cm}$. The average value of $I_{\text{out}}$ is 1.308 W/cm$^2$ and the peak value of $I_{\text{out}}$ is 319.8 W/cm$^2$. The distance between the two lenses $D = 5 \text{ cm}$.

Lens A is a plano-concave ZnSe lens of diameter 1.27 cm with the concave surface (Figure 5.4) designed as

$$z = \frac{4.091 \cdot r^2}{1 + \sqrt{1 - (1 - 2.492) \cdot 4.091^2 \cdot r^2}} - 1.158 \cdot r^2 + 3.242 \cdot r^4$$  \hspace{1cm} (5.19)

Lens B is a plano-convex ZnSe lens of diameter 5.08 cm with the convex surface (Figure 5.5) designed as

$$Z = 0.070 \cdot R^2 + 0.019 \cdot R^4$$  \hspace{1cm} (5.20)

The variables $r$ and $z$ are in units of cm in expressions (5.19) and (5.20).
Figure 5.4 Concave aspheric surface profile of lens A.
Figure 5.5 Convex aspheric surface profile of lens B.
5.3 Conclusions

A refractive optical system with phase and transform elements is designed to transform a Gaussian laser beam into a pitchfork beam having a predetermined irradiance. The phase element is made up of two aspherical lenses and the transform element is a focusing lens. Ray tracing of geometric optics is used to design the phase elements based on the conservation of energy, the constancy of optical path length and Snell’s law. The Fresnel diffraction is used to predict a pitchfork beam profile near the focal plane.
CHAPTER 6: OPTIMIZATION OF THE BEAM SHAPING OPTICS

6.1 Optimization Consideration

For the beam profile (Figure 5.6) designed by the method in Chapter 5, the first order side lobe of the beam contains 16.6 ~ 25.8% of the total laser energy at different axial position. This original design of the pitchfork beam has large side lobes. Those side lobes can cause heat affected zone or damage the surface around the hole. Figure 6.1 shows the drilling front profile after one laser shot calculated by the numerical model in Chapter 3. The first order side lobe containing 16.6% of the laser energy is considered in the calculation for extreme case. The central pitchfork lobe is considered to contains 83.4% of the laser energy. The laser pulse energy is 0.9 mJ, pulse on time is 0.43 μs and repetition rate = 20 kHz. It can be inferred from Figure 6.1 that the side lobe already damages the substrate surface. To avoid the surface damage around the hole, laser energy contained in the side lobe has to be reduced. If the energy in the side lobe reduces to 10%, there is no damage on the substrate surface due to side lobe which is shown in Figure 6.2.

As a result if the laser energy inside the first order side lobe is less than 10%, substrate surface will not be damaged. The result can be used in the optimization of the pitchfork beam in optical system design. Aberration and beam profile steepness will be optimized in the phase of optimization of optical system design.
Figure 6.1 Drilling front profile after one laser shot of ramp-up pulse. The central pitchfork lobe and the first order side lobe contain 83.4% and 16.6% of the laser energy. Pulse energy = 0.9 mJ, pulse on time = 0.43 μs, repetition rate = 20 kHz.
Figure 6.2 Drilling front profile after one laser shot of ramp-up pulse. The central pitchfork lobe and the first order side lobe contain 90% and 10% of the laser energy. Pulse energy = 0.9 mJ, pulse on time = 0.43 μs, repetition rate = 20 kHz.

6.2 Iterative Method for Designing Diffractive Optical Element to Transform a Gaussian Beam into a Pitchfork Beam

The optical system arrangement is different from the one in Chapter 5, which is shown in Figure 6.3. A beam expander is put before the phase element. In this case, the pitchfork beam can be easily introduced into the conventional laser drilling system by inserting the phase element. It is also convenient to compare the drilling results between Gaussian beam drilling and pitchfork beam drilling. The beam expander shown in Figure 6.4 has an expansion ratio of 10 which is
required to produce the diameter of the airy disk to be 23 μm. The expanded Gaussian beam is focused by a 2 inch focusing lens into a pitchfork beam on the focal plane.

The optimization goal of the pitchfork beam profile $U_p(r)$ is shown in Figure 6.4. The diameter of the pitchfork beam is about 2 times of the airy disk diameter.

Figure 6.3 Optimized optical system for pitchfork beam shaping
The phase element is optimized by iterative method using Adaptive Additive algorithm [Soifer (2002)]. In the studies of Fourier optics and diffractive optical elements, optical waves with different spatial phase functions and identical beam profile (such as Gaussian shape) can produce different profile in the image plane. For beam shaping problems, the beam profile of the source and the goal for the beam profile in the image plane is known and the unknown is the phase function. In order to obtain this phase function, the Adaptive-Additive Algorithm algorithms, can be used. The AA algorithm is an iterative algorithm that utilizes the Fourier Transform to calculate an unknown part of a propagating wave, which is related to the solution (using a successive approximation method) of a nonlinear integral equation:

Figure 6.4 Desired amplitude of the pitchfork beam
\[ U(\alpha, \beta, L) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} U_0(x, y) \exp[i\Phi(x, y)]H(x - \alpha, y - \beta, L) \, dx \, dy \]  \hspace{1cm} (6.1)

where \( U_0(x, y) \) is the light amplitude incident on the phase element, \( \Phi(x, y) \) is the desired phase function introduced by the phase element, \( U(\alpha, \beta, L) \) is the desired amplitude distribution that should be shaped by the phase element and the fourier transform element at a distance of \( L \). If \( L \) is a constant, the amplitude can be written as \( U(\alpha, \beta) \). \( H(x, y, L) \) is the function of pulse response of free space. In Fresnel diffraction approximation, it has the following expression:

\[ H(x, y, L) = \frac{k}{z} \exp \left[ \frac{ik}{2z} (x^2 + y^2) \right] \]  \hspace{1cm} (6.2)

where \( k = \frac{2\pi}{\lambda} \) is the spatial frequency.

The AA algorithm, which is shown in Figure 6.5, starts with an initial value for \( \Phi_0(x, y) \) and an initial input wavefront which is a Gaussian profile in present research.

\[ U_1(x, y) = U_0(x, y) \exp(i\Phi_0(x, y)) \]  \hspace{1cm} (6.3)

The Fresnel transform of this wavefront is the first estimate for the output electric field on the image plane:

\[ U(\alpha, \beta) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} U_1(x, y)H(x - \alpha, y - \beta, L) \, dx \, dy \]  \hspace{1cm} (6.4)
Normally this amplitude is different than the desired amplitude profile \( U_p(\alpha, \beta) \). To evaluate the convergence of the optimization process, an error function is introduced as:

\[
\varepsilon = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left| U(\alpha, \beta) - U_p(\alpha, \beta) \right|^2 d\alpha d\beta
\]  

(6.5)

To make the iteration converge, the error is reduced by mixing a proportion, \( a \), of the desired amplitude into the field in the image plane:

\[
\overline{U}(\alpha, \beta) = [aU_p(\alpha, \beta) + (1-a)\|U(\alpha, \beta)\|U(\alpha, \beta)]^{-1}
\]  

(6.6)
In this research, $a$ is chosen as 1.5. Inverse Fresnel transform of $\bar{U}(\alpha, \beta)$ gives the corresponding amplitude and phase function in the input plane, $\bar{U}_1(x, y) = \bar{U}_0(x, y) \exp(i\Phi_1(x, y))$. The amplitude of the input wavefront after the transform is usually different than the actual laser profile. Thus, $\bar{U}_0(x, y)$ is replaced with the Gaussian profile $U_0(x, y)$. The result is an improved estimate for the input field: $U_1(x, y) = U_0(x, y) \exp(i\Phi_1(x, y))$. This completes one iteration of the AA algorithm. The error function Eq. (5) can be reduced with more iterations. The cycle is repeated until the error, $\epsilon$, in the n-th iteration converges to within an acceptable tolerance. In this case, the desired phase function $\Phi(x, y) = \Phi_n(x, y)$, can produce the acceptable amplitude profile $U_p(\alpha, \beta)$.

6.3 Design Results

Figure 6.6 shows that the error function decreases as iteration number increases. After 50 iterations the calculated amplitude distribution is shown in Figure 6.7. The side lobe only contains 4.7% of the total laser energy. The peak in the periphery can be used to remove the residue at the corner. The irradiance shown in Figure 6.7 is on the focal plane. The irradiances at different z positions are shown in Figure 6.8. The pitchfork irradiance is good within the depth of 30 μm (2Δz) near the focal plane. When the z position is 76 μm out of focus, an annular shaped irradiance is obtained.
Figure 6.6 Error function as a function of number of iterations
Figure 6.7 Optimized amplitude of the pitchfork beam
6.3.1 Profile of the phase element

The phase function of the phase element is optimized in the iteration method. The corresponding shape of the phase element is shown in Figure 6.9. Because the diffractive optics on ZnSe is difficult to fabricate, a $\pi$ shift is given to the central region to make the curve smooth. The continuous phase function gives continuous height of the phase element which can be produced by the method of diamond turning.
The surface profile of the phase element is shown in Figure 6.10. The optimized profile is fitted by 9 order polynomial, which has the following expression:

$$Z = -1.27 \times 10^{-1} \cdot R + 1.18 \times 10^{-1} \cdot R^2 - 3.42 \times 10^{-2} \cdot R^3 + 3.32 \times 10^{-3} \cdot R^4 - 1.36 \times 10^{-4} \cdot R^5 + 2 \times 10^{-6} \cdot R^6 \quad (6.7)$$

where $Z$ is in the unit of $\mu$m and $R$ is in the unit of mm.
6.3.2 Dependence of the optimization on the airy disk diameter

In the optimization above, the diameter of the pitchfork beam diameter is approximately equal to two airy disk diameters \((d_0 = 2d_a)\). If the pitchfork beam diameter is equal to more airy disk diameters, the optimization can be better. In Figure 6.11, the focal length of the focusing lens reduces to 1 inch, so the ideal airy disk diameter reduces to its half value. In this case the diameter of the pitchfork beam diameter is approximately equal to 4 airy disk diameters \((d_0 = 4d_a)\). When the diameter of the pitchfork beam diameter is approximately equal to 8 airy disk diameters \((d_0 = 8d_a)\), the optimization result is even better as shown in Figure 6.12. However, due to the aberration and the cost of the short focal length lens, the final diameter of the pitchfork beam diameter is still equal to two airy disk diameters \((d_0 = 2d_a)\).
Figure 6.11 Optimized amplitude of the pitchfork beam when $d_0 = 4d_a$
6.3.3 Optimization for depth of focus

The depth of focus for the design above is only 30 μm. In reality, a depth of focus of 150 μm is required. To increase the depth of focus, another phase element is inserted before the focusing lens. The phase element is designed by the same optimization above. The difference is that the design goal is in \( r-z \) plane.

The amplitude on the optical axis (\( \rho=0 \)) can be calculated as:

\[
U(0, z) = \frac{k \rho}{z} \left[ U_0(r) \exp[i\Phi(r)] \exp\left( i \frac{k}{2z} r^2 \right) \right] rdr
\]  

(6.8)
where \( k \) is the optical wave number; \( R \) is the DOE radius; \( r \) and \( \rho \) are the radial variables in the DOE plane and the observation plane. Change the variables to:

\[
\xi = \frac{k}{z}, \quad x = \frac{r^2}{2}
\]

So Eq. (6.8) can be written as:

\[
U(\xi) = \int_0^{x_0} U_0(x) \exp[i\Phi(x)] \exp(ix\xi) dx
\] (6.9)

Eq. (6.9) can also be solved by the Adaptive Additive algorithm to obtain the phase function to produce the desired amplitude along the \( z \)-axis. After optimization for depth of focus, the irradiances at different \( z \) positions are shown in Figure 6.13. The depth of focus is larger than 150 \( \mu \)m. The beam diameter is 100 \( \mu \)m. By introducing a focusing lens with shorter focusing lens (1 inch), the beam diameter can be 50 \( \mu \)m which is shown in Figure 6.14. However, the difficulties to produce such short focal length focusing lens have to been considered. The phase function of the phase element is optimized. The corresponding shape of the phase element is shown in Figure 6.15.
Figure 6.13 Laser irradiances at different z positions (f = 50.8 mm)

Figure 6.14 Laser irradiances at different z positions (f = 25.4 mm)
The optimized profile is fitted by 9 order polynomial, which has the following expression:

$$Z = 7.84 - 4.72 \cdot R + 1.72 \cdot R^2 - 3.10 \times 10^{-1} \cdot R^3 + 3.00 \times 10^{-2} \cdot R^4 - 1.59 \times 10^{-3} \cdot R^5 + 4.25 \times 10^{-5} \cdot R^6 + 4.53 \times 10^{-7} \cdot R^7$$  \tag{6.10}$$

where $Z$ is in the unit of $\mu$m and $R$ is in the unit of mm.

The entire optical system is shown in Figure 6.16. Phase element A introduces the phase function to produce optimized pitchfork beam. Phase element B introduces the phase function to increase the depth of focus.
Figure 6.16 Output pitchfork beam produced by the optical system.
6.4 Conclusions

The beam shaping system for pitchfork profile is optimized in this chapter. Two phase-elements are introduced in the conventional optical system for laser microvias drilling. Phase element A is used to optimize the pitchfork beam shape and phase element B is used to increase the depth of focus.

1. Only with phase element A, the laser spot diameter is 50 \( \mu \text{m} \), depth of focus is 30 \( \mu \text{m} \) and energy content in the first side lobe (diffraction pattern) is 4.7\% of the total laser energy.

