A Laser Radar Employing Linearly Chirped Pulses From A Mode-locked Laser For Long Range, Unambiguous, Sub-millimeter Resolution Ranging And Velocimetry

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A LASER RADAR EMPLOYING LINEARLY CHIRPED PULSES FROM A MODE-LOCKED LASER FOR LONG RANGE, UNAMBIGUOUS, SUB-MILLIMETER RESOLUTION, RANGING AND VELOCIMETRY

by

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A thesis submitted in the partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Electrical Engineering and Computer Engineering in the College of Engineering and Computer Science at the University of Central Florida
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Major Professor: Peter. J. Delfyett
ABSTRACT

Chirped pulses refer to optical signals that exhibit a shift in wavelength across the temporal pulse duration. This dissertation provides a brief review of the different methods of generating chirped pulses and how they are used in different applications. This is followed by a description of a linearly chirped pulse source that utilizes a mode-locked laser and a chirped fiber Bragg to generate pulses at 20 MHz repetition rate and ~750 GHz optical bandwidth with pulse durations of ~10 ns.

The emphasis of this dissertation however, is on the development of a laser radar system that utilizes this chirped pulse source. A quick review of different laser ranging techniques is given followed by a description of the chirped pulse laser radar setup. The laser radar system offers sub-millimeter range resolution at a target range of 10.1 km (in fiber) with update rates of 20 MHz. Coherent detection at the receiver results in a signal to noise ratio of at least 25 dB which can be further increased by using a stronger local oscillator signal. The chirped pulses can be easily amplified to high power levels using chirped pulse amplification to perform long distance ranging.

In order to avoid range ambiguities, a pulse tagging scheme based on phase modulation is demonstrated to obtain absolute distance measurements. A signal to noise ratio of ~30 dB is observed at an unambiguous target distance of 30 meters in fiber. In a separate experiment, the system design is modified in order to achieve simultaneous, range and Doppler velocity measurements using a target with a velocity of > 330 km/h inside the laboratory.
A closer evaluation of the chirped pulse lidar performance reveals the detrimental effect of group delay ripple and amplitude modulation noise on the chirped pulses. A spectral pulse shaper is used to remove these detrimental effects and the lidar performance is improved to achieve a range resolution of ~284 μm. Finally, the work is concluded and some future directions for further research are suggested.
This work is dedicated to science.
ACKNOWLEDGEMENTS

I would like to thank my advisor, Prof. Peter Delfyett who believed in me and guided me through the course of my PhD, and also the members of the Ultrafast Photonics Group. Everyone in the group was very helpful and provided many stimulating discussions and guidance in matters not only related to photonics research, but also life in general.
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<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>AM</td>
<td>Amplitude Modulation</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>AOM</td>
<td>Acousto-Optic Modulator</td>
</tr>
<tr>
<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
</tr>
<tr>
<td>CFBG</td>
<td>Chirped Fiber Bragg Grating</td>
</tr>
<tr>
<td>CIRC</td>
<td>Circulator</td>
</tr>
<tr>
<td>CPA</td>
<td>Chirped Pulse Amplification</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>dBm</td>
<td>Decibel relative to 1mW</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DCF</td>
<td>Dispersion Compensating Fiber</td>
</tr>
<tr>
<td>DFB</td>
<td>Distributed Feedback</td>
</tr>
<tr>
<td>DSF</td>
<td>Dispersion Shifted Fiber</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium Doped Fiber Amplifier</td>
</tr>
<tr>
<td>FDML</td>
<td>Fourier Domain Mode-Locked Laser</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>FL</td>
<td>Fiber Launcher</td>
</tr>
<tr>
<td>FMCW</td>
<td>Frequency Modulated Continuous Wave</td>
</tr>
<tr>
<td>FSR</td>
<td>Free Spectral Range</td>
</tr>
<tr>
<td>FT</td>
<td>Fourier Transform</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
</tr>
<tr>
<td>GDR</td>
<td>Group Delay Ripple</td>
</tr>
<tr>
<td>IFT</td>
<td>Inverse Fourier Transform</td>
</tr>
<tr>
<td>IM</td>
<td>Intensity Modulator</td>
</tr>
<tr>
<td>LIDAR</td>
<td>Light Detection and Ranging</td>
</tr>
<tr>
<td>LADAR</td>
<td>Laser Detection and Ranging</td>
</tr>
<tr>
<td>MLL</td>
<td>Mode-Locked Laser</td>
</tr>
<tr>
<td>OCT</td>
<td>Optical Coherence Tomography</td>
</tr>
<tr>
<td>OTDR</td>
<td>Optical Time Domain Reflectometry</td>
</tr>
<tr>
<td>OFDR</td>
<td>Optical Frequency Domain Reflectometry</td>
</tr>
<tr>
<td>OFDI</td>
<td>Optical Frequency Domain Imaging</td>
</tr>
<tr>
<td>PC</td>
<td>Polarization Controller</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<td>--------------</td>
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</tr>
<tr>
<td>PD</td>
<td>Photodetector</td>
</tr>
<tr>
<td>PM</td>
<td>Phase Modulation</td>
</tr>
<tr>
<td>PRF</td>
<td>Pulse Repetition Frequency</td>
</tr>
<tr>
<td>RBW</td>
<td>Resolution Bandwidth</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RFSA</td>
<td>Radio Frequency Spectrum Analyzer</td>
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<tr>
<td>SMF</td>
<td>Single Mode Fiber</td>
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<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
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<tr>
<td>SRI</td>
<td>Spectrally Resolved Interferometry</td>
</tr>
<tr>
<td>STEAM</td>
<td>Serial Time-Encoded Amplified Microscopy</td>
</tr>
<tr>
<td>SWI</td>
<td>Synthetic Wavelength Interferometry</td>
</tr>
<tr>
<td>t-λ</td>
<td>Time-to-Wavelength</td>
</tr>
<tr>
<td>TD-OCT</td>
<td>Time Domain Optical Coherence Tomography</td>
</tr>
<tr>
<td>TOF</td>
<td>Time of Flight</td>
</tr>
<tr>
<td>TS-ADC</td>
<td>Time-Stretch Analog to Digital Converter</td>
</tr>
<tr>
<td>VBW</td>
<td>Visual Bandwidth</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>VOD</td>
<td>Variable Optical Delay</td>
</tr>
<tr>
<td>XCPA</td>
<td>eXtremely Chirped Pulse Amplification</td>
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</table>
1.1 Introduction

Chirped (or wavelength swept) pulses refer to signals that exhibit an increase or decrease in the optical frequency (or wavelength) across the temporal pulse duration. In most cases, it is beneficial to have pulses that are linearly chirped. In the case of optical signals, if the pulses have a large amount of chirp with reasonably long temporal durations (with repetition rates usually between 10 MHz to 100 MHz), the optical spectrum of the signal resembles its temporal intensity profile and this is usually referred to as ‘wavelength to time mapping’. This chapter discusses how chirped pulses in the ‘wavelength to time mapping regime’ are generated, and how they are utilized in various applications.