2. Phase element A for pitchfork beam is optimized using an iterative procedure. The surface profile can be expressed as:

\[
Z = -127.11392 \cdot R + 118.22704 \cdot R^2 - 34.17872 \cdot R^3 + 3.32179 \cdot R^4 - 0.13583 \cdot R^5 + 0.002 \cdot R^6
\]

where \( Z \) is in the unit of \( \mu \text{m} \) and \( R \) is in the unit of \( \text{mm} \).

3. Phase element B to increase the depth of focus is also optimized using an iterative method. The surface profile can be expressed as:

\[
Z = 7.84 - 4.72 \cdot R + 1.72 \cdot R^2 - 3.10 \times 10^{-1} \cdot R^3 + 3.00 \times 10^{-2} \cdot R^4 - 1.59 \times 10^{-3} \cdot R^5 + 4.25 \times 10^{-5} \cdot R^6 + 4.53 \times 10^{-7} \cdot R^7
\]

where \( Z \) is in the unit of \( \mu \text{m} \) and \( R \) is in the unit of \( \text{mm} \).

4. Phase elements A and B and a two-inch focal length aspheric lens (Lens C in Figure 6.16) lead to laser spot diameter 100 \( \mu \text{m} \), depth of focus 150 \( \mu \text{m} \) and energy content in the first side lobe (diffraction pattern) is 20\% of the total laser energy.
5. Phase elements A and B and a one-inch focal length aspheric lens (Lens C in Figure 6.16) lead to laser spot diameter 50 – 60 µm, depth of focus 60 µm and energy content in the first side lobe (diffraction pattern) is 20% of the total laser energy.
CHAPTER 7: EXPERIMENTAL STUDY OF MICROVIAS DRILLING WITH CO$_2$ LASERS

7.1 Experimental Setup

Before using the pitchfork beam generated from Chapter 5 and 6 to drill microvias, beam profile need to be verified. The pitchfork beam is formed near the focal plane of lens C and the beam diameter at the focal plane is approximately 50 μm. It is generally not possible to measure the profile of such small, focused and very high irradiance beams using conventional means, i.e., beam analyzer or beam profilometer. A pinhole scanning method is presented in this paper for measuring the pitchfork beam profile using an experimental setup shown in figure 7.1.

The laser source in this experiment was a GEM-Q600 Q-switched CO$_2$ laser from Coherent/DEOS, which generates a Gaussian (TEM$_{00}$) beam. After passing through a collimator, the Gaussian beam is converted into a super Gaussian beam by lenses A and B, and then lens C transforms the super Gaussian beam into a pitchfork beam near the focal plane of lens C. A pinhole is placed at the plane where the beam irradiance profile needs to be measured. A power sensor is placed beneath the pinhole to detect the laser power passing through the pinhole. The average laser irradiance within the area of the pinhole can be calculated as $I = P/A_p$, where $P$ is the power detected by the power sensor and $A_p$ is the area of the pinhole. By moving the pinhole together with the power sensor on a XYZ stage, the beam profile can be resolved at any $z$ plane. The scanning speed can affect the accuracy of the power measurement due to the response time...
of the power sensor which was 2 second for this study. Higher power was detected by the sensor when the scanning speed was reduced. The scanning speed need to be set in the range where the detected laser power stabilized to constant values at various points. For measuring the Gaussian beam irradiance profile (figure 7.2) before lens A at the position shown in figure 7.1, a 50 μm diameter pinhole was traversed across the beam at the speed of 0.1 mm/s. To measure the super Gaussian beam irradiance profile (figure 7.3) after lens B at the position shown in figure 7.1, a 100 μm diameter pinhole was used to scan the beam at the speed of 1 mm/s. The measured profiles are in good agreement with the theoretical predictions. The pitchfork beam irradiance profile was measured on the focal plane of lens C with a 10 μm diameter pinhole (which is comparable to the wavelength of the laser to permit sufficient light to pass through the pinhole) at the scanning speed of 2 μm/s. The experimental pitchfork irradiance profile is compared to the theoretical profile predicted by the diffraction calculation (Eq. 5) in figure 7.4, showing fairly good agreement between the experiment and theory. However the experimental data shows a diffraction ring of radius 30 μm which is absent in the theoretical prediction. This disagreement may be due to the beam quality (mode structure) of the input Gaussian beam, the misalignment and aberration of the optical system, vibrations of the experimental setup, accuracy of the power detector and spatial resolution of the XYZ stage.
Figure 7.1 Experimental setup to measure the irradiance profile at three longitudinal positions.
Figure 7.2 Comparison of the theoretical Gaussian beam irradiance profile to the experimental data.
Figure 7.3 Comparison of the theoretical super Gaussian beam irradiance profile to the experimental data.
Figure 7.4 Comparison of the theoretical pitchfork beam irradiance profile to the experimental data.
7.2 Comparison of the Drilling Results by Gaussian Beam, Bessel Beam and Pitchfork Beam

Microvia drilling experiments were carried out with the pitchfork laser beam. The experimental setup was the same as in figure 7.1 except that the pin-hole was replaced with a PCB (printed circuit boards) substrate having sandwiched structure of polymer-copper-polymer.

The microvias drilled by the Gaussian beam, Bessel beam and the pitchfork beam are compared in figures 7.5, 7.6 and 7.7 respectively. For the Gaussian beam, the optimized laser parameters to drill a via of diameter less than 67 μm were: pulse energy = 0.336 mJ and pulse width = 430 ns. Under these laser parameters, a thin layer of polymeric residue is left behind in the peripheral region at the bottom of the via as shown in figure 7.5. The Gaussian beam also produces microvias with large tapering angle (θ), which is defined as

$$\tan \theta = \frac{(D_t - D_b)/2}{D^*}$$  \hspace{1cm} (7.1)

where $D_t$ and $D_b$ are the diameters at the top and bottom of the via respectively, and $D^*$ is the depth of the via. Based on the values of $D_t$ and $D_b$ obtained from figure 7.5 and the microvia depth $D^* = 40 \mu m$, the tapering angle for the Gaussian beam is $16.7^0$. For the Bessel beam, the optimized laser parameters to drill a via of diameter less than 67 μm were: pulse energy = 0.13 mJ and pulse width = 430 ns. There is noticeable residue at the bottom of the via and the tapering angle is $10.6^0$ as shown in figure 7.6. The microvia drilled by the pitchfork beam is shown in figure 9 for which the laser parameters were 0.3 mJ pulse energy and 430 ns pulse width to drill a via of diameter less than 67 μm. The tapering angle is $5^0$ in this case, which is
much smaller than the tapering angles produced by the Gaussian and Bessel beams. Figure 7.7 shows that the pitchfork beam can produce better vias with reduced polymeric residue at the bottom of the via than the other two beams.

A scanning electron microscopic cross-sectional view of the microvia drilled by a pitchfork laser beam is shown in Figure 7.8. The laser parameters for the drilling experiment were: pulse energy = 0.3 mJ, beam radius = 21 μm, pulse width = 430 ns and repetition rate = 83.3 kHz. The optics to convert an incident Gaussian beam into the pitchfork beam was so designed that the central valley and peripheral peak regions (Figure 7.4) of the beam contained 1.1% and 17.8% of the total laser energy respectively. 8 pulse trains each containing 8 pulses were used to drill one microvia. The drilling front profile calculated by the model with the same laser parameters is also shown in Figure 7.8 as the white solid line which agrees the experimental data very well.
Figure 7.5 Microvia produced with a Gaussian beam of pulse energy $= 0.336 \text{ mJ}$. Top diameter $= 62 \mu\text{m}$, bottom diameter $= 38 \mu\text{m}$ and tapering angle $= 16.7^\circ$. 
Figure 7.6 Microvia produced with a Bessel beam of pulse energy = 0.13 mJ. Top diameter = 64 μm, bottom diameter = 49 μm and tapering angle = 10.6°.
Figure 7.7 Microvia produced with a pitchfork beam of pulse energy = 0.3 mJ. Top diameter = 55 μm, bottom diameter = 48 μm and tapering angle = 5°.
Figure 7.8 Drilling front profile produced with a pitchfork laser beam (pulse energy = 0.3 mJ, beam radius = 21 μm, pulse width = 430 ns, repetition rate = 83.3 kHz). Due to diffraction the central lobe of the beam only contains 18.9% of the total laser energy.
7.3 Optimization of the Laser Parameter for Drilling of Microvias by Pitchfork Beam

7.3.1 Optimization of the Laser Parameter with the optical system designed by ray tracing technique.

7.3.1.1 Evaluate drilling as a function of peak power
The results of drilling experiments are evaluated as a function of laser peak power. Here the laser peak power = pulse energy / pulse width. The laser peak power as a function of repetition rate is shown in Figure 7.9. The top diameters of the hole as a function of laser peak power are shown in Figure 7.10. For each laser peak power, 1 to 10 pulses are used for the drilling experiment. Figure 7.10 shows that, the top diameter of the hole increases as the laser peak power increases or the pulse number increases. To optimize the drilling process producing holes with diameters ~50 μm, the following parameters are chosen: laser peak power = 641.86 W with 7 to 10 pulses; laser peak power = 790.7 W with 6 to 10 pulses; laser peak power = 1.367 kW with 3 to 4 pulses; laser peak power = 1.419 kW with 1 to 2 pulses; laser peak power = 1.426 kW with 1 to 2 pulses; laser peak power = 1.440 kW with 1 to 2 pulses; laser peak power = 1.449 W with 2 pulses. Figure 7.11 shows the bottom diameter of the hole as a function of laser peak power. As the laser peak power increases or the pulse number increases, the bottom diameter of the hole increases. In this figure, the information of how many pulses is need to finish one hole at different laser peak power can be obtained.
Figure 7.9 Laser peak power as a function of repetition rate for pitchfork laser beam, pulse on time = 430 ns.

Figure 7.10 Top diameter of the hole as a function of laser peak power for pitchfork laser beam, pulse on time = 430 ns, beam diameter = 50 μm.
Figure 7.11 Bottom diameter of the hole as a function of laser peak power for pitchfork laser beam, pulse on time = 430 ns, beam diameter = 50 μm.

7.3.1.2 Laser drilling process optimization for TPT minimization

Based on the evaluation of the drilling as a function of laser peak power, the laser drilling process optimization for TPT minimization is performed. Optical micrographs of the microvias are given in Figs. 7.12 – 7.16 and the corresponding laser drilling parameters are listed in the captions of each figure. The optical qualities of the microvias are listed in Table 7.1.
Figure 7.12 Microvias processed with parameter set I: repetition rate = 100 kHz, 6 pulse trains, 8 pulses in each pulse train, pulse length = 430 ns, time delay for each train is 1.4 ms.

Figure 7.13 Microvias processed with parameter set II: repetition rate = 100 kHz, 5 pulse trains, 9 pulses in each pulse train, pulse length = 430 ns, time delay for each train is 1.6 ms.
Figure 7.14 Microvias processed with parameter set III: repetition rate = 50 kHz, 5 pulse trains, 5 pulses in each pulse train, pulse length = 430 ns, time delay for each train is 1.8 ms.

Figure 7.15 Microvias processed with parameter set IV: repetition rate = 12.5 kHz, 4 pulse trains, 2 pulses in each pulse train, pulse length = 430 ns, time delay for each train is 1.8 ms.
Figure 7.16 Microvias processed with parameters set V: repetition rate = 6.25 kHz, 3 pulse trains, 2 pulses in each pulse train, pulse length = 430 ns, time delay for each train is 2.0 ms.

Table 7.1. Optical evaluation of the microvia quality.

<table>
<thead>
<tr>
<th>Figure</th>
<th>Peak power</th>
<th>Repetition rate</th>
<th>Pulse number</th>
<th>Drilling time</th>
<th>Throughput rate</th>
<th>Top diameter</th>
<th>Bottom diameter</th>
<th>Tapering angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>641.9 W</td>
<td>100 kHz</td>
<td>8 pulses x 6 pulse trains</td>
<td>8.88 ms</td>
<td>113 holes/s</td>
<td>40 μm</td>
<td>34 μm</td>
<td>4.3°</td>
</tr>
<tr>
<td>5</td>
<td>641.9 W</td>
<td>100 kHz</td>
<td>9 pulses x 5 pulse trains</td>
<td>8.45 ms</td>
<td>118 holes/s</td>
<td>47 μm</td>
<td>42 μm</td>
<td>3.6°</td>
</tr>
<tr>
<td>6</td>
<td>1125.6 W</td>
<td>50 kHz</td>
<td>5 pulses x 5 pulse trains</td>
<td>9.5 ms</td>
<td>105 holes/s</td>
<td>50 μm</td>
<td>42 μm</td>
<td>5.7°</td>
</tr>
<tr>
<td>7</td>
<td>1448.8 W</td>
<td>12.5 kHz</td>
<td>2 pulses x 4 pulse trains</td>
<td>7.84 ms</td>
<td>128 holes/s</td>
<td>41 μm</td>
<td>29 μm</td>
<td>8.5°</td>
</tr>
<tr>
<td>8</td>
<td>1425.6 W</td>
<td>6.25 kHz</td>
<td>2 pulses x 3 pulse trains</td>
<td>8.96 ms</td>
<td>112 holes/s</td>
<td>46 μm</td>
<td>38 μm</td>
<td>5.7°</td>
</tr>
</tbody>
</table>
7.3.2 Optimization of the Laser Parameter with the optimized optical system.

7.3.2.1 Comparison between experimental profile and model prediction:

Scanning method is used to measure the beam profile generated by the optimized optics. The designed beam spot size with 2 inch focal length aspheric lens in experimental setup in Figure 7.17 is 50 μm. The beam profiles at different position are shown in Figure 7.18.