1.2 Overview of Various Chirped Pulse Sources

1.2.1 Dispersed Pulses

One of the most straightforward approaches for generating chirped pulses is by propagating pulses in a long span of dispersion compensation fiber (DCF) to achieve a large value of dispersion. Originally, DCF was developed to compensate for the anomalous dispersion of single mode fibers in long haul optic fiber communication links. Dispersion compensation modules that offer dispersions of over 1.6 ps/nm are now commercially available but suffer from insertion losses that are as high as 11 dB [1]. Moreover, the dispersion profile of DCF is not uniform across the C-band, therefore the linearity of the wavelength chirp across the duration of the pulses is not ideal.
1.2.2 Fourier Domain MLL

Fourier domain mode-locking is a technique for achieving frequency swept operation of a laser. This is done by tuning the transmission wavelength of a narrowband optical filter that is placed inside the fiber laser cavity as shown in Fig. 1. The filter is tuned periodically at the cavity round-trip time, (or a harmonic of the round-trip time) so that each time a certain wavelength completes a roundtrip in the fiber laser cavity, the filter transmission is perfectly aligned to transmit only that wavelength, (while blocking other wavelengths) and lasing does not have to build up each time from amplified spontaneous emission (ASE). This results in the generation of frequency chirped pulses directly from the laser [2]. Recently, FDMLs with coherence lengths > 20 mm, and sweep rates in the MHz regime have been demonstrated [3, 4].

![Figure 1 Simplified schematic of a Fourier domain mode-locked laser (adapted from [2])](image)

1.2.3 Polygon Mirror based Wavelength Scanning Laser

A wavelength scanning laser employing an external reflection type filter (a polygon) was demonstrated with a repetition rate of 15.7 kHz with a 70 nm wavelength span centered at 1.3 µm [5]. The reflection type filter consists of a diffraction grating, an afocal telescope and a
polygonal scanner as shown in Fig. 2. The orientation of the beam’s incidence angle and the rotation direction of the polynomial mirror determine the direction of wavelength tuning. A complete wavelength sweep is accomplished through a partial rotation of the polygon mirror through an angle of $2\pi / N$, where $N$ is the number of mirror facets. The swept pulse repetition rate is therefore determined by the product of the rotational speed and the number of facets of the polygon. Since the initial demonstration of the polygon mirror based wavelength swept source in 2003, some changes have been made in the setup to achieve a 115 kHz repetition rate with a tuning rate of 9200 nm/ms by utilizing a double pass configuration [6]. Most recently, a repetition rate of 400 kHz was achieved with a tuning range of 104 nm with pulse interleaving [7].

![Figure 2. Schematic of a high speed wavelength-scanning filter (adapted from [5])](image)
1.2.4 Theta Laser

The Theta laser is a mode-locked laser that involves a chirped fiber Bragg grating (CFBG) to temporally stretch the pulses before amplification within the cavity. This enables the use of chirped pulse amplification (CPA) within the cavity to maximize the optical gain that can be derived from the semiconductor optical amplifier. The extremely chirped pulse mode-locked laser is an evolution of the dispersion managed oscillator but the duration of the temporally stretched pulses (and therefore, the pulse repetition period) is adjusted to be longer than the gain recovery time of the SOA by using a CFBG with a dispersion of 340 ps/nm [8]. In this regime, since the gain dynamics of the SOA operate in the CW injection regime, the limitation to the extracted pulse energy under transient optical amplification is overcome, resulting in maximum optical gain. The same CFBG is used for compression of the amplified, temporally stretched pulses, within the cavity to minimize the effect of the group delay ripple (GDR). There are two output ports – one for stretched pulses, and the other for high peak power compressed pulses. Chirped pulses of 510 ps duration were generated centered at a wavelength of 1551 nm [8].
1.2.5 Tunable Semiconductor Sources

One of the relatively simple ways to generate wavelength swept signals is by tuning the injection current to a diode laser. As the electrical drive current is varied, the output emission wavelength of the laser changes. In section 4.2, the output emission of a Distributed Feedback (DFB) laser is discussed and the optical frequency is experimentally observed to decrease by 1.1
GHz for a 1 mA increase in drive current. However, the linearity of the wavelength sweep as a function of time (or drive current) becomes a concern at fast tuning rates (~10s of kHz) and becomes more serious when large excursions in optical frequency are required. Previous tunable semiconductor sources have also used thermal tuning [9, 10] (with large bandwidth but slow response), acousto-optic tuning [11] (with relatively poor wavelength resolution), or continuously tuned grating external cavity designs [12] (with slow mechanical response).

1.2.6 Wavelength Swept Mode-Locked Laser based on Dispersion Tuning

The free spectral range (FSR) of a laser cavity is given by $F = \frac{c}{nL}$ where $c$ is the speed of light in vacuum, $n$ is the refractive index in the cavity, and $L$ is the cavity length. If a laser cavity contains dispersion, then the FSR becomes a function of wavelength. Fiber based mode-locked lasers can be actively mode-locked by modulating an element in the cavity. In this case, the gain medium of the laser is modulated using a chirped (frequency modulated) electrical waveform resulting in the generation of wavelength swept pulses [13]. The lasing wavelength can be changed by tuning the modulation frequency. The wavelength tuning range is determined by the gain bandwidth of the SOA. Wavelength tuning ranges of 178.7 nm with a tuning rate of 200 kHz have been demonstrated [14].
Figure 5. Schematic of an actively mode-locked, dispersion tuned, wavelength swept laser (adapted from [14]).

1.3 Overview of Chirped Pulse Applications

1.3.1 Optical Coherence Tomography

Optical coherence tomography (OCT) is an optical interferometric technique that was originally developed in 1991, for in situ cross-sectional imaging of biological tissues with micron level resolution over thicknesses of a few millimeters [15]. OCT is based on the measurement of the time delay of an optical signal that is reflected or back scattered from a sample under observation. Several years later, frequency domain OCT was proposed, which offers faster scans, better signal to noise ratio (SNR), and a higher level of sensitivity by using a frequency swept laser source [16-20]. Moreover, swept source OCT does not require charged coupled device (CCD) cameras or spectrometers, and can benefit from dual balanced detection to achieve higher SNR.