Figure 7.17 Experimental Setup for pitchfork beam profile measurement using diffractive optics (Lenses A and B and Phase element C) and a 2-inch focal length aspheric lens.
Figure 7.18 Comparison between the optical model results and experimental data for the beam profiles with new optics.
The advantage of this optimized optics is that the diffraction ring energy is small. However, the disadvantage is that the measured beam spot diameter ranges from 80 to 100 μm, which could be due to the error in manufacturing the optics surfaces, beam quality ($M^2 = 1.3$) of the laser system and the effect of polarization on focusing the beam. The polarization effect requires a rigorous diffraction analysis based on the electric filed vector (complete Maxwell equations) instead of the scalar diffraction analysis used in the present case. The beam quality involves a detailed analysis of the electromagnetic field of the laser produced by the laser system. These studies were beyond the scope of this project.

Figure 7.19 Microvias processed with a 2-inch aspheric focusing lens. Repetition rate = 5 kHz pulse energy = 0.61 mJ, pulse length = 430 ns.
The microvias drilled with the optimized optics and a 2-inch aspheric focusing lens has small heat affected zone but large diameters that are unacceptable.

Possible solutions to achieve small (~40 μm) diameter vias:

(1) To reduce the spot size, a lens with shorter focal length is used as shown in Figure 7.20a. Meniscus lens is used in Figure 7.20a, which introduces a large amount of spherical aberration. The measured beam profile is shown in Figure 7.21. The beam profile steepness is low in this case. The laser parameters can be optimized in this case to produce good quality microvias with diameters less than 50 μm.

(2) The results in Figure 7.19 show that the 2-inch focal length aspheric lens reduces the effect of aberration on the formation of laser ring around the microvia entrance; but large diameter vias are obtained due to the long focal length of the aspheric lens. Therefore, a smaller (e.g., 1-inch) focal length aspheric lens can be used (see Figure 7.18b) instead of the 2-inch aspheric lens (Lens D in Figure 7.17) to reduce the microvia diameter and at the same time reduce the effect of aberration. From the comparison between the optical model results and experimental data for the beam profiles in Figure 7.18, when the predicted diameter of the beam from the optical model is 50 μm, the actual beam diameter is 80 μm from the experimental measurement. So it is reasonable to deduce that when the beam diameter predicted by the optical model is 25 μm for a 1-inch focal length lens (see Figure 7.22), the actual beam diameter would be 40 μm.
a. With 1-inch focal length meniscus lens  
b. With 1-inch focal length aspheric lens

Figure 7.20 Experimental Setup for Pitchfork beam profile measurement with a 1-inch focal length lens.
Figure 7.21 Comparison between the optical model results and experimental data for the beam profiles with optics in Figure 7.20a.
Figure 7.22 Beam profile predicted by the optical model for a 1-inch focal length aspheric lens and other optics in Figure 7.20b.

The top diameters of the vias, which are less than 50 µm, are plotted in Figure 7.23 as a function of the laser peak power. The top diameter increases as the laser peak power increases for a fixed number of pulses used for drilling. Similarly, the top diameter increases as the number of pulses increases for a fixed laser peak power used for drilling. Figure 7.23 can be used to select the optimum laser parameters for producing vias with diameters less than 50 µm.
Laser drilling process optimization for throughput time minimization

To accomplish laser drilling process optimization, systematic drilling experiments have been carried out using the experimental setup shown in Figure 7.20a, for various laser peak powers, number of pulses and pulse energy. Optical micrographs of the microvias are presented in Figures 7.22 – 7.30 and the corresponding laser drilling parameters are listed in the captions of each figure as well as in Table 7.2. The optical microscopic evaluations of the microvia quality are also listed in Table 7.2. The optimum laser parameters are: Laser peak power = 1027.9 W, repetition rate = 62.5 kHz, 3 pulse trains, 6 pulses in each pulse train, pulse length = 430 ns, time delay for each train is 1000 μs. The corresponding outputs are: drilling time = 3.29 ms, throughput rate = 304 holes / sec with diameter = 34/30 μm and tapering angle = 2.9°, which is shown in Fig. 7.30.
Figure 7.24 Microvias processed with parameters: repetition rate = 2 kHz, 8 pulses, pulse energy = 0.61 mJ, pulse length = 430 ns.

Figure 7.25 Microvias processed with parameters: repetition rate = 1 kHz, 8 pulses, pulse energy = 0.613 mJ, pulse length = 430 ns.
Figure 7.26 Microvias processed with parameters: repetition rate = 1 kHz, 7 pulses, pulse energy = 0.619 mJ, pulse length = 430 ns.

Figure 7.27 Microvias processed with parameters: repetition rate = 12.5 kHz, 3 pulse trains, 2 pulses in each pulse train, pulse length = 430 ns, time delay for each train is 1000 μs.
Figure 7.28 Microvias processed with parameters: repetition rate = 25 kHz, 3 pulse trains, 3 pulses in each pulse train, pulse length = 430 ns, time delay for each train is 2000 μs.

Figure 7.29 Microvias processed with parameters: repetition rate = 50 kHz, 3 pulse trains, 5 pulses in each pulse train, pulse length = 430 ns, time delay for each train is 2000 μs.
Figure 7.30 Microvias processed with parameters: repetition rate = 62.5 kHz, 3 pulse trains, 6 pulses in each pulse train, pulse length = 430 ns, time delay for each train is 1000 μs.

Figure 7.31 Microvias processed with parameters: repetition rate = 83.3kHz, 3 pulse trains, 9 pulses in each pulse train, pulse length = 430 ns, time delay for each train is 1000 μs.
Figure 7.32 Microvias processed with parameters: repetition rate = 100 kHz, 3 pulse trains, 10 pulses in each pulse train, pulse length = 430 ns, time delay for each train is 1000 µs.
Table 7.2 Summary of laser drilling parameters for the experimental setup shown in Figure 1 and optical microscopic evaluation of the microvia quality.

<table>
<thead>
<tr>
<th>Fig.</th>
<th>Peak power [W]</th>
<th>Repetition rate [kHz]</th>
<th>Pulse number</th>
<th>Drilling time [ms]</th>
<th>Throughput rate [via/s]</th>
<th>Top diameter [μm]</th>
<th>Bottom diameter [μm]</th>
<th>Tapering angle [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.24</td>
<td>1418.6</td>
<td>2</td>
<td>8</td>
<td>4</td>
<td>250</td>
<td>40</td>
<td>32</td>
<td>5.7</td>
</tr>
<tr>
<td>7.25</td>
<td>1425.6</td>
<td>1</td>
<td>8</td>
<td>8</td>
<td>125</td>
<td>35</td>
<td>24</td>
<td>7.8</td>
</tr>
<tr>
<td>7.26</td>
<td>1439.5</td>
<td>1</td>
<td>7</td>
<td>7</td>
<td>142</td>
<td>33</td>
<td>22</td>
<td>7.8</td>
</tr>
<tr>
<td>7.27</td>
<td>1448.8</td>
<td>12.5</td>
<td>2 pulses x 3 pulse trains</td>
<td>3.48</td>
<td>287</td>
<td>34</td>
<td>30</td>
<td>2.9</td>
</tr>
<tr>
<td>7.28</td>
<td>1367.4</td>
<td>25</td>
<td>3 pulses x 3 pulse trains</td>
<td>6.36</td>
<td>157</td>
<td>34</td>
<td>27</td>
<td>5.0</td>
</tr>
<tr>
<td>7.29</td>
<td>1125.6</td>
<td>50</td>
<td>5 pulses x 3 pulse trains</td>
<td>6.3</td>
<td>158</td>
<td>34</td>
<td>31</td>
<td>2.1</td>
</tr>
<tr>
<td>7.30</td>
<td>1027.9</td>
<td>62.5</td>
<td>6 pulses x 3 pulse trains</td>
<td>3.29</td>
<td>304</td>
<td>34</td>
<td>30</td>
<td>2.9</td>
</tr>
<tr>
<td>7.31</td>
<td>790.7</td>
<td>83.3</td>
<td>9 pulses x 3 pulse trains</td>
<td>15.32</td>
<td>65</td>
<td>40</td>
<td>36</td>
<td>2.9</td>
</tr>
<tr>
<td>7.32</td>
<td>641.9</td>
<td>100</td>
<td>10 pulses x 3 pulse trains</td>
<td>15.3</td>
<td>65</td>
<td>38</td>
<td>35</td>
<td>2.1</td>
</tr>
</tbody>
</table>
The laser parameter map for microvias drilling is shown in figure 7.33. To read data from the figure, let us take point D in figure one as an example. To get the laser peak irradiance for point D, draw a line from point D which is perpendicular to plane A. The projection of point D on plane A can give the laser peak irradiance which is 20.4 MW/cm$^2$. To get the number of pulses and number of pulse trains, draw a line from point D which is perpendicular to plane B. The projection of point D on plane B can give the information of number of pulses in a pulse train and also number of pulse trains totally used. For point D, 6 pulses are used in each pulse train and there are 3 pulse trains to finish the drilling. The time delay between each pulse train for point D is 1 ms which indicated by the arrow in the figure. In the time domain the arrangement of the pulses for point D is shown in Figure 7.34.
Figure 7.33 Laser parameters for microvias drilling

Figure 7.34 The arrangement of the pulses in the time domain for point D
7.4 Conclusions

A pinhole scanning method is developed to measure the laser beam profile, showing good agreement between the theoretical prediction and the experimental pitchfork beam profile. The drilling front profile calculated by the model agrees the experimental data well. Drilling result shows that the pitchfork beam can produce better vias with reduced polymeric residue at the bottom of the via than the Gaussian beam and the Bessel beam.

Laser parameters are optimized for microvias drilling:

For the optical system designed by ray tracing technique, the optimized laser parameters are:
laser peak power = 641.9 W, repetition rate = 100 kHz, 6 pulse trains, 8 pulses in each pulse train, pulse length = 430 ns, time delay for each train is 1.4 ms. The corresponding outputs are:
drilling time = 8.88 ms / hole, throughput rate = 113 holes / sec with diameter = 40/34 μm and tapering angle = 4.3°.

For the optical system optimized by iterative method, the optimum laser parameters are: Laser peak power = 1027.9 W, repetition rate = 62.5 kHz, 3 pulse trains, 6 pulses in each pulse train, pulse length = 430 ns, time delay for each train is 1000 μs. The corresponding outputs are:
drilling time = 3.29 ms, throughput rate = 304 holes / sec with diameter = 34/30 μm and tapering angle = 2.9°.
Compared to the optics designed by ray tracing, the optimized optics have allowed improving the following microvia parameters: Via diameter, Tapering angle, Through-put time.
CHAPTER 8: EXPERIMENTAL STUDY OF MICROVIAS DRILLING WITH ND: YAG LASERS

8.1 Drilling Mechanism

Microvia drilling with Nd:YAG lasers is analyzed in this study because of its potential advantages over CO₂ lasers. The shorter wavelength (1.06 μm or 0.532 μm for 2ⁿᵈ harmonic) of Nd:YAG lasers enables focusing to smaller beam diameters than CO₂ lasers and, therefore, Nd:YAG lasers are more readily adaptable for smaller diameter via drilling than the CO₂ lasers. Also the reflectivity of copper at the Nd:YAG laser wavelength is not as high as for CO₂ lasers. So the copper layer will be heated more during the Nd:YAG laser microvia drilling and it will provide an additional mechanism to heat the polymer layer from bottom at the polymer-copper interface. Thus a rapid heating mechanism may be maintained with a Nd:YAG laser during the entire drilling process to avoid the formation of residue at the bottom of the hole, which will allow cleaner (residue-free) microvia drilling than in the case of CO₂ lasers. Excessive heating, however, may damage the copper layer and cause delamination at the bottom surface of the copper layer. The laser parameters need to be chosen properly to avoid such damages.
8.2 Microvias Drilling Experiment with Fundamental Frequency Nd:YAG Laser

The microvia drilling experiments were carried out with a Nd:YAG laser of wavelength of 1.06 μm. The experimental setup is shown in figure 8.1. A spatial filter was placed after the shutter of the laser system to extract a laser beam of improved mode structure. The beam was focused with a 50 mm focal length lens and the multilayer substrate was placed on a x-y stage at the focal plane of the lens. The laser was run at the repetition rate of 10 KHz and a pulse width of 126 ns which was controlled with a Q-switch assembly. The number of pulses was controlled with a pulse generator. Various laser parameters such as the laser pulse energy, number of pulses and beam diameter are varied to investigate the drilling process. The diameters of the microvias were in the range of 60 to 400 μm for the laser energies ranging from 0.05 to 0.7 mJ/pulse. As representative results, the cases for the energies of 0.05 to 0.7 mJ/pulse will be discussed. An optical microscope was used to examine the geometrical features of the microvias. The laser irradiance profile was obtained with a laser beam analyzer.

From the analytic thermal model in Chapter 2, overheating occurs inside the polymer layer due to volumetric heating. Figure 8.2 shows the temperature distribution along z direction for r = 0 at the end of different pulses. The laser parameters are: energy = 0.05 mJ/pulse, pulse-on time = 126 ns and repetition rate = 10 KHz. As the number of pulses increases, the maximum temperature inside the polymer increases because more pulses deposit more energy. The maximum temperature exceeds the vaporization point by 9769 K after 50 pulses. It is impossible for any polymer to maintain its thermochemical and thermomechanical integrity at such high superheating. Chemical degradation will occur inside the polymer layer. The degradation will
produce different kinds of gases and thus generate high pressures within the polymer layer. The thermomechanical effect of very high temperature is that the thermal stress will exceed the yield stress of the material, causing sudden rupture of the layer. These factors lead to the removal of materials explosively. The onset of polymer rupture due to thermal stresses is analyzed in this study.