A simplified schematic of a frequency swept OCT system is given in Fig. 5. A laser source that is linearly swept in optical frequency is used to probe a biological sample. The
reflected signals from a reference mirror and the sample under observation are combined using a directional coupler resulting in interference fringes across the optical spectrum. After photodetection, the interference fringes manifest themselves as a temporal modulation of the photodetected electrical signal that can be observed on an oscilloscope. A Fourier transform of the time domain waveform reveals the frequency of the beat signal that contains 1-D information of the sample thickness. A 2-D (or 3-D) plot of the different layers and structures in the sample can be observed by scanning the laser beam across the sample and recording the thickness/depth information at each point. A wider optical frequency sweep provides higher depth resolution, while a fast frequency sweep enables acquisition of image data at higher speeds. A review of the design and scaling principles of frequency swept lasers for frequency domain OCT and optical frequency domain reflectometry (OFDR) is given in [21].

Figure 6. A simplified schematic of a swept source optical coherence tomography setup (adapted from [17])

1.3.2 Optical Frequency Domain Reflectometry

Optical reflectometry is a powerful technique for remote sensing. In optical time domain reflectometry (OTDR), optical pulses of short temporal durations are transmitted to an optical
fiber and the time of flight of different reflected signals is analyzed. The concept of optical frequency domain reflectometry (OFDR) is very similar to frequency swept OCT except that in OFDR, a wavelength swept source with narrow optical linewidth (and long coherence length) is used [22]. The reflected (echo) signal interferes with a reference signal to result in a beat frequency. The value of the beat frequency corresponds to the relative temporal delay between the two signals. The principle of OFDR is extensively described in previous works [10, 23] Recently, chirped fiber Bragg gratings (CFBGs) have been used to generate wavelength swept optical pulses for OFDR [24, 25]

1.3.3 Laser Ranging

As described in the previous section, OFDR is a technique that is based on the interference of a frequency swept optical signal with a delayed version of itself. The same concept is applied in frequency modulated continuous wave (FMCW) lidars, where a laser source with a longer coherence length is used to achieve metrology and sensing of targets at long range. Conventional FMCW lidar systems rely on tuning the wavelength of a diode laser using current injection modulation. However, obtaining perfectly linear optical frequency sweeps at fast swept rates with large frequency excursions is challenging.

Recently, a new approach that relies on passively generating chirped pulses has been presented [25-27], which is based on using a CFBG for the generation of temporally stretched, frequency chirped pulses from a MLL. Unlike conventional lasers, the optical spectrum of a MLL consists of many individual axial modes that provide optical bandwidths of hundreds of GHz, sufficient for sub-millimeter range resolution. Moreover, the coherence length of a MLL is
dictated by the optical linewidth of a single axial mode which can be a few kHz or less, enabling ranging at target distances of hundreds of kilometers with coherent detection at the receiver. This approach is described in detail in chapter 3.

### 1.3.4 Serial Time Encoded Amplified Microscopy

While most optical imaging techniques attempt to achieve high spatial resolution in measurements, in some cases imaging with superior temporal resolution can be beneficial. Applications that require a high temporal resolution imaging system include the study of shock waves, laser fusion, laser ablation, fuel injection in internal combustion engines and biochemical waves in cells and tissues. In CCD sensors there is a trade-off between imaging speed and sensitivity due to reduction in integration time at higher acquisition speeds while pump-probe experiments are useful only for imaging repetitive events. The serial time encoded amplified microscopy (STEAM) camera has been developed to image single shot ultrafast events in real time [28].

---

Figure 7. Schematic of a STEAM camera (adapted from [28])
The STEAM camera is based on the mapping of a 2-D image on to a serial time domain waveform. Its schematic is shown in Fig. 7. The broadband optical spectrum of a pulsed laser source is spatially separated and projected on a 2-D surface. The reflected signal is converted to a serial time domain waveform, and a dispersive element is used to map the optical spectrum to a time domain waveform. Raman amplification is also implemented in the dispersive element, followed by a single pixel photodetector and oscilloscope. Frame rates of 6.1 MHz and a shutter speed of 440 ps have been demonstrated [28]. An in depth analysis of analysis of its spatial resolution, frame rate, and detection sensitivity is given in [29].

![Conceptual schematic of a photonic assisted time-stretch analog to digital converter](image)

**Figure 8.** Conceptual schematic of a photonic assisted time-stretch analog to digital converter

### 1.3.5 Photonic Assisted, Time Stretch - Analog to Digital Converters

An analog to digital converter (ADC) is a device that converts an analog electrical voltage to digital bits via sampling. The performance of an ADC is defined by the sampling rate and the number of voltage levels (steps) that it can accurately resolve [30]. In a time-stretch analog to digital converter (TS-ADC), a broad bandwidth optical pulse propagates in a dispersive optical medium, resulting in a temporally stretched pulse of nanosecond duration. The stretched pulse is directed to an amplitude modulator that is driven by the analog RF signal, therefore the
RF signal information is imparted to a segment of the temporally stretched optical pulse. A highly dispersive element is used to further stretch the encoded pulse by a larger amount, thereby stretching the encoded RF waveform. A photodetector is used to convert the RF encoded optical waveform back to the electrical domain and is sent to an electrical ADC. If the dispersion of the second dispersive element is significantly larger than the first element, the encoded RF signal will be down-converted to a lower frequency value due to the temporal stretching, making it possible to use a low bandwidth ADC to sample the RF waveform at a higher effective sampling rate, as shown in Fig. 6 [29, 31]. J Chou et al reported an effective sampling rate of 10 tera-samples per second [32].

1.3.6 Microwave Signal Analyzer

Saperstein et al demonstrated a novel method for analyzing microwave signals by using stretched optical pulses [33]. Anomalous dispersion is used to perform a Fresnel transform of an ultrashort pulse and is then modulated by the microwave signal. A dispersive element with normal dispersion may be used to compress the modulated pulse resulting in an inverse Fresnel transformation that will generate an ultrashort pulse that is convolved with the microwave spectrum.

1.3.7 Time Domain Waveform Processing for Pulse Shaping and Chirped Pulse Amplification

A stretching element such as Dispersion Compensating Fiber (DCF) or a chirped fiber Bragg grating (CFBG) may be used to stretch picosecond pulses to nanosecond time durations, enabling the use of conventional optical modulators to shape the temporal intensity profiles of
pulses [34]. A dispersive element with opposite dispersion profile may be subsequently used to
compress the pulses. One of the advantages of frequency chirped, temporally stretched pulses is
the easy amplification to high powers using chirped pulse amplification (CPA). This technique
was originally introduced in the 1960s to increase radar signal power [35] but has been modified
and improved over the past few decades and is now also used for amplifying optical signals [36].
However, in fiberized systems, when desired energy levels are in the 10 millijoule range, pulse
amplification is limited because nonlinearities and dispersion of the gain media can cause severe
pulse distortion and consequently degrade the pulse quality. Since self phase modulation (SPM)
is proportional to the derivative of the intensity, optical pulses, whose temporal shape is
parabolic result in the generation of a linear chirp due to SPM that can be compensated in a
straightforward manner by using an approach such as a grating pair pulse compressor.

Parabolic pulse generation has been demonstrated in several different techniques, but the
quality of the parabolic pulses generated with these approaches is only moderate, because the
input pulses evolve asymptotically into a near-parabolic shape [37-42]. Moreover, as the pulses
propagate, even as they retain their parabolic shape, their width and amplitude changes so there
is not a well-defined mechanism to actively and dynamically control pulse characteristics. Also,
it has been shown that third order dispersion and linear absorption have detrimental effects on
parabolic pulse evolution and thus, on the performance of configurations utilizing DDF [43].
Recently, a technique for dynamic shaping of pulses has been demonstrated using an approach
based on the temporal stretching of pulses using a dispersion element [34, 44]. This technique
enables dynamic control of the pulse properties such as pulse shape, pulse width and amplitude
with high resolution and a large signal to noise ratio making it suitable for a variety of
applications including supercontinuum generation, optical communication, high power femtosecond lasers, fiber amplifiers, and chirped pulse amplification.
CHAPTER 2: A CHIRPED PULSE SOURCE BASED ON A MODE-LOCKED LASER AND CHIRPED FIBER BRAGG GRATING

2.1 Introduction

This chapter introduces a chirped pulse source that utilizes a mode-locked laser (MLL) source and a chirped fiber Bragg grating (CFBG) to generate temporally stretched, frequency chirped pulses. The characteristics of the MLL and the CFBG are discussed briefly, followed by a description of the chirped pulse source.

2.2 Mode-Locked Laser

A commercially available mode-locked laser (MLL) manufactured by Calmar Optocom Inc, (model: FPL–M2TFTBH12) is used as the source. It has a repetition rate of 20 MHz with a center wavelength of 1.55 µm. The pulse duration and the corresponding optical spectrum can be changed slightly by varying the pump current but pulses with full width at half maximum (FWHM) durations of below 1 ps are typical, with an average output power of about 3.5 mW.

The laser is passively mode-locked using a semiconductor saturable absorber with erbium doper fiber serving as the gain medium. The erbium doped fiber is pumped by a 980 nm diode laser driven by a current source. The pump current has a strong influence on the mode-locking behavior in terms of the number of pulses in the cavity, and the output pulse width. A schematic of the laser is given in Fig. 8. The saturable absorber provides the mode-locking mechanism. Its absorption is high for low optical intensities, but reduces significantly when it is saturated by high input optical signals. When a saturable absorber is placed inside the laser cavity, it operates on the random temporal intensity profile of the amplified spontaneous emission (ASE), and after
a number of round trips in the cavity, an optical pulse slowly evolves. When the laser reaches steady state, it is said to be mode-locked.

![Schematic of the mode-locked laser source](image)

**Figure 9.** Schematic of the mode-locked laser source (adapted from [45])

### 2.3 Experimental Characterization of Mode Locked Laser Performance

#### 2.3.1 Frequency Resolved Optical Gating (FROG) Results

The pulse characteristics generated by a mode locked laser are experimentally analyzed by constructing a second harmonic generation frequency resolved optical gating (SHG-FROG) setup [46, 47]. Details on the construction and operation of the SHG-FROG setup are given in Appendix. It must be noted that pulse duration and optical spectrum is susceptible to dispersion and non-linear effects after propagation of ultra-short optical pulses in an optical fiber. The results presented here were taken when a fiber patch cord of < 1 m length was used to direct the pulses from the source laser to the FROG setup. The SHG-FROG data was taken using 128 delay
points of 20 fs step size (on the x-axis), and 1001 points on the wavelength with a step size of 0.01502 nm, a center wavelength of 776 nm and a total span of 15 nm on the y-axis. The FROG error was 0.0058 on a 128 size grid. The FROG results indicated an optical bandwidth (FWHM) of ~9.5 nm, and a temporal width (FWHM) of ~0.35 ps.

Figure 10. FROG Traces of the laser source (a) Original trace (b) Retrieved trace
Figure 11. The retrieved temporal intensity and phase profile of the optical pulses, as calculated by the SHG-FROG setup

Figure 12. The retrieved spectral intensity and phase profile of the optical pulses, as calculated by the SHG-FROG setup

2.3.2 Optical Linewidth Measurement

The MLL linewidth is characterized by beating it with a CW laser (Orbits Lightwave, Inc) that has an optical linewidth of 1 kHz in a heterodyne configuration. The beat signal is observed on an RF spectrum analyzer (RFSA). The results are shown in Fig. 1 (c) and a
linewidth of < 3 kHz is observed, (limited by the RFSA resolution bandwidth), implying an optical coherence length of tens of kilometers.

Figure 13. Experimentally observed heterodyne beat signal indicating a MLL linewidth of < 3 kHz

2.4 Chirped Fiber Bragg Grating

The chirped fiber Bragg grating (CFBG) is a very critical component for any system employing temporally stretched, chirped pulses. Traditionally, CFBGs were primarily used for dispersion management of optical pulses in long haul, high bit rate communication systems. Recently, they have also found use in many other applications, such as laser development, optical sensing, chirped pulse amplification systems, imaging, and laser ranging [48]. The performance of CFBGs is defined by various parameters such as their operational optical bandwidth, dispersion, group delay ripple (GDR), and insertion loss. Progress in fiber grating fabrication technology has resulted in an increase in the maximum amount of dispersion which can be obtained from broadband CFBGs, and gratings with dispersions of up to 2 ns/nm across the C-band are now available. However, due to imperfections and noise in the grating fabrication
process, larger dispersion values come at the price of larger ripple in the group delay. The GDR can be removed by spectral phase modulation, and is discussed in detail in chapter 6. The specifications of the CFBG used in our experiments are given in the next section.

2.5 Chirped Fiber Bragg Grating Characteristics

For the purposes of our experiments, two CFBGs (manufactured by Proximion Inc.) with dispersions of 1651 ps/nm at 1545 nm were used. The operational bandwidth of the CFBGs was from 1527 nm to 1567 nm. The group delay across the C band for the red and blue ports of the two CFBGs is given in Fig. 14.