Figure 8.1 Experimental setup for Nd:YAG laser microvia drilling experiments.
Figure 8.2 Temperature distribution for different laser pulses in the coordinate system moving with the vaporization front at $r = 0$.

Figure 8.3 Thermal stress distribution along $z$ direction for different laser pulses in the coordinate system moving with the vaporization front at $r = 0$. 
Since the temperature difference in the z-direction is much larger than in the other directions, only the thermal stress in the z-direction is considered. The axial stress around the heated polymer is given by,

\[ \sigma_{zz} = \frac{\alpha_e E (T - T_0)}{1 - \nu} \quad (8.1) \]

where \( \alpha_e \) is the thermal expansion coefficient, \( E \) is the elastic modulus and \( \nu \) is the Poisson ratio.

The thermal stress along the z-direction is shown in figure 8.3 for different numbers of pulses with a Gaussian laser beam of energy = 0.05 mJ/pulse, pulse-on time = 126 ns and pulse repetition rate = 10 KHz. The thermal stress is proportional to the temperature as evident in Eq. (20). The yield stress of the polymer is 0.5 GPa, which is shown as a horizontal dash line in figure 8.3. The region where the value of thermal stress exceeds the yield stress will rupture or explode.

Figures 8.4 and 8.5 show the development of overheating and thermal stress inside the polymer layer for laser energy = 0.7 mJ/pulse. Since the laser power is relatively high in this case, the results are obtained for different irradiation times within one pulse, i.e., within the first pulse-on time. As discussed in section 2, the coordinate system moves with the vaporization front in this model. The temperature distributions have been plotted in figure 8.4 in the moving coordinate for different irradiation times. So the depth \( z = 0 \) in the moving coordinate actually represents three different locations of the vaporization front in a stationary coordinate system with the vaporization front being deeper as the irradiation time increases, that is, as one considers the case of curve A compared to curve C. The distance from the vaporization front to any isotherm inside the substrate depends on the vaporization speed and the speed of isotherms. This distance
decreases as in the case of curve A compared to curve C because the vaporization speed can increase as the irradiation time increases, while the isotherm speed generally remains unchanged in the solid phase. After 126 ns which is the end of the first pulse-on time, the maximum temperature inside the polymer exceeds the vaporization point by 4512 K. The corresponding thermal stress shown in figure 8.5 is 0.508 GPa which is higher than the yield stress of the polymer material. So the materials removal will occur explosively during the first pulse.

![Figure 8.4](image.jpg)  

Figure 8.4 Temperature distributions at different irradiation times in the coordinate system moving with the vaporization front at r = 0.
Figure 8.5 Thermal stress distribution along z direction at different irradiation times in the coordinate system moving with the vaporization front at r = 0.

Because of the complexity of the explosion process, the motion of the drilling front is calculated by considering the thermal phase change only. The calculated depth of microvia at r = 0 is presented in figure 8.6 as a function of time for laser energy 0.7 mJ/pulse, 126 ns pulse-on time and 10 KHz pulse repetition rate, showing that the depth increases as the drilling time increases. The temperature within a portion of the polymer exceeds the vaporization point at the end of the pulse-on time as shown in figure 8.4. The drilling process continues during the pulse-off time due to this excess heat in the overheated region providing the necessary thermal energy to vaporize the polymer material. Figure 8.6 shows that the via depth increases sharply during the pulse-on time 126 ns which is very small compared to the period of the pulse, indicating very
high drilling speed. Only a very small amount of material is removed during the pulse-off time. As the drilling front proceeds towards the bottom of the via, the drilling speed decreases. The thicknesses of the polymer removed are 19, 16 and 2 μm for the first, second and third pulses respectively. This reduction in the material-removing ability of the laser in subsequent pulses is due to less absorption of the laser energy by the polymer and energy loss through heat conduction and reflection of the laser beam by the copper layer. As the thickness of the polymer layer decreases above the copper pad, more laser light can pass through the polymer layer and therefore less energy is absorbed in the polymer. The transmitted light reaches the copper surface where it is reflected back to the ambient. Thus much of the laser energy is lost instead of being used for drilling the polymer and consequently the drilling time increases.

Figure 8.6 Drilling depth as a function of drilling time for three pulses at r = 0.
The model predicts that three pulses would be necessary to drill the microvia with a laser of energy is 0.7 mJ/pulse. However, only one pulse was sufficient to create microvias in experimental studies as shown in figure 8.7. This discrepancy may be explained by considering the temperature distribution and thermal stresses in the polymer. It can be seen in figure 8.5 that the thermal stress inside the polymer exceeds the yield stress at the end of the first pulse-on time, indicating a stress-induced explosion in the material. The explosion can improve the efficiency of the drilling process. More materials can be removed by explosions than by vaporization only at the drilling front. Figure 8.7 shows that the edge of the hole is very clean at the top surface of the hole; heat-affected zone can not be observed. So it may be interpreted that the drilling process starts from inside the substrate to the top surface. For drilling to occur downward by material removal from the vaporization front only (i.e., from the top surface of the hole only), more heating would be necessary at the top surface than at the copper-polymer interface and this phenomenon is likely to form a heat-affected zone at the mouth of the hole. So the experimental result (figure 8.7) suggests that the material removal occurs explosively during the drilling process.

Now let us analyze whether the drilling process occurs from below the polymer surface. Since a Gaussian laser beam was used in the experiment and such beams have very high and low irradiances at the center and edge of the beam respectively, more material would be removed from the central region than from the periphery of the hole if the drilling process occurs due to vaporization only at the top surface of the polymer. This, in turn, would create a concave surface at the bottom of the hole with a large amount of residue at the periphery. To examine how flat the bottom surface of the hole is, a flatness ratio is defined for the hole which is given
by \( D_b/D_t \) where \( D_b \) and \( D_t \) are the diameters of the hole at the bottom and top surfaces respectively. The flatness ratio for the hole in figure 8.7 is 0.9 which is close to 1 and thus the flatness ratio indicates that the amount of residue is small in the corner at the bottom of the hole. So the drilling process can be considered to occur from below the polymer surface. Another phenomenon that might contribute to such large flatness ratio, even when the thermal stress does not exceed the yield stress, is the delamination at the copper-polymer interface due to the difference in the coefficient of thermal expansion of these two materials. Additionally the depolymerization of a typical polymer PMMA results in about 20% increase in the volume of the polymer, which is large compared to the thermal expansion of copper layer, and thus provides another mechanism for the delamination. A small gap is formed at the interface due to delamination, which may cause multiple reflections of the laser beam and thus enhance the absorption of more laser energy. So the delamination process becomes faster and at the same time the pressure inside the polymer becomes high due to volumetric heating and due to the increase in volume caused by depolymerization. The polymer becomes soft when its temperature exceeds the glass transition temperature. The high internal pressure can expel the entire soft region. This mechanism needs to be utilized with appropriate laser parameters to create clean microvias, otherwise the copper pad beneath the polymer layer will be damaged as shown in figure 8.8.
Figure 8.7 Optical micrographs (200x) of a hole produced with 1 laser pulse (Focal length = 50 mm, Hole size = 400 μm, Pulse energy = 0.7 mJ, Pulse width = 126 ns and Repetition rate = 10 kHz).

Figure 8.8 Damaged copper layer after 5 and 10 laser pulses (Focal length = 50 mm, Pulse energy = 0.7 mJ, Pulse width = 126 ns and Repetition rate = 10 kHz).
The diameters at the top and bottom of the hole are 400 μm and 360 μm respectively for the laser energy of 0.7 mJ/pulse. Lower pulse energy can be used to drill microvias of smaller diameters. Figure 8.9 shows the model prediction of a hole profile for the laser energy of 0.05 mJ/pulse. For low laser peak powers, the existence of residue is predicted at the bottom and corner of the hole even after 200 laser pulses, although the thickness of the residue decreases as the number of pulses increases. However, the experimental result in figure 8.10 shows that the bottom of the hole is reached after 100 pulses. The explosive mechanism of material removal due to high internal pressures may account for the difference in the model prediction and experimental data as explained earlier. It can be seen in figure 8.3 that the thermal stress exceeds the yield stress of the polymer after 50 pulses for the laser energy of 0.05 mJ/pulse, indicating that explosion will occur during the drilling process at this pulse energy. The flatness ratio of the hole is 0.58 for this pulse energy, which is smaller than for the case of 0.7 mJ/pulse. So the copper-polymer interface delaminates less extensively at lower pulse energies than at higher pulse energies. This leaves a large amount of residue or a heat-affected zone around the periphery at the bottom of the hole as can be seen in Figure 8.10.
Figure 8.9 Drilling depth for different pulses.

Figure 8.10 Optical micrographs (500x) of a hole produced with 100 laser pulses (Focal length = 50 mm, Hole size = 60 μm, Pulse energy = 0.05 mJ, Pulse width = 126 ns and Repetition rate = 10 kHz).
Finally the development of high internal pressure exceeding at least the atmospheric pressure is demonstrated through an optical micrograph in Figure 8.11. After 50 laser pulses, the surface of the irradiated region bulges up, forming a convex surface which is contrary to the common notion that a concave surface be formed by a Gaussian beam. This suggests that the pressure inside the polymer is high to push the material outwards but still insufficient to expel the material out of the substrate. Some of the material is removed due to vaporization at the top surface, providing a mechanism for the formation of a concave surface. However, the internal pressure is sufficiently high to compensate for this mechanism and eventually form the convex surface. As the pressure builds up with higher number of laser pulses, the radius of curvature of the convex surface increases and ultimately the surface will rupture and the material will be removed explosively.

Figure 8.11 An optical micrograph (500x) of a convex surface formed after 50 pulses (Focal length = 50 mm, Pulse energy = 0.05 mJ, Pulse width = 126 ns and Repetition rate = 10 kHz).
8.3 Microvias Drilling Experiment with Second Harmonic Nd:YAG Laser

The laser drilling of microvias was studied in this work. The experimental setup is shown in Fig. 8.12. The laser used in the experiment is 532 nm frequency-doubled, diode-pumped Nd: YAG laser (LDP-200MQG, Lee Laser) with pulse duration of 120 ns. The laser power is adjusted with an optical attenuator which is composed of a half wave plate (HWP) and a thin film plate polarizer (TFPP). The output beam from the laser is linearly polarized in the horizontal direction (P-Polarized), indicated by the straight lines in Fig. 8.12, and is transmitted by the thin film plate polarizer. By rotating the half-wave-plate, the laser output is converted from P-polarized to S-polarized light, (indicated by the circle in the figure) which is reflected by the polarizer. In this case the laser could be operated in a regime that gives the best output power and pulse-to-pulse stability. To drill a microvia, a single pulse sometimes is needed. If use the internal Q-switch to generate the single pulse, the energy contained in this pulse is giant. This giant pulse may damage the laser crystal. To prevent the damage, an external pulse picker is used. The pulse picker is an acousto optic modulator from NEOS Technologies, Inc. (AOM 35085-3). It can diffract the beam into the optical path when sending signal to it. Since the frequency of the acousto optic modulator is 85 MHz and the frequency of the laser is 10 kHz, the pulse picker can efficiently pick a single pulse outside of the laser cavity. A beam expander was placed in the beam path. After going through the beam expander, the laser beam was focused by a lens system with an effective focal length of 50.8 mm onto the substrate, which was fixed on a xy-stage.
The laser was run at the repetition rate of 10 KHz and a pulse width of 120 ns which was controlled with a Q-switch assembly. The number of pulses was controlled with a pulse generator. Various laser parameters such as the laser pulse energy, number of pulses and beam diameter are varied to investigate the drilling process. An optical microscope was used to examine the geometrical features of the hole.

Figure 8.12 Experimental setup for microvias drilling with frequency-doubled Nd:YAG laser.

The laser parameters for 532 nm frequency-doubled, diode-pumped Nd: YAG laser are selected to perform the drilling process. Without beam expander, the laser beam has larger diameter on
the focal plane. Following process parameter sets are used for the drilling experiment without beam expander: pulse energy = 0.0592 mJ, repetition rate = 10 kHz, 200 pulses; pulse energy = 0.0592 mJ, repetition rate = 10 kHz, 100 pulses; pulse energy = 0.11 mJ, repetition rate = 10 kHz, 50 pulses; pulse energy = 0.166 mJ, repetition rate = 10 kHz, 20 pulses; pulse energy = 0.215 mJ, repetition rate = 10 kHz, 40 pulses; pulse energy = 0.158 mJ, repetition rate = 10 kHz, 40 pulses; pulse energy = 0.0731 mJ, 10 kHz, 50 pulses; pulse energy = 0.0691 mJ, 10 kHz, 100 pulses. The microvias produced by these parameters can be seen in Table 8.1. The parameter set: pulse energy = 0.166 mJ, repetition rate = 10 kHz, 20 pulses, can give the maximum throughput rate which is 500 holes / sec. The via produced by this parameter set has a diameter of 26 μm which is shown in Figure 8.13. Since the laser system has maximum pulse energy of 11 mJ, the laser beam can be split into multiple beams to drilling the microvias at the same time, e.g. 66 beams at the same time. The potential throughput of the laser system can be 500 × 66 = 33000 holes / sec.

Figure 8.13 Microvia produce by the process parameter set: Pulse energy = 0.166 mJ, repetition rate = 10 kHz, 20 pulses. The throughput is 500 holes / sec.
With beam expander, the laser beam size on the focal plane can be reduced. Following parameters are used for microvias drilling: Pulse energy = 0.275 mJ, repetition rate = 10 kHz, 10 pulses; pulse energy = 0.275 mJ, repetition rate = 10 kHz, 20 pulses. The microvias produced by these parameters can be seen in Table 8.1. The throughput in this case can be as high as 1000 holes / sec and the microvia diameter is 13 μm which is shown in Figure 8.14. If splitting the pulse energy of 11 mJ of the laser system into 40 beams, the potential throughput can reach 1000 × 40 = 40000 holes / sec.