![Figure 14. Group Delay of the CFBGs](image)

The CFBGs also exhibit a ripple in the group delay that is not evident in Fig 14, and therefore, has been re-plotted below in Fig. 15. A group delay ripple (GDR) of < 50 ps is observed for both the CFBGs. The GDR may be compensated by using spectral phase modulation, as discussed in section 6. The reflection and transmission properties of the CFBGs are given in Fig. 16.
Figure 15. Group Delay Ripple of the CFBGs

Figure 16. Reflection and transmission of the CFBGs
2.6 Chirped Pulse Source Setup

![Diagram of Chirped Pulse Source]

Figure 17. Schematic of a chirped pulse source employing a mode-locked laser and chirped fiber Bragg grating. PC: Polarization controller.

The schematic of the chirped pulse source is given in Fig. 17. Optical pulses from the MLL are directed to a CFBG via a circulator. The optical pulses experience a wavelength dependent temporal delay that results in a stretching of the pulse in the time domain, with a frequency chirp across the pulse duration. A linear polarizer is added in the setup to ensure that the polarization of the chirped pulses is uniform across the pulse duration. Since the CFBG is not polarization maintaining, therefore spectral filtering due to polarization occurs at the polarizer. The polarization controller is introduced before the CFBG in order to optimize the shape and bandwidth of the output optical spectrum from the chirped pulse source. For the experiments discussed in this report, the optical spectrum was centered at 1.55 µm, with a FWHM of ~6 nm (~750 GHz). The duration of the temporally stretched, frequency chirped pulses was therefore 6 nm x 1651 ps/nm = ~10 ns.
CHAPTER 3: LASER RANGING USING CHIRPED PULSES

Light detection and ranging (lidar) is used for metrology, velocimetry, imaging, and remote sensing applications [49-54]. Techniques for distance measurement can be divided into three main categories: triangulation, time of flight and interferometry [55, 56]. For velocimetry, the change in target distance as a function of time can be recorded to obtain velocity information. Lidar systems that measure Doppler shifts due to target motion are also routinely used [53, 54]. An overview of some common lidar architectures is given below.

3.1 Introduction to Laser Ranging Techniques

3.1.1 Optical Triangulation

The triangulation architecture consists of a light source (usually a laser), a lens, and a light sensor as shown in Fig. 18 [57-59]. The light source illuminates a small spot on the target and its image is formed on a photodetector pixel array or charge coupled device (CCD). When the object distance (D) changes, its image shifts to a different location on the sensor (ξ) which is used to calculate the target distance. However, the speckle noise of the laser generally limits the range resolution to a few micrometers. Triangulation techniques have been used to measure distances up to tens of centimeters [58].
Figure 18. Simplified schematic of a laser ranging using triangulation (adapted from [59])

3.1.2 Time of Flight Ranging

The time of flight (TOF) technique is based on measuring the time it takes for a pulse to complete a round trip between an observer and a target (Fig. 19). The distance \( d \) to the target is then calculated by \( d = \frac{c \cdot t}{2} \) where \( c \) is the speed of light in air and \( t \) is the round trip propagation time. The range resolution is limited by the pulse duration and short pulses of \(< 6.7 \text{ ps} \) duration are required for sub-millimeter resolution [55, 60]. For long range and high resolution operation, short pulses with high peak power have to be launched to ensure detection at the receiver. Unfortunately, amplifying short pulses to high power levels is not straightforward and can result in peak powers that may damage, or reduce the lifetime of various system components. Furthermore, short pulses require more bandwidth which increases receiver noise. For unambiguous long range measurements with TOF lidar systems, low pulse repetition rates must be used to prevent aliasing. Moreover, pulsed TOF systems suffer from inaccuracies due to
noise generated timing jitter. In addition to this, high resolution TOF lidars require expensive receiver electronics to accurately measure extremely small time intervals. Meanwhile, the amplitude of the launched pulses also decreases proportionally to the square of distance[61] and distortion of the pulse shape due to noise introduces additional timing errors. Recently, a photon counting pseudorandom noise code altimeter with a resolution of \( \sim 1 \text{ cm} \) was demonstrated [62]. Unambiguous ranging at several hundred meters with GHz clock rates was also demonstrated using a photon counting technique with cm resolution [63].

![Figure 19. Block diagram of a TOF ranging system (adapted from [50])](image)

Femtosecond lasers and frequency combs have recently gained considerable attention for their use in ranging applications [64-66]. Joohyung et al. were able to improve the time of flight precision to the nanometer regime by timing femtosecond pulses through phase-locking control of the pulse repetition rate using the optical cross-correlation technique [67]. High resolution absolute distance measurements were demonstrated by Codington et al. using a novel multi-
heterodyne approach using optical frequency combs [68]. Unfortunately, the amplification of femtosecond pulses to high power levels to enable long-distance ranging remains a challenge.

![Figure 20. Conceptual schematic of continuous wave phase shift lidar](image)

3.1.3 Continuous Wave, Phase Shift Measurement Method

In continuous wave (CW) lidar systems based on the phase-shift measurement method, the optical signal is intensity modulated by varying the drive signal sinusoidally using a local oscillator [69]. The received echo signal is photodetected and the difference in phase due to time of flight ($\Delta \phi$), (shown in Fig. 3) is compared with the local RF oscillator to obtain the target distance using the formula: 

$$D = \frac{1}{2} \times c \times \frac{\Delta \phi}{2\pi} \times \frac{1}{f}$$

where $\Delta \phi$ is the phase shift, $c$ is the speed of light and $f$ is the modulation frequency. Higher modulation frequencies can lead to higher resolution but the modulo $2\cdot\pi$ nature of the phase reduces the maximum unambiguous range. Similarly, in single wavelength phase shifting interferometry, distances are measured by recording the phase of the optical fringe patterns. One way to solve the $2\cdot\pi$ ambiguity problem is by using Synthetic Wavelength Interferometry (SWI) that relies upon multiple wavelengths to generate a synthetic wavelength that improves system performance [70-73]. In Spectrally Resolved Interferometry (SRI) an interferogram is split into its monochromatic components and the phase of each wavelength is measured using a spectrometer to obtain unambiguous
measurements with nanometer resolution [74]. The TOF, SRI and SWI techniques can be incorporated and implemented simultaneously, as demonstrated by Ki-Nam Joo, et al. [75].

### 3.1.4 Frequency Modulated Continuous Wave Lidar for Ranging

The earliest reported use of a frequency modulated radar was in 1926 by Appleton et al., when they wished to obtain evidence of the existence of the ionosphere [76]. This technique was later applied to frequency modulated continuous wave (FMCW) lidars [77-81]. The optical frequency of a laser is modulated linearly and periodically in time. Usually, semiconductor lasers are used because they can easily be tuned by current injection. A portion of the modulated optical signal is launched to probe a target, while the remainder is used as the reference signal. After reflection from the target, the echo signal and the reference signal are combined, resulting in optical interference (Fig. 21). The relative delay ($\tau$) between the two signals results in the generation of a beat tone that is observed on an RF spectrum analyzer (RFSA) after photodetection. The beat signal shifts in frequency as the relative delay between the reference and echo signals changes, and is used to calculate the target distance. Coherent detection at the receiver allows detection of weak echo signals.

![Conceptual schematic of an FMCW lidar](image)

**Figure 21.** Conceptual schematic of an FMCW lidar
The performance of FMCW lidars is affected by the span, duration, and linearity of the optical frequency sweep. As shown in Fig. 22, a non-linear optical frequency sweep results in the broadening of the interference beat signal. Optical frequency sweeps of several tens of GHz were reported in [82, 83] but to achieve sub-millimeter resolution, optical bandwidths of hundreds of GHz are required. An algorithmic stitching approach was used in [84] to increase the effective bandwidth of a FMCW system resulting in 500 μm range resolution. A range resolution of 100 μm was obtained using a two section DFB laser as a coherent source [85]. Some early efforts to improve the linearity of the frequency sweep relied on using an additional reference arm [86] but recently, active chirp linearization for broadband FMCW has been demonstrated [87] and a frequency chirp bandwidth of 4.8 THz was reported using a self-heterodyne technique [88].

![Diagram of Optical Frequency Sweep](image)

Figure 22. A non-linear optical frequency sweep results in a broadening of the interference beat signal

The maximum range of a FMCW lidar system is limited by the coherence length of the laser source. A distance of 18.5 km was measured with a resolution of 2 cm using a frequency shifted feedback laser [89]. By employing a diode-pumped single-frequency piezoelectrically tuned fiber laser with narrow spectral linewidth, optical frequency domain reflectometry with
95 km of optical fiber was demonstrated [90]. For imaging applications, Beck et al. demonstrated a synthetic aperture laser radar employing a tunable laser with ~1 km coherence length, and a digital reference channel signal was used to correct for phase errors [91]. It is possible to determine the range and velocity of a target simultaneously. This is done by using optical waveforms with triangular waveform frequency modulation (i.e. periodic, opposite frequency chirps) that result in the generation of Doppler beat signals that are directly measured to obtain target velocity [54, 92, 93].

### 3.1.5 Doppler Lidar

Doppler lidars, as the name implies, are based on the measuring the frequency shift that is imparted to the echo signal due to the motion of a target (Doppler effect). The Doppler shift ($f_d$) in the transmitted sound frequency of a fast moving train approaching an observer is given by: $f_d = v / \lambda$ where $v$ is the line of sight velocity, and $\lambda$ is the wavelength of sound frequency. In the case of a Doppler lidar system where the laser signals are transmitted and received from a platform that is stationary with reference to a moving target, the Doppler shift in the optical frequency is doubled. At the lidar receiver, the echo signal is mixed with a reference signal ($f_r$) to observer the difference frequency corresponding to the Doppler shift, which reveals the target velocity. A block diagram of a simple CW lidar is given in Fig. 23. Doppler lidars have been demonstrated with operation in pulsed [53] [94] and continuous wave regimes.
3.1.6 Optical Feedback Interferometry

Optical feedback interferometry (or self-mixing, or injection interferometry) is based on the coupling of backscattered light from a target back into the laser diode cavity so that laser operation is affected, causing a substantial variation in the optical output power [95]. Optical feedback interferometry performs a special type of coherent detection, called injection detection [96] which is the optical counterpart of superheterodyne detection in the microwave community. The laser cavity facets and the target surface provide the necessary feedback which removes the need for an external interferometer and optical alignment. Since the sensing information is carried by the laser signal, it can be analyzed at the remote target location as well. With weak feedback, a moving target causes a periodic, saw-tooth like optical power fluctuation, with one power swing corresponding to a displacement of half a wavelength. The displacement direction is obtained by analyzing the slope of the saw-tooth like power signal. Distance measurements with an accuracy of +/- 1.5 mm at a range of a few meters, and velocity measurements at 200 km/h with an error of 5% have been demonstrated [95].
3.2 Ranging using Chirped Pulses

In this section, a lidar system that combines the benefits of the FMCW and TOF techniques is presented. The proposed lidar concept is based on the generation of temporally stretched, frequency chirped pulses from a mode locked laser using a chirped fiber Bragg grating (CFBG) [25]. Unlike TOF systems, the range resolution is not defined by the width of the laser pulses but by the optical bandwidth, and sub-millimeter resolution is obtained using pulses that are a few meters long. A signal to noise ratio of at least 25 dB is obtained. A pulse repetition rate of 20 MHz provides fast update rates. In addition to this, the proposed lidar design allows easy amplification of optical signals to high power levels for long-distance ranging using the extremely stretched pulse amplification (XCPA) technique [97, 98], while minimizing fiber non-linearities. The narrow optical linewidth (< 3 kHz) of an individual axial mode of the mode locked laser results in optical pulses with coherence lengths on the order of ~100 km that enables long-distance operation with coherent detection at the receiver. A pulse tagging scheme based on phase modulation is also demonstrated to ensure unambiguous long-distance measurements [26].

In a separate experiment, a train of oppositely chirped pulses is used to demonstrate velocimetry [27]. When a fast moving target is probed with the oppositely chirped pulse train, a Doppler shifted beat signal is generated that provides range and velocity measurements simultaneously. This is to the best of our knowledge, the first experimental demonstration of velocimetry inside a laboratory with a target moving at speeds of over 330 km/h. Moreover, for slow moving targets that have extremely small Doppler shifts, the change in target distance is observed as a function of time to obtain high resolution velocity measurements. Simulations are
performed to confirm the effect of the non-ideal behavior of the CFBG on lidar performance and a close agreement between theory and experiments is observed.