Figure 8.14 Microvia produce by the process parameter set: Pulse energy = 0.275 mJ, repetition rate = 10 kHz, 10 pulses. The throughput is 1000 holes / sec.
Table 8.1 Parameters for microvias drilling with frequency-doubled Nd:YAG laser

<table>
<thead>
<tr>
<th>Intensity (W/m²)</th>
<th>7.538x10^7</th>
<th>2.114x10^8</th>
<th>2.012x10^8</th>
<th>9.307x10^7</th>
<th>8.798x10^7</th>
<th>1.401x10^9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average power (W)</td>
<td>0.592</td>
<td>1.66</td>
<td>1.58</td>
<td>0.731</td>
<td>0.691</td>
<td>2.75</td>
</tr>
<tr>
<td>Pulse energy (mJ)</td>
<td>0.0592</td>
<td>0.166</td>
<td>0.158</td>
<td>0.0731</td>
<td>0.0691</td>
<td>2.75</td>
</tr>
<tr>
<td>Tapering angle</td>
<td>12.7°</td>
<td>7.1°</td>
<td>7.1°</td>
<td>8.5°</td>
<td>7.8°</td>
<td></td>
</tr>
<tr>
<td>Optics with beam expander</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Pulse number</td>
<td>200</td>
<td>20</td>
<td>40</td>
<td>50</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>Number of holes per second for a single beam</td>
<td>50</td>
<td>500</td>
<td>250</td>
<td>200</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Number of beams that can be obtained from the Nd:YAG laser</td>
<td>185</td>
<td>66</td>
<td>70</td>
<td>150</td>
<td>159</td>
<td>40</td>
</tr>
<tr>
<td>Total number of holes per second</td>
<td>9250</td>
<td>33000</td>
<td>17500</td>
<td>30000</td>
<td>15900</td>
<td>40000</td>
</tr>
<tr>
<td>Top surface of the hole</td>
<td>Can not be measured by optical microscope</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom surface of the hole</td>
<td>52 μm</td>
<td>26 μm</td>
<td>44 μm</td>
<td>35 μm</td>
<td>32 μm</td>
<td>13 μm</td>
</tr>
</tbody>
</table>
8.4 Conclusions

The drilling data by fundamental frequency Nd:YAG laser shows that fewer pulses are necessary to drill microvias than the number of pulses predicted by the model in which the material removal mechanism is based on only vaporization at the top surface. This discrepancy between the theory and experiment, and the high internal pressure suggest that explosion occurs inside the polymer substrate during the drilling process due to chemical degradation of the polymer and thermomechanical breakage. The material removal is more efficient through the explosion mechanism than just by the vaporization at the top surface of the substrate. The thermomechanical breakage, i.e., the debonding of the polymer originally appears at the polymer-copper interface, which tends to reduce the amount of residue at the bottom of the hole at relatively high pulse energies. 2\textsuperscript{nd} harmonic Nd:YAG laser was also used to drilling microvias. Acousto optic modulator was used as an external pulse picker to pick a single pulse from the laser. Throughput of 1000 holes / sec can be achieved for microvias with diameter = 13 µm. If beam splitting technique is used, the throughput can be further improved to 40000 hole / sec.
CHAPTER 9: SUMMARY

9.1 Conclusions

Laser is the predominant tool for microvias drilling. This study focused on the research of microvias drilling with CO$_2$ laser and Nd:YAG laser. Analytical thermal model and numerical thermal model are built to simulate the microvias drilling process. Beam shaping technique is used to produce the laser irradiance spatial distribution a pitchfork profile. Experiments were performed to research the effect of the design pitchfork beam shape. Following conclusions are drawn:

(1) The CO$_2$ laser drilling of polymer substrates is mainly due to ablation. The Nd:YAG laser drilling mechanism involves thermomechanical breakage or expulsion of the material by high internal pressure.

(2) An overheated metastable state of material is found to exist inside the workpiece. It also causes thermomechanical breakage of the material when the thermal stress exceeds a critical value, leading to material removal through explosion under certain laser parameters. A thicker heat-affected zone (HAZ) in the polymer material is produced due to the overheating. The HAZ, which will be referred to as “smear residue”, is formed in the region where the temperature exceeds the thermal decomposition point.
(3) The self-defocusing effect in the microvia drilling process in polymer substrates is studied by a numerical thermal model. Results show that self-defocusing of the laser beam by the drilling front can reduce the drilling speed. So the refractive index of the material at a specific wavelength is an important parameter for laser drilling. Correspondingly the self-focusing effect can be utilized advantageously with pitch fork beams to increase the drilling speed compared to uniform and Gaussian beam shapes.

(4) The effects of the embedded copper plane for microvia drilling in multilayered polymeric substrates are analyzed by the numerical thermal model. Three drilling mechanisms, super-critical, critical and sub-critical drilling stages have been identified. The drilling speed increases sharply when the polymer layer thins down to the absorption depth because both the incident and reflected laser beams contribute to the volumetric heating over a small polymer volume. Nanosecond pulsed laser can produce less residue in microvias drilling. Laser pulse shaping is necessary to efficiently utilize the laser energy and to remove the residue.

(5) The thermal conductivity, specific heat capacity at constant pressure, density, thermal decomposition temperature and specific ablation heat are measured in this study for epoxy resin sheets of high glass transition temperature filled with fused silica (ABF-GX13). Laser heating method is presented for the measurement of the thermal conductivity and specific ablation heat. A constant value of thermal diffusivity fits the theory and experimental data over a large range of temperature, indicating that the thermal diffusivity of the polymer material may be considered constant over this temperature range. The complex interactions between the laser and polymers may be represented by a single material property which is referred to as the specific ablation
heat. These thermophysical properties can be used for modeling and understanding laser microvia drilling processes.

(6) Pitchfork beam profile was found to be the optimum laser beam shape for microvias drilling. With the theory of the refractive optics and diffraction effect, optical system with phase and transform elements is designed to transform a Gaussian laser beam into a pitchfork beam. The phase element is made up of two aspherical lenses and the transform element is a focusing lens. Ray tracing of geometric optics is used to design the phase elements based on the conservation of energy, the constancy of optical path length and Snell’s law. The Fresnel diffraction is used to predict a pitchfork beam profile near the focal plane.

(7) The refractive beam shaping system for pitchfork profile is optimized by diffractive optics. Iterative method with Adaptive Additive algorithm is used for the optimization. Two phase-elements are introduced in the conventional optical system for laser microvias drilling to optimize the pitchfork beam shape and to increase the depth of focus respectively. After the optimization the energy contained in the diffraction side lobe is reduced. The pitchfork beam profile can be maintained within a longer distance on the optical axis.

(8) Experiments of microvias drilled with CO₂ laser are performed. A pinhole scanning method is developed to measure the laser beam profile, showing good agreement between the theoretical prediction and the experimental pitchfork beam profile. The drilling front profile calculated by the model agrees the experimental data well. Drilling result shows that the pitchfork beam can
produce better vias with reduced polymeric residue at the bottom of the via than the Gaussian beam and the Bessel beam.

(9) Laser parameters are optimized for microvias drilling in terms of laser peak power, repetition rate, pulse number, etc. The process parameter map for CO2 laser microvias drilling is shown in Figure 9.1.
To read data from the figure, let us take point D in figure one as an example. To get the laser peak irradiance for point D, draw a line from point D which is perpendicular to plane A. The projection of point D on plane A can give the laser peak irradiance which is 20.4 MW/cm$^2$. To get the number of pulses and number of pulse trains, draw a line from point D which is perpendicular to plane B. The projection of point D on plane B can give the information of number of pulses in a pulse train and also number of pulse trains totally used. For point D, 6 pulses are used in each pulse train and there are 3 pulse trains to finish the drilling. The time delay between each pulse train for point D is 1 ms which indicated by the arrow in the figure. In the time domain the arrangement of the pulses for point D is shown in Figure 9.2.

![Figure 9.2 The arrangement of the pulses in the time domain for point D](image)

The corresponding outputs after the optimization are: drilling time = 3.29 ms, throughput rate = 304 holes/sec with diameter = 34/30 μm and tapering angle = 2.9°.
Experimental results of microvias drilling with fundamental frequency Nd:YAG laser suggest that explosion occurs inside the polymer substrate during the drilling process due to chemical degradation of the polymer and thermomechanical breakage. The material removal is more efficient through the explosion mechanism than just by the vaporization at the top surface of the substrate. The thermomechanical breakage, i.e., the debonding of the polymer originally appears at the polymer-copper interface, which tends to reduce the amount of residue at the bottom of the hole at relatively high pulse energies. 2nd harmonic Nd:YAG laser was also used for microvias drilling. Acousto optic modulator was used as an external pulse picker to pick a single pulse from the laser. Throughput of 1000 holes / sec can be achieved for microvias with diameter = 13 μm.

9.2 Future Work

Due to the overheating effect inside the polymer materials, internal expulsion can occur during the drilling process. The current thermal model cannot simulate the material removal process due to this internal expulsion. In the present thermal model, the thermal decomposition process is simplified as a constant temperature process. To make the simulation more accurate, models considering chemical reaction and aerodynamics need to be built for this complex process.

The pitchfork beam is found to be the optimum beam shape for microvias drilling. The design work and the optimization can guarantee the pitchfork shape in the long distance. However, the
third order aberration and tolerance analysis are not consider in this research. The spherical aberration leads to large heat affected zone and large beam size and reduces the throughput rate. For low tolerance system, the misalignment of the optic and defocus may ruin the whole performance of the design. Optics to correct for third order aberration need to be designed. Due to the high cost of far infrared optical material, aspheric lens is preferred for the design. Tolerance analysis need to be perform to make the system more compatible to be integrated in the industry.

For the current experimental setup of CO$_2$ microvias drilling, to improve the throughput time, the experimental setup shown in Figure 9.3 can be used. F-theta lens system with 1 inch effective focal length will substitute the 2 inch focal length in the experimental setup in Figure 9.3 to reduce the diameter of the via and to improve the throughput rate.
Nd:YAG lasers at fundamental frequency and doubled frequency have large potentials in microvias drilling. The beam shaping technique for CO2 lasers is ready to be transplanted into the Nd:YAG laser system. Beam splitting technique need to be integrated in the laser microvias drilling system to maximize the utilization of the high power Nd:YAG laser. The throughput of the microvias drilling can be as high as 40000 holes / sec if the laser beam is efficiently split.
Figure 9.4 Experimental Setup for microvias drilling with beam splitting optics.
APPENDIX A: MATLAB PROGRAM FOR NUMERICAL THERMAL MODEL FOR LASER MICROVIAS DRILLING
This is an example program in Matlab for simulation of the microvias drilling process by a CO₂ laser. The laser parameters are: laser wavelength = 9.3 μm, laser pulse energy = 0.392 mJ, repetition rate = 50 kHz, pulse on time = 430 ns. The properties of the polymer material are shown in Table 3.1. The structure of the substrate is shown in Figure 3.1. The thickness of the polymer layer is 40 μm and the thickness of the copper layer is 15 μm.

clear;
startover=menu(sprintf('New calculation?'),'Yes', 'No', 'Cancel');
if startover==3;
    return;
end;

%% material parameter

D=1440. ;% Kg/m³ Density
Cp=1040. ;% Specific heat J/Kg.K
k=0.18; %Thermal Conductivity W/m.k
a=k/(D*Cp); % diffusivity m²/sec
Lv=4.96*10^-6 ;% Latent heat of Vaporization J/Kg
Tv=539. ;% 1.5 times the glass transition temperature
T0=298. ;% Room Temperature K
u=0.103*10^6; % Absorption coefficient
Rth=15*10^-6/390+1.118*10^-6/k; %thermal resistance of the copper layer and the polymer layer

%% laser parameter
P=0.392*50;%power W
f=50000 ;% Frequency Hz
tON=0.43*10^-6 ;% Pulse on time sec
tp=1/f ;% Pulse duration sec
tOFF=tp-tON ;% Pulse off time sec

Lamda=9.3*10^-6 ;% Wavelength in microns
if abs(Lamda-9.3*10^-6)<10^-12; %CO2 laser
    ni=1.923; % Refractive index
    Acu=0.001; % Absorptivity for copper
    A=0.9003; % Absorptivity for polymer
    u=0.103*10^6; % Absorption coefficient
elseif abs(Lamda-1.06*10^-6)<10^-12; %Nd:YAG laser
    ni=10.629; %
    Acu=0.01; % Absorptivity for copper
    u=0.041*10^6; % Absorption coefficient
    A=0.3144; % Absorptivity for polymer
end
ki=Lamda*u/4/pi; % imaginary part of refractive index
Lam_m=Lamda/ni; % Wavelength in the material

%% Discretizing
Zp = 40*10^{-6}; % thickness of the polymer layer  
Rp = 60*10^{-6}; % Calculation region in r direction  
nz = 400; % number of grid in z direction  
mr = 600; % number of grid in r direction  
dz = Zp/nz; % space step in z direction  
dr = Rp/mr; % space step in r direction  
nton = 1000;  
ntoff = 2500;  
dt = tON/nton; % time step  
z = zeros(1,nz+1); % preallocating the maximum amount of space  
r = zeros(1,mr+1); % preallocating the maximum amount of space  
R = zeros(1,mr+1); % Reflectivity of the sample  
Wz = zeros(1,nz+1); % preallocating the maximum amount of space  
Wzi = zeros(1,nz+1); % inner radius of the pitchfork beam  
Wzr = zeros(1,nz+1); % beam waist of reflected beam by the copper layer  
Wzri = zeros(1,nz+1);  
I0 = zeros(1,nz+1); % preallocating the maximum amount of space  
I0r = zeros(1,nz+1); % preallocating the maximum amount of space  
It = zeros(nz+1,mr+1); % preallocating the maximum amount of space  
Ir = zeros(nz+1,mr+1); % reflected beam by the copper layer  
g = zeros(nz+1,mr+1); % preallocating the maximum amount of space  
Ia = zeros(1,mr+1); % Laser irradiance absorbed by copper layer  
H1 = zeros(nz+1,mr+1); % intermediate enthalpy for TSMM

for n=1:nz+1;  
z(n)=(n-1)*dz; % vector in z direction  
end;  
for m=1:mr+1;  
r(m)=(m-1)*dr; % vector in r direction  
end;  
if startover==1;  
s = zeros(1,mr+1); % preallocating the maximum amount of space  
T = zeros(nz+1,mr+1); % initial value for temperature (T=T0-T)  
T1 = zeros(nz+1,mr+1); % intermediate temperature for TSMM  
H = zeros(nz+1,mr+1); % initial value for enthalpy (H=H0-D*Cp*T0)  
t=0;  
for m=1:mr+1;  
s(m)=0/10*Zp; % the initial depth of drilling front  
end;  
else  
load('data.mat')  
end;

%% Boundary Conditions  
% At z=0: T(1,m)=C01.*(k.*T(2,m)+dz.*Ib0(m))./(dz.*h0+k)+Th0;  
B0=2;  
Ib0=zeros(1,mr+1); % heat flux at z=0 is zero;  
if B0==1; % first boundary condition  
h0=0;  
C01=0;  
elseif B0==2; % second boundary condition  
C01=1;  
h0=0;  
Th0=0;  
elseif B0==3; % third boundary condition  

C01=1; 
h0=1/Rth; 
Th0=0;
end;

% At z=Zp T(nz+1,m)=Cn1.*(k.*T(nz,m)+dz.*Ia(m))./(dz.*hn+k)+Thn;
Bn=3;
for m=1:mr+1;
    Ia(m)=Acu.*It(nz+1,m); % Laser irradiance absorbed by copper layer
end;
if Bn==1; %first boundary condition
    Cn1=1;
    hn=1/Rth;
    Thn=0;
elseif Bn==2; %second boundary condition
    Cn1=1;
    hn=0;
    Thn=0;
elseif Bn==3; %third boundary condition
    Cn1=0;
    hn=0;
    Thn=0;
end;

% At r=0: dT/dr=0;

% At r=Rp: T(n,mr+1)=Cm1.*(k.*T(n,mr)+dz.*Ibm)./(dz.*hm+k)+Thm;
Bm=1;
Thm=0; %Temperature at r=Rp is zero;
if Bm==1; %first boundary condition
    Cm1=0;
    hm=0;
    Ibm=0;
elseif Bm==2; %second boundary condition
    Cm1=1;
    hm=0;
    Thm=0;
elseif Bm==3; %third boundary condition
    Cm1=0;
    hm=1/Rth;
    Thm=0;
end;

while t<6*tp+tON;

%% Gaussian beam propagation
W0a=12.2*10^-6; % Beam waist on the substrate in microns
zwa=0; % The laser beam is focused on the top surface

%% Fitting the drilling front with least square fitting method
m2=0;
for m=1:mr+1; %finding the edge of the hole
    if s(m)>10^-7;
        m2=m2+1;
    end;
end;
r2=r(1:m2);
s2=s(1:m2);
if m2<=7;
    p=zeros(1,3);
p2=zeros(1,6);
else
    p = polyfit(r2,s2,2); %fitting
    p2 = polyfit(r2,s2,6);
end
if p(1)==0;
    F=150*10^15;% Effective focal length of the drilling front in m
    W0=W0a;
zw=s(1);
else
    F=ni./(ni-1).*1./p(1);
    W0=1/(1/((W0a)^2)*2+1/F^2*(pi*W0a/Lam_m)^2))^0.5; %Beam waist after self focusing
    zw=F-(zw+F)*F^2/((zw+F)^2+(pi*W0a^2/Lam_m)^2); %location of the beam waist after self focusing
end;

zR=pi*W0.^2./Lam_m; %Rayleigh range
if (t>=0&&t<tON)||(t>=tp&&t<tON+tp)||(t>=2*tp&&t<tON+2*tp)||(t>=3*tp&&t<tON+3*tp
||(t>=4*tp&&t<tON+4*tp)||(t>=5*tp&&t<tON+5*tp)||(t>=6*tp&&t<tON+6*tp); %for pulse on time
dt=tON/nton; % time step
for n=1:nz+1;
    Wz(n)=W0*sqrt(1+((z(n)-zw)./zR).^2); % Spot size in m
    Wzi(n)=0.72*Wz(n);
    Wzr(n)=W0*sqrt(1+((Zp-zw+Zp-z(n))./zR).^2); % Reflected spot size in m
    Wzri(n)=0.72*Wzr(n);
    I0(n)=2*P/(pi*Wz(n)^2*f*tON)/(3.694); % laser irradiance at the center of the beam W/m^2
    %R=1-A;
    I0r(n)=2*A*P/(pi*Wzr(n)^2*f*tON)/(3.694);
    for m=1:mr+1;
        if m<=2||m>=m2;
            R(m)=1-A;
        else
            %theta=atan((s (m+1)-s (m-1))./2./dr);
            theta=atan((s (m-2)-8*s (m-1)+8*s (m+1)-s (m+2))./12./dr);
            %theta=atan(6.*p2 (1).*r (m).^5+5.*p2 (2).*r (m).^4+4.*p2 (3).*r (m).^3
+3.*p2 (4).*r (m).^2+2.*p2 (5).*r (m)+p2 (6));
            R1=(cos(theta)-ni*(1-(sin(theta)/ni)^2)^0.5)^2/(cos(theta)+ni*(1-(sin(theta)/ni)^2)^0.5)^2;
            R2=(ni*cos(theta)-(1-(sin(theta)/ni)^2)^0.5)^2/(ni*cos(theta)+(1-(sin(theta)/ni)^2)^0.5)^2;
            R(m)=(R1+R2)/2;
        end;
        if z(n)<s (m);
            It(n,m)=I0(n).*(exp(-2*((r (m)-Wzi(n))./Wz(n)).^2)+exp(-2*((z (m)+Wzi(n))./Wz(n)).^2)); % laser irradiance distribution
        end;
    end;
end;
\[ \text{Ir}(n,m) = (1-\text{Acu}) \cdot \text{I0r}(n) \cdot \left( \exp\left(-2\left(\frac{(r(m) - Wzri(n))}{Wzr(n)}\right)^2\right) + \exp\left(-2\left(\frac{(r(m) + Wzri(n))}{Wzr(n)}\right)^2\right) \right) \times \exp\left(-u \cdot (Zp-s(m) + Zp-s(m))\right); \]

%reflected beam irradiance
\[ g(n,m) = 0; \]

%volumetric heat source

else
\[ \text{It}(n,m) = (1-R(m)) \cdot \text{I0}(n) \cdot \left( \exp\left(-2\left(\frac{(r(m) - Wzi(n))}{Wz(n)}\right)^2\right) + \exp\left(-2\left(\frac{(r(m) + Wzi(n))}{Wz(n)}\right)^2\right) \right) \times \exp\left(-u \cdot (z(n) - s(m))\right); \]

\[ \text{Ir}(n,m) = (1-\text{Acu}) \cdot \text{I0r}(n) \cdot \left( \exp\left(-2\left(\frac{(r(m) - Wzri(n))}{Wzr(n)}\right)^2\right) + \exp\left(-2\left(\frac{(r(m) + Wzri(n))}{Wzr(n)}\right)^2\right) \right) \times \exp\left(-u \cdot (Zp-s(m) + Zp-z(n))\right); \]

\[ g(n,m) = u \cdot \text{It}(n,m) + u \cdot \text{Ir}(n,m); \]

\[ %g(n,m) = 0; \]

end;
end;
end;

end

dt=tOFF/ntoff; % time step

g = zeros(nz+1,mr+1);

end;
t=t+dt;

for m=1:mr+1;
    \[ \text{Ia}(m) = \text{Acu} \cdot \text{It}(nz+1,m); \]
    % Laser irradiance absorbed by copper layer
end

%% Temperature distribution using Time-Split MacCormack Method

%Lt(dt/2)
for n=2:nz;
    for m=2:mr;
        \[ H1(n,m) = H(n,m) + k/D \cdot \frac{1}{r(m)} \cdot \text{dt} / \frac{\text{dr}}{\text{dr}} \cdot (T(n,m+1) - T(n,m)) + k/D \cdot \text{dt} / \frac{\text{dr}}{\text{dr}} \cdot (T(n,m+1) - 2 \cdot T(n,m) + T(n,m-1)) / \frac{\text{dr}}{\text{dr}}; \]
        if \[ H1(n,m) < \text{Cp} \cdot (Tv-T0); \]
            \[ T1(n,m) = H1(n,m) / \text{Cp}; \]
        elseif \[ (H1(n,m) >= \text{Cp} \cdot (Tv-T0)) \&\& (H1(n,m) <= \text{Cp} \cdot (Tv-T0)+Lv); \]
            \[ T1(n,m) = Tv-T0; \]
        else
            \[ T1(n,m) = T1(n,m) = Tv-T0; \]
        end;
    end;
end;

%boundary conditions:
\[ T1(n,1) = T1(n,2); \]
\[ % at r=0, k \cdot \text{dT}/\text{dr}=0 \]
\[ T1(n,\text{mr}+1) = \text{Cm1} \cdot (k \cdot T1(n,\text{mr}) + \text{dz} \cdot \text{Ibm}) / (\text{dz} \cdot \text{hm} + k) + \text{Thm}; \]
for m=2:mr;
    \[ H(n,m) = 1/2 \cdot (H(n,m) + H1(n,m)) + k/D \cdot \frac{1}{r(m)} \cdot \text{dt} / \frac{\text{dr}}{\text{dr}} \cdot (T1(n,m)-T1(n,m-1)) + k/D \cdot \frac{1}{r(m)} \cdot \text{dt} / \frac{\text{dr}}{\text{dr}} \cdot (T1(n,m+1) - 2 \cdot T1(n,m) + T1(n,m-1)) / \frac{\text{dr}}{\text{dr}}; \]
    if \[ H(n,m) < \text{Cp} \cdot (Tv-T0); \]
        \[ T(n,m) = H(n,m) / \text{Cp}; \]
    elseif \[ (H(n,m) >= \text{Cp} \cdot (Tv-T0)) \&\& (H(n,m) <= \text{Cp} \cdot (Tv-T0)+Lv); \]
        \[ T(n,m) = Tv-T0; \]
    else
        \[ T(n,m) = Tv-T0; \]
    end;
end
%boundary conditions:
T(n,1) = T(n,2); % at r=0, k*dT/dr=0
T(n,mr+1)=Cm1.*(k.*T(n,mr)+dz.*Ibm)./(dz.*hm+k)+Thm;
end

%boundary conditions:
T(1,1:mr+1)=C01.*(k.*T(2,1:mr+1)+dz.*Ib0(1:mr+1))./(dz.*h0+k)+Th0;
T(1,1:mr+1) = T(2,1:mr+1); % at z=0, k*dT/dz=0
T1(1,1:mr+1)=C01.*(k.*T1(2,1:mr+1)+dz.*Ib0(1:mr+1))./(dz.*h0+k)+Th0;
T1(1,1:mr+1) = T1(2,1:mr+1); % at z=0, k*dT/dz=0
T(nz+1,1:mr+1)=Cn1.*(k.*T(nz,1:mr+1)+dz.*Ia(1:mr+1))./(dz.*hn+k)+Thn;
T(nz+1,1:mr+1) = T(nz+1,1:mr+1); % at z=0, k*dT/dz=0

for m=1:mr+1;
  Ia(m)=Acu.*It(nz+1,m); % Laser irradiance absorbed by copper layer
  T(nz+1,m)=(k.*T(nz,m)+dz.*Ia(m))./(dz./Rth+k);
  T1(nz+1,m)=(k.*T1(nz,m)+dz.*Ia(m))./(dz./Rth+k);
end;

%Lz(dt/2)
for m=2:mr;
  for n=2:nz;
    H1(n,m)=H(n,m)+k./D.*dt./2.*(T(n+1,m)-2.*T(n,m)+T(n-1,m))./(dz.^2+dt./2./D.*g(n,m));
    if H1(n,m)<Cp*(Tv-T0);
      T1(n,m)=H1(n,m)./Cp;
    elseif (H1(n,m)>=Cp*(Tv-T0)) && (H1(n,m)<=Cp*(Tv-T0)+Lv);
      T1(n,m)=Tv-T0;
    else
      T1(n,m)=Tv-T0;
    end;
  end
end;

%boundary conditions:
T1(1,m)=C01.*(k.*T1(2,m)+dz.*Ib0(m))./(dz.*h0+k)+Th0;
T1(1,m) = T1(2,m); % at z=0, k*dT/dz=0
T(nz+1,m)=Cn1.*(k.*T1(nz,m)+dz.*Ia(m))./(dz.*hn+k)+Thn;

for n=2:nz;
  H(n,m)=1/2*(H(n,m)+H1(n,m)+k./D.*dt./2.*(T(n+1,m)-2.*T(n,m)+T(n-1,m))./(dz.^2+dt./2./D.*g(n,m));
  if H(n,m)<Cp*(Tv-T0);
    T(n,m)=H(n,m)./Cp;
  elseif (H(n,m)>=Cp*(Tv-T0)) && (H(n,m)<=Cp*(Tv-T0)+Lv);
    T(n,m)=Tv-T0;
  else
    T(n,m)=Tv-T0;
  end;
end;