3.3 Conceptual Overview

The interference of two identical, temporally stretched, linearly chirped pulses is shown in Fig. 24. A relative temporal delay between the pulses results in the generation of a beat signal (f). Since a chirped fiber Bragg grating (CFBG) is used to temporally stretch and chirp the pulses, its dispersion (D = 1651 ps/nm) can be expressed in terms of a chirp parameter S that is obtained by converting the dispersion units (from temporal delay per unit wavelength), to distance per unit optical frequency and then taking its inverse. This yields S = 250 MHz/mm, which implies a shift of 250 MHz in beat frequency for a 1 mm change in the target round trip distance. Therefore when a chirped pulse is transmitted to a distant target, the interference of the received pulse with a reference pulse results in the generation of a beat frequency (f) that is measured using an RF Spectrum analyzer, after photodetection. The one way target distance (d) is calculated by d = f / 2S.

![Figure 24](image)

Figure 24. The interference of a two identical, linearly chirped pulses generates a beat frequency that depends on the relative delay between the overlapping pulses.
### 3.4 Experimental Setup

The experimental setup of the lidar system is shown in Fig. 25. A commercially available passively mode-locked laser with a repetition rate of 20 MHz and a center wavelength of 1553 nm is used to generate pulses with a full width at half maximum (FWHM) duration of < 1 ps duration corresponding to an optical bandwidth of ~750 GHz. On the other hand, the optical linewidth of a single axial mode component of the MLL is < 3 kHz, enabling coherent lidar operation at distances of several tens of kilometers. The pulses pass through a polarization controller before they are directed by a circulator to a CFBG with a dispersion of 1651 ps/nm. The CFBG imparts a wavelength dependent temporal delay on the optical pulses. This leads to a stretching of the pulses to ~10 ns (FWHM) in time, or 15 m (FWHM) in free space, and a time bandwidth product of ~7500.

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**Figure 25.** Temporally stretched, frequency chirped lidar schematic. MLL, Mode-locked Laser; PC, Polarization Controller; CFBG, Chirped Fiber Bragg Grating; CIRC, Circulator; FL, Fiber Launcher; VOD, Variable Optical Delay; EDFA, Erbium Doped Fiber Amplifier; RFSA, RF Spectrum Analyzer.
A directional coupler splits the stretched pulses into a reference arm and a delay arm. A polarization controller in the reference arm is used to match the polarizations of the two arms. In the delay arm, a circulator and telescope can be used to launch and receive optical signals in free space. However, in the laboratory, measurements are made by simulating short or long target distances (as shown in Fig. 25). For short range measurements, a free space variable optical delay (VOD) is used in the delay arm of the setup to introduce a relative path length difference between the two interferometer arms.

For long range measurements, the long delay consists of a fiber spool of 20.2 km followed by a VOD and an erbium doped fiber amplifier (EDFA). The 20.2 km of fiber delay consists of SMF-28 fiber and dispersion shifted fiber (DSF) to minimize the additional dispersion in the delay arm. However, due to the different dispersion slopes of the DSF and SMF-28 fibers, some residual dispersion remains. A circulator directs the amplified pulses to a fiber launcher that transmits the pulses towards the target (a flat aluminum plate), located 10 cm away. The reflected signal from the target is received and combined with a reference signal with the help of a circulator and directional coupler. An EDFA amplifies the interfering optical signal, followed by photodetection at the receiver. An RF spectrum analyzer or a real time oscilloscope with Fourier transform capability is used to analyze the beat signal.

### 3.5 Short Range Lidar Performance

The short delay consisting of a VOD (as shown in Fig. 25) is used for short range measurements. A pulse repetition rate of 20 MHz corresponds to a period of 50 ns (or 10 meters in fiber). Since the duration of the stretched pulses is 10 ns (or 2 meters in fiber), the optical path
difference between the reference arm and the delay arm is kept below 2 meters to ensure pulse overlap. A VOD is initially used to balance the two arms accurately, and then used to introduce delays in the target arm while the corresponding shift in the beat frequency is measured. The experimentally observed beat frequencies corresponding to different target distances are shown in Fig. 26.(a). A SNR of > 30 dB is observed. The shift in the beat frequency as a function of target distance is plotted in Fig. 26.(b). A slope of 484 MHz/mm is observed which corresponds to a frequency shift of 242 MHz for each millimeter of relative pulse delay (round trip delay). This is in close agreement with the theoretical value of CFBG dispersion (S = 250 MHz/mm).

![Photodetected RF Spectra](image1.png)

(a) Photodetected RF Spectra

![Ranging Data](image2.png)

(b) Ranging Data

Figure 26. (a) Detected coherent heterodyned signals at different target distances b) Shift in the peak of the beat frequency as a function of target distance.

A closer examination of Fig. 26.(a) reveals a broadening of the RF signal and a decrease in its magnitude as the delay is increased. Moreover, the envelope of the detected signal exhibits an undesirable modulation (noise) that is more prominent at longer delays. This is due to the group delay ripple (GDR) of the CFBGs, as verified by simulations in chapter 6. Moreover, the
CFBG used in this setup has a dispersion that is linear with respect to wavelength. Therefore it generates stretched pulses that do not have a perfectly linear chirp in the optical frequency domain.

3.6 Long Range Lidar Performance

To demonstrate the long distance ranging capability of the lidar system, the setup shown in Fig. 25 is used with a fiber delay of 20.2 km. A relative fiber path length difference of 20.2 km leads to a temporal overlap of pulse 1 in the delay arm with the 2021st pulse in the reference arm. A beat signal with a -3 dB width of ~200 MHz is observed at a target distance of 1010 pulses + 1.3 mm, as shown in Fig. 27.(a). The VOD is used to vary the target distance in 1 mm increments and the shift of the beat signal frequency is recorded to reveal a slope of 466 MHz/mm as shown in Fig. 27.(b). We define the range resolution of the lidar system as the -3 dB width of the beat signal divided by the dispersion slope. A resolution of < 500 µm at a target distance of 1010 pulses + 1.3 mm is experimentally observed.

One of the advantages of using a MLL as a laser source is its axial mode coherence length of tens of kilometers that enables high resolution measurements at long range. However, since the temporally stretched pulses do not completely cover the 50 ns pulse period, the repetition rate of the MLL can be tuned to shift the relative position between two pulse trains to ensure pulse overlap. For example, at a target distance of 10 km, changing the pulse repetition rate by 10 kHz will shift the relative position between two pulse trains by 50 ns. In addition to this, a MLL with a higher repetition rate, a CFBG with higher dispersion, or a MLL with a larger
optical bandwidth can also be used to completely fill the pulse periods to ensure pulse overlap at all times.