%boundary conditions:
T(1,m)=C01.*(k.*T(2,m)+dz.*Ib0(m))./(dz.*h0+k)+Th0;
T(1,m) = T(2,m); % at z=0, k*dT/dz=0
T(nz+1,m)=Cn1.*(k.*T(nz,m)+dz.*Ia(m))./(dz.*hn+k)+Thn;

for n=2:nz;
  H1(n,m)=H(n,m)+k./D.*dt./2.*(T(n+1,m)-2.*T(n,m)+T(n-1,m))./(dz.^2+dt./2./D.*g(n,m));

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if $H_1(n,m) < Cp \times (Tv - T_0)$

$T_1(n,m) = H_1(n,m) / Cp$

elseif $(H_1(n,m) \geq Cp \times (Tv - T_0)) \& \& (H_1(n,m) \leq Cp \times (Tv - T_0) + Lv)$

$T_1(n,m) = Tv - T_0$

else

$T_1(n,m) = Tv - T_0$

end;

end;

% boundary conditions:

$T_1(1,m) = C_01 \times (k \times T_1(2,m) + dz \times Ib0(m)) / (dz \times h0 + k) + Th0$

$T_1(1,m) = T_1(2,m); \quad \% \text{at } z=0, \ k \times dT/dz = 0$

$T_1(nz+1,m) = C_{n1} \times (k \times T_1(nz,m) + dz \times Ia(m)) / (dz \times hn + k) + Thn$

$T_1(nz+1,m) = (k \times T(nz,m) + dz \times Ia(m)) / (dz / Rth + k)$

for $n = 2:nz$

$H_1(n,m) = 1/2 \times (H(n,m) + H_1(n,m) + k \times D \times dt / 2 \times (T_1(n+1,m) - 2 \times T_1(n,m) + T_1(n-1,m)) / dz \times 2 + dt / 2 / D \times g(n,m))$

if $H(n,m) < Cp \times (Tv - T_0)$

$T(n,m) = H(n,m) / Cp$

elseif $(H(n,m) \geq Cp \times (Tv - T_0)) \& \& (H(n,m) \leq Cp \times (Tv - T_0) + Lv)$

$T(n,m) = Tv - T_0$

else

$T(n,m) = Tv - T_0$

end

end;

% boundary conditions:

$T(1,m) = C_01 \times (k \times T(2,m) + dz \times Ib0(m)) / (dz \times h0 + k) + Th0$

$T(1,m) = T(2,m); \quad \% \text{at } z=0, \ k \times dT/dz = 0$

$T(nz+1,m) = C_{n1} \times (k \times T(nz,m) + dz \times Ia(m)) / (dz \times hn + k) + Thn$

$T(nz+1,m) = (k \times T(nz,m) + dz \times Ia(m)) / (dz / Rth + k)$

end;

% boundary conditions:

$T(1:nz+1,1) = T(1:nz+1,2); \% \text{at } r=0, \ k \times dT/dr = 0$

$T(1:nz+1,1) = T(1:nz+1,2); \% \text{at } r=0, \ k \times dT/dr = 0$

$T(1:nz+1,mr+1) = C_{mr1} \times (k \times T(1:nz+1,mr) + dz \times Ib(m)) / (dz \times hm + k) + Thm$

$T(1:nz+1,mr+1) = C_{mr1} \times (k \times T(n+1,mr) + dz \times Ib(m)) / (dz \times hm + k) + Thm$

$% Lr(dt/2)$

for $n = 2:nz$

for $m = 2:mr$

$H_1(n,m) = H(n,m) + k \times D \times 1 / r(m) \times dt / 2 / dr \times (T(n,m+1) - T(n,m)) + k \times D \times dt / 2 \times (T(n,m+1) - 2 \times T(n,m) + T(n,m-1)) / dr \times 2$

if $H_1(n,m) < Cp \times (Tv - T_0)$

$T_1(n,m) = H_1(n,m) / Cp$

elseif $(H_1(n,m) \geq Cp \times (Tv - T_0)) \& \& (H_1(n,m) \leq Cp \times (Tv - T_0) + Lv)$

$T_1(n,m) = Tv - T_0$

else

$T_1(n,m) = Tv - T_0$

end

end;

% boundary conditions:

$T_1(n,1) = T_1(n,2); \% \text{at } r=0, \ k \times dT/dr = 0$

$T_1(n,mr+1) = C_{mr1} \times (k \times T(n,mr) + dz \times Ib(m)) / (dz \times hm + k) + Thm$

for $m = 2:mr$

$H(n,m) = 1/2 \times (H(n,m) + H_1(n,m) + k \times D \times 1 / r(m) \times dt / 2 / dr \times (T_1(n,m+1) - T_1(n,m)) + k \times D \times dt / 2 \times (T_1(n,m+1) - 2 \times T_1(n,m) + T_1(n,m-1)) / dr \times 2)$

if $H(n,m) < Cp \times (Tv - T_0)$

end
T(n,m) = H(n,m) / Cp;
else if (H(n,m) >= Cp * (Tv - T0)) & (H(n,m) <= Cp * (Tv - T0) + Lv);
    T(n,m) = Tv - T0;
else
    T(n,m) = Tv - T0;
end;
end

% boundary conditions:
T(n, 1) = T(n, 2); % at r=0, k*dT/dr = 0
T(n, mr+1) = Cm1.*(k.*T(n, mr) + dz.*Ibm) / (dz.*hm + k) + Thm;
end

% boundary conditions:
T(1, 1:mr+1) = C01.*(k.*T(2, 1:mr+1) + dz.*Ib0(1:mr+1)) / (dz.*h0 + k) + Th0;
T(l, 1:mr+1) = T(l, 2:mr+1); % at z=0, k*dT/dz = 0
T(l, 1:mr+1) = C01.*(k.*T(2, 1:mr+1) + dz.*Ib0(1:mr+1)) / (dz.*h0 + k) + Th0;
T(l, 1:mr+1) = T(l, 2:mr+1); % at z=0, k*dT/dz = 0
T(nz+1, l:mr+1) = Cn1.*(k.*T(nz, l:mr+1) + dz.*Ia(l:mr+1)) / (dz.*hn + k) + Thn;
T(l, 1:mr+1) = Cn1.*(k.*T(l, 1:mr+1) + dz.*Ia(l:mr+1)) / (dz.*hn + k) + Thn;

% for m=1:mr+1;
    Ia(m) = Acu.*It(nz+1, m); % Laser irradiance absorbed by copper layer
    T(nz+1, m) = (k.*T(nz, m) + dz.*Ia(m)) / (dz./Rth + k);
    T1(nz+1, m) = (k.*T(nz, m) + dz.*Ia(m)) / (dz./Rth + k);
end;

% boundary conditions:
T(1, 1:mr+1) = T(2, 1:mr+1); % at z=0, k*dT/dz = 0
T(l, 1:mr+1) = T(l, 2:mr+1); % at z=0, k*dT/dz = 0
H(1, 1:mr+1) = C01.*(k.*H(2, 1:mr+1) + Cp.*dz.*Ib0(1:mr+1)) / (dz.*h0 + k) + Th0;
H(l, 1:mr+1) = H(l, 2:mr+1); % at z=0, k*dH/dz = 0
H(nz+1, l:mr+1) = Cn1.*(k.*H(nz, l:mr+1) + Cp.*dz.*Ia(l:mr+1)) / (dz.*hn + k) + Thn;
H(l, 1:mr+1) = Cn1.*(k.*H(l, 1:mr+1) + Cp.*dz.*Ia(l:mr+1)) / (dz.*hn + k) + Thn;

% for m=1:mr+1;
    Ia(m) = Acu.*It(nz+1, m); % Laser irradiance absorbed by copper layer
    Ia(m) = 0;
    T(nz+1, m) = (k.*T(nz, m) + dz.*Ia(m)) / (dz./Rth + k);
    T1(nz+1, m) = (k.*T(nz, m) + dz.*Ia(m)) / (dz./Rth + k);
    H(nz+1, m) = (k.*T(nz, m) + dz.*Ia(m)) / (Cp.*dz./Rth + k);
end;

T(l, nz+1:mr+1) = T(l, nz+1, 2); % at r=0, k*dT/dr = 0
T(l, nz+1, l) = T(l, nz+1, 2); % at r=0, k*dT/dr = 0
H(l, nz+1:mr+1) = H(l, nz+1, l); % at r=0, T=0
H(l, nz+1:mr+1) = Cm1.*(k.*H(l, nz+1, mr) + Cp.*dz.*Ibm) / (dz.*hm + k) + Thm;
T(l, nz+1, mr+1) = 0; % at r=r0, T=0
T(l, nz+1, mr+1) = 0;
H(l, nz+1, mr+1) = 0;
% tracing the drilling front
for m=1:mr+1;
    ns=0;
    for n=1:nz+1;
        if H(n,m) > Cp * (Tv - T0) + Lv;
            ns=ns+1; % the index for the drilling front in z direction
        elseif H(n,m) == Cp * (Tv - T0) + Lv;
            s(m) = (n-1)*dz;
        else
            break;
        end;
    end;
end;
if ns==0;
  s(m)=0;
elseif ns==nz+1;
  s(m)=Zp;
else
  ds=(Cp*(Tv-T0)+Lv-H(ns+1,m))./(H(ns,m)-H(ns+1,m)).*dz; %assuming linear change of enthalpy within one grid, find the drilling front within this grid
  s(m)=z(ns+1)-ds;
end;
end;

%% save intermediate data
for ttn=1:5;
  if (t>(ttn-1)*tp&t<=tON+(ttn-1)*tp);
    tt=round((t-(ttn-1)*tp)/dt);

    if rem(tt,100)==0;
      file=num2str(t);
      filename=[file '.mat'];
      save(filename,'t','r','z','s','R','T');
    end;
  elseif (t>tON+(ttn-1)*tp&t<=ttn*tp);
    tt=round((t-tON-(ttn-1)*tp)/dt);

    if rem(tt,500)==0;
      file=num2str(t);
      filename=[file '.mat'];
      save(filename,'t','r','z','s','R','T');
    end;
  end;
end;

%%
save('data.mat',t,'s', 'T', 'T1','H');
APPENDIX B: CALCULATED LENS SURFACE BY RAY TRACING FOR PITCHFORK BEAM SHAPING SYSTEM
The lens surface is calculated in MathCAD. The symbols here have the same meaning as those in Chapter 5.2.2.

\[ \begin{align*} R_\infty &:= 0.02 \quad R_0 := 2 \quad r_0 := 0.2 \quad B := \frac{0.7377}{0.6951} \quad C := \frac{-0.766}{0.6951} \quad \lambda := 9. \end{align*} \]

\[ n := \left( \frac{9.01536 \cdot 0.24482 + 7229.931303}{\lambda^2 - 0.29934} \right)^{1/2} \]

\[ n_0 := 1 \]

\[ D := 5 \]

\[ \text{In}(r_1) := \frac{R_0^2}{2} \sum_{n=0}^{150} \frac{(-2)^n r_1^{5n+1}}{n!(5n + 1)} \]

\[ R_0 := \begin{cases} 2, & R \leq 0.02 \end{cases} \]

\[ r_0 := \begin{cases} 0.2, & R \leq 0.02 \end{cases} \]

\[ \tilde{A}_{10a} := \frac{R_0}{4} \int_0^{R_0} \exp \left[ -2 \left( \frac{R}{R_0} \right)^{10} \right] R \, dR \]

\[ r(R) := \begin{cases} -\frac{r_0^2}{2} \ln \left( 1 - \text{Al}_{10a} \right), & R \geq 0.2 \end{cases} \]

\[ \gamma := \frac{n_0}{n} \quad F := (\gamma - 1) \cdot D \]

\[ Z_\infty(R) := \frac{-F + \sqrt{F^2 - 1 - \gamma^2 \left[ F^2 - \gamma^2 (R-r)^2 \right]}}{1 - \gamma^2} \]

\[ dZ(R) := \frac{(R - r(R)) \cdot \gamma}{\sqrt{F^2 - (R-r)^2 \cdot \gamma^2 + (R-r)^2}} \]
\[ Z(R) := \int_0^R dZ(R) \, dR \]

\[ z(R) := Z(R) - Z'(R) \]

\[ \frac{ddz(R)}{dR} = \frac{d^2z(R)}{dR^2} - \left( \frac{d}{dR} r(R) \right)^2 \left( \frac{d}{dR} t(R) \right)^3 \]

<table>
<thead>
<tr>
<th>R</th>
<th>Z(R) =</th>
<th>r(R) =</th>
<th>z(R) + D =</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>2.81474·10^{-5}</td>
<td>1.48054·10^{-4}</td>
<td>2.08366·10^{-7}</td>
</tr>
<tr>
<td>0.04</td>
<td>1.12586·10^{-4}</td>
<td>2.96108·10^{-4}</td>
<td>8.33443·10^{-7}</td>
</tr>
<tr>
<td>0.06</td>
<td>2.53307·10^{-4}</td>
<td>4.44162·10^{-4}</td>
<td>1.87516·10^{-6}</td>
</tr>
<tr>
<td>0.08</td>
<td>4.50294·10^{-4}</td>
<td>5.92217·10^{-4}</td>
<td>3.33341·10^{-6}</td>
</tr>
<tr>
<td>0.1</td>
<td>7.03524·10^{-4}</td>
<td>7.40273·10^{-4}</td>
<td>5.20802·10^{-6}</td>
</tr>
<tr>
<td>0.12</td>
<td>1.01297·10^{-3}</td>
<td>8.83331·10^{-4}</td>
<td>7.4988·10^{-6}</td>
</tr>
<tr>
<td>0.14</td>
<td>1.37859·10^{-3}</td>
<td>1.03639·10^{-3}</td>
<td>1.02055·10^{-5}</td>
</tr>
<tr>
<td>0.16</td>
<td>1.80035·10^{-3}</td>
<td>1.18445·10^{-3}</td>
<td>1.33278·10^{-5}</td>
</tr>
<tr>
<td>0.18</td>
<td>2.2782·10^{-3}</td>
<td>1.33251·10^{-3}</td>
<td>1.68654·10^{-5}</td>
</tr>
<tr>
<td>0.2</td>
<td>2.81209·10^{-3}</td>
<td>1.48058·10^{-3}</td>
<td>2.08179·10^{-5}</td>
</tr>
<tr>
<td>0.22</td>
<td>3.40195·10^{-3}</td>
<td>1.62864·10^{-3}</td>
<td>2.51848·10^{-5}</td>
</tr>
<tr>
<td>0.24</td>
<td>4.04772·10^{-3}</td>
<td>1.77671·10^{-3}</td>
<td>2.99657·10^{-5}</td>
</tr>
<tr>
<td>0.26</td>
<td>4.74932·10^{-3}</td>
<td>1.92479·10^{-3}</td>
<td>3.51601·10^{-5}</td>
</tr>
<tr>
<td>0.28</td>
<td>5.50668·10^{-3}</td>
<td>2.07286·10^{-3}</td>
<td>4.07675·10^{-5}</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

0 0.01 0.015 0 5·10^{-3} 0.005 0.01 0.015 0 1 1.5 2 R

r(R)
APPENDIX C: MATLAB PROGRAM FOR ADAPTIVE ADDITIVE ALGORITHM IN DIFFRACTIVE LENS DESIGN
This program is for pitchfork beam shaping on the plane perpendicular to the beam propagation direction.

clear;
startover=menu(sprintf('New calculation?'), 'Yes', 'No', 'Cancel');
if startover==3;
    return;
end;

lamda=9.249*10^-6; %Laser wavelength
k=2*pi/lamda; %space frequency
rw=2.25*10^-3; %beam waist
r1=0.02*10^-2; %radius of the first lens
r2=2.5*10^-2; %radius of the second lens
r3=r2; %radius of the focal lens
r4=2.54*10^-2;
ri=0.7*r3; %radius of the ring
f=50.8*10^-3; %focal length of r3
z1=5*r2; %distance between the first two lens
z2=z1; %distance between the second lens and the focal lens
z3=1.00*f; %distance between the focal lens and the image plane
n=(9.01536+0.24482*10^-12/(lamda^2-(0.29934*10^-6)^2)+7229.931303*10^-12/(lamda^2-(48.38*10^-6)^2))^0.5; %refractive index of ZnSe
N=1024;%number of sampling
A=(N*lamda*f*1000)^0.5;%space extension
dx=A/N;%space interval
dy=dx;
x3=-A/2+dx*1/2-dx/2:dx:A/2-dx*1/2-dx/2;
y3=-A/2+dy*1/2-dy/2:dy:A/2-dy*1/2-dy/2;
dw=1/N/dx*lamda*z3;%the interval in frequency domain
Omega=N/A*lamda*z3; %frequency extension
w3=-Omega/2+dw*1/2-dw/2:dw:Omega/2-dw*1/2-dw/2;
x4=-A/2+dx*1/2:dx:A/2-dx*1/2;
u2 = zeros(N,N);
u2f = zeros(N,N);
u3 = zeros(N,N); %preallocating the maximum amount of space
I3 = zeros(N,N);
phi3 = zeros(N,N);
phi4 = zeros(N,N);
u3f = zeros(N,N);

Pi=0;
Pout=0;
% the input laser irradiance and desired output pitchfork laser irradiance
for m=1:N
    for l=1:N
        if ((x3(m)^2+y3(l)^2)<=r2^2)
            u2(m,l)=exp(-(u3(m)^2+y3(l)^2)^0.5)^2/r2^2);
        else
            u2(m,l)=0;
        end
    end
end
\[ u_3(m,l) = \exp \left( -\left( \frac{(x_4(m)^2 + x_4(l)^2)^{0.5}}{r_3} \right)^{200} - 0.15 \exp \left( -\left( \frac{(x_4(m)^2 + x_4(l)^2)^{0.5}}{r_1} \right)^6 \right) \right); \]

\[ \text{design goal} \]

\[ \phi_3(m,l) = k / 100 \times (n-1) \times \left( 4.091 \times (x_3(m)^2 + y_3(l)^2) \times 10000. / (1 + (1 - 2.492) \times 4.091 \times (x_3(m)^2 + y_3(l)^2) \times 10000. \times 0.5) - 1.158 \times (x_3(m)^2 + y_3(l)^2) \times 10000 + 3.242 \times (x_3(m)^2 + y_3(l)^2) \times 2 \times 100^4) \];

\[ \text{initial phase function} \]

\[ I_3(m,l) = u_3(m,l)^2; \]

\[ u_2f(m,l) = u_2(m,l) \times \exp(i \phi_3(m,l)); \]

\[ I_0 = \Pi / \text{Pout} \times 1.5; \]

\[ \text{peak irradiance for the output pitchfork beam} \]

\[ A_0 = I_0^{0.5}; \]

\[ \text{peak amplitude for the output pitchfork beam} \]

\[ \text{Iterative method for designing DOE (Adaptive additive algorithm in "Methods for Computer Design of Diffractive Optical Elements", p60)} \]

\[ \alpha = 1.5; \]

\[ \text{weight of replacement} \]

\[ \text{if startover==1} \]

\[ u_3 = \exp(i \times k \times z_3) / (i \times \lambda \times z_3) \times \text{fftshift(fft2(u2f))} \times dx \times dy; \]

\[ \text{complex amplitude on the focal plane} \]

\[ u_3R = \text{abs}(u_3); \]

\[ \phi_3 = \text{angle}(u_3); \]

\[ \text{phase function on the focal plane} \]

\[ u_3R_a = \text{abs}(\alpha \times A_0 \times u_3 + (1 - \alpha) \times u_3R); \]

\[ u_3R_\times = u_3R_a \times \exp(i \times \phi_3); \]

\[ \text{else} \]

\[ \text{load('data.mat')} \]

\[ \text{end} \]

\[ \text{for nn=1:50} \]

\[ \text{back transform} \]

\[ u_3f = \exp(-i \times k \times z_3) / (-i \times \lambda \times z_3) \times \text{fft2(u3R)} \times dw \times dw; \]

\[ \phi_3 = \text{angle}(u_3f); \]

\[ \text{phase function of DOE} \]

\[ \text{for m=1:N} \]

\[ \text{if ((x_3(m)^2 + x_3(l)^2) > r_4^2)} \]

\[ \phi_3(m,l) = 0; \]

\[ \text{end} \]

\[ \text{end} \]

\[ u_3f_a = \text{abs}(u_3f); \]

\[ u_3f = u_2 \times \exp(i \times \phi_3); \]

\[ \text{forward transform} \]

\[ u_3 = \exp(i \times k \times z_3) / (i \times \lambda \times z_3) \times \text{fft2(u3f)} \times dx \times dy; \]

\[ \text{complex amplitude on the focal plane} \]

\[ u_3R = \text{abs}(u_3); \]

\[ \text{amplitude on the focal plane} \]

\[ u_3R_a = \text{abs}(\alpha \times A_0 \times u_3 + (1 - \alpha) \times u_3R); \]

\[ u_3R_\times = u_3R_a \times \exp(i \times \phi_3); \]

\[ e_0(nn) = \sum(\sum((A_0 \times u_3 - u_3R) \times 2 \times dw \times dw)); \]

\[ \text{end for m=1:N} \]

\[ \text{end} \]
if \( \phi_3(m,l) < 0 \)
\[
\phi_4(m,l) = \phi_3(m,l) + \pi;
\]
else
\[
\phi_4(m,l) = \phi_3(m,l);
\]end

\[I_3R = u_3R.^2;\]
\[
\text{plot} \ (w3(1:N), I_3R(1:N,N/2), \ 'DisplayName', \ 'x3, I_3');\]
\[
\text{save} \ ('data.mat', 'u3R_', 'psi3');\]

This program is to increase the depth of focus. The beam shaping technique is applied to the plane containing the optical axis.

clear;
startover=menu(sprintf('New calculation?'), 'Yes', 'No', 'Cancel');
if startover==3;
    return;
end;

\[\lambda = 9.249 \times 10^{-6}; \quad \% \text{Laser wavelength}\]
\[k = 2\pi/\lambda; \quad \% \text{space frequency}\]
\[r_w = 2.25 \times 10^{-3}; \quad \% \text{beam waist}\]
\[r_1 = 0.02 \times 10^{-2}; \quad \% \text{radius of the first lens}\]
\[r_2 = 2.5 \times 10^{-2}; \quad \% \text{radius of the second lens}\]
\[r_3 = r_2; \quad \% \text{radius of the focal lens}\]
\[r_4 = 2.54 \times 10^{-2};\]
\[r_i = 0.7r_3; \quad \% \text{radius of the ring}\]
\[f = 50.8 \times 10^{-3}; \quad \% \text{focal length of } r_3\]
\[z_1 = 5r_2; \quad \% \text{distance between the first two lens}\]
\[z_2 = z_1; \quad \% \text{distance between the second lens and the focal lens}\]
\[z_3 = 1.00f; \quad \% \text{distance between the focal lens and the image plane}\]
\[dz = 100 \times 10^{-6};\]
\[n = (9.01536 + 0.24482 \times 10^{-12}/(\lambda^2 - (0.29934 \times 10^{-6})^2) + 7229.931303 \times 10^{-12}/(\lambda^2 - (48.38 \times 10^{-6})^2))^0.5; \quad \% \text{refractive index of ZnSe}\]
\[N = 5112; \quad \% \text{number of sampling}\]
\[A = (N^2 \lambda f^2 0.5)^{0.5}; \quad \% \text{space extension}\]
\[dx = A/N; \quad \% \text{space interval}\]
\[dy = dx;\]
\[x_3 = -A/2 + dx*1/2 - dx/2:dx:A/2 - dx*1/2 - dx/2;\]
\[y_3 = -A/2 + dy*1/2 - dy/2:dy:A/2 - dy*1/2 - dy/2;\]
\[r = (2.*x3).^0.5;\]
\[dw = 1/N/dx*2*pi; \quad \% \text{the interval in frequency domain}\]
\[\Omega = N/A*2*pi; \quad \% \text{frequency extension}\]
\[w_3 = -\Omega:dw:1/2-dw/w_3:dw:Omega/2-dw*1/2-dw/2;\]
\[z = f.^2.*w_3./k;\]
\[x_4 = -A/2 + dx*1/2 - dx/2:A/2 - dx*1/2;\]
%r = (2.*x3).^0.5;
%u2 = zeros(N);
%u3 = zeros(N);

Pi = 0;
Pout = 0;

for m=1:N
    if x3(m) < 0
        r(m) = -(2.*x4(m)).^0.5;
    else
        r(m) = (2.*x4(m)).^0.5;
    end
    if (r(m) <= r2 && r(m) >= 0)
        u2(m) = exp(-(r(m))^2/r2^2);
    else
        u2(m) = 0;
    end
    u3(m) = exp(-(z(m)/dz)^200);
    phi3(m) = k*(r(m)).^1/2000000/f; % Fourier transfer function of r3
    I3(m) = u3(m).^2;
    u2f(m) = u2(m).*exp(i*phi3(m)); % Things to be fourier transformed after the focal lens
end

% I0 = Pi/Pout*1.5; % peak irradiance for the output pitchfork beam
A0 = 0.3; % I0.^0.5; % peak amplitude for the output pitchfork beam
alfa = 1.5; % weight of replacement

if startover == 1;
    u_3 = k/f*fftshift(ifft(u2f))*dx; % complex amplitude on the focal plane
    u3R = abs(u_3); % amplitude on the focal plane
    psi3 = angle(u_3); % phase function on the focal plane
    I_3 = u3R.^2; % irradiance on the focal plane
    % adaptive-additive algorithm
    u3R_a = abs(alfa.*A0.*u3+(1-alfa).*u3R);
    u3R_ = u3R_a.*exp(i*psi3);
else
    load('data.mat');
end;

for nn=1:100
    for m=1:N
        if (r(m) > r4 || r(m) < 0)
            phi3(m) = 0;
        end
    end
end
u3f_a = abs(u3f_);
u3f=exp(i*phi3); %forward transform
u_3=k/f*(ifft(u3f))*dx; %complex amplitude on the focal plane
u3R=abs(u_3); %amplitude on the focal plane
u3R_a=abs(alfa.*A0.*u3+(1-alfa).*u3R);
psi3=angle(u_3);
u3R_=u3R_a.*exp(i*psi3);
e0(nn)=sum((A0.*u3-u3R).^2.*dw)/sum((A0.*u3).^2.*dw);
end
for m=1:N
    if (phi3(m)<0)
        phi4(m)=phi3(m)+pi;
    else
        phi4(m)=phi3(m);
    end
end
I3R=u3R.^2;
plot(z(1:N),u3R(1:N), 'DisplayName', 'x3,I_3');
save('data.mat','u3R_','psi3');
REFERENCES


Lin, Y., Kessler, T. J. and Lawrence, G. N. (1996), Design of continuous surface-relief phase
plates by surface-based simulated annealing to achieve control of focal-plane irradiance,