Figure 27. (a) Observed beat signal with a -3 dB width of ~200 MHz (b) Shift in the peak of the beat frequency as a function of target distance.
CHAPTER 4: RESOLVING THE LIDAR RANGE AMBIGUITY

For unambiguous long distance measurements with pulsed TOF lidar systems, low repetition rates are used to prevent aliasing. In the chirped pulse lidar system presented, a laser pulse repetition rate of 20 MHz implies a pulse period of 15 meters in space. When targets with round trip distances greater than 15 meters are probed, the lidar system has no means of differentiating between the received pulses resulting in range ambiguities. This problem is overcome by phase modulating the pulses.

4.1 Unambiguous Range Measurement using Phase Modulation

To perform unambiguous range measurements, a frequency swept RF drive signal is used to drive a phase modulator, resulting in each stretched pulse acquiring phase modulation at a different frequency. We denote the difference in phase modulation frequencies between adjacent pulses as $\nu_a$. The phase modulated pulse train is then split into a reference arm and a delay arm (with a delay of ‘N’ pulses) before being recombined. The beating between the phase modulation optical side bands of the delayed and reference pulses generate a beat frequency at an offset of $\nu_b = N \cdot \nu_a$ from the center tone, as shown in Fig. 28.

![Conceptual schematic of chirped lidar for unambiguous ranging.](image)

Figure 28. Conceptual schematic of chirped lidar for unambiguous ranging.
The round trip delay (in terms of the number of pulses) is calculated by rounding off \((\nu_b / \nu_a)\) to the nearest integer. The position of the center tone on the RF spectrum provides the target distance value that is added to the round trip delay value (in terms of number of pulses) to obtain the total unambiguous round trip target distance.

### 4.2 Generation of Frequency Swept RF Drive Signal

The RF drive signal for the phase modulator is generated by using two lasers (an HP-81682A narrow linewidth laser and a distributed feedback (DFB) laser) in a heterodyne configuration, shown in Fig. 29 (a). Fig. 29 (b) shows the RF spectrum of the beat signal when the wavelengths of the two lasers are fixed at 1552 nm and 1552.022 nm respectively and a FWHM of ~22 MHz is observed. The DFB laser wavelength can be tuned by changing the drive current and a slope of 1.1 GHz / mA is observed, as shown in Fig. 30.(a). A function generator is used to produce a saw-tooth current waveform while a diode driver provides the DC Bias. The two signals are combined using a bias-tee and are used to tune the DFB wavelength via current injection modulation resulting in the generation of a heterodyne beat signal that sweeps in frequency, as shown in Fig. 30.(b).
Figure 29. (a) Heterodyne schematic for frequency swept RF signal generation. PC, Polarization Controller; PD, Photodetector (b) Beat tone generated from heterodyne setup.
Figure 30. (a) Optical frequency versus drive current for DFB laser (b) Observed RF beat signal spectrum with laser current injection modulation (sawtooth waveform) at 250 kHz.
If $F_s$ is the total span of the frequency sweep of the heterodyne beat signal and $T_s$ is the period of the sweep, then the rate of change of beat frequency is given by $R_{RF} = \frac{F_s}{T_s}$, assuming a linear DFB laser frequency response.

Figure 31. (a) Schematic of CWFM setup for measurement of sweep rate of the RF drive signal. DFB, Distributed Feedback Laser; VOD, Variable Optical Delay, PC, Polarization Controller; EDFA, Erbium Doped Fiber Amplifier; RFSA, RF Spectrum Analyzer. (b) Observed RF beat signal using a CWFM setup with laser current injection modulation at 350 kHz with an optical frequency excursion of ~7 GHz.
For lidar experiments, the amplitude and period of a saw-tooth current waveform is adjusted to produce an RF beat signal that sweeps from ~3 GHz to ~10 GHz in 2.86 μs ($F_s = ~7$ GHz, $T_s = 2.86$ μs) which results in a frequency shift rate of $R_{RF} = ~7$ GHz / 2860 ns = ~2.5 MHz / ns. To obtain a more accurate value of $R_{RF}$, an experiment is performed using the CWFM setup (shown in Fig. 31.(a)). 60 m of optical fiber with a Faraday mirror, VOD and circulator provides a total fiber delay of 120 m (0.6 μs time delay or 12 pulses). Theoretically, a linear frequency sweep with a fiber delay of 120 m (0.6 μs) should result in a beat tone at $R_{RF} \times$ delay = 2.5 MHz / ns x 600 ns = 1.5 GHz. However, a beat tone at 2 GHz is obtained (as shown in Fig. 31)). This indicates an experimentally observed value of $R_{RF} = 3.34$ MHz / ns due to the nonlinear frequency response of the DFB laser.

### 4.3 Lidar Setup for Unambiguous Range Measurements

The setup for unambiguous lidar ranging is shown in Fig. 32. A polarization controller and phase modulator are introduced in the setup after the polarizer. A broadband RF amplifier amplifies the frequency swept signal that drives the phase modulator. When the phase modulator is driven with the frequency swept signal of Fig. 29, the difference in phase modulation frequency between two adjacent pulses, is given by $\nu_a = R_{RF} \cdot T_p = 167$ MHz / pulse, where $T_p$ is the period of the optical pulse train (50 ns). 57 optical pulses are phase modulated in single frequency sweep resulting in a maximum unambiguous round trip range of 570 m in fiber (~855 m in free space).
Figure 32. Schematic of chirped lidar setup for unambiguous ranging. MLL, Mode Locked Laser; PM, Phase Modulator; PC, Polarization Controller; CFBG, Chirped Fiber Bragg Grating; CIRC, Circulator; VOD, Variable Optical Delay; EDFA, Erbium Doped Fiber Amplifier; RFSA, RF Spectrum Analyzer.

A fiber delay of 60 m is used in the delay arm to simulate a round trip delay of 6 pulses. The VOD is then adjusted to add an additional free space round trip delay of 26.7 mm. In Fig. 33, the envelope of the observed beat signal is plotted. A center heterodyne beat at 6.67 GHz corresponds to a round trip distance of 26.7 mm. A SNR of > 30 dB is observed. The phase modulation sidebands are observed at an offset of 1 GHz from the center tone, indicating a round trip delay of \( n = \frac{v_b}{v_a} = \frac{1 \text{ GHz}}{0.17 \text{ GHz}} = 5.9 \) which is rounded off to the nearest integer to obtain a round trip delay of 6 pulses. Therefore the total target round trip distance is 6 pulses plus a distance of 26.7 mm in free space. If the VOD is changed, the main beat note and sidebands shift while maintaining a 1 GHz spacing between them. Increasing the span, duration and linearity of the frequency swept RF drive signal by using a technique such as [82-84, 86-88] will
result in narrower side bands with larger SNR and the ability to tag more pulses resulting in a larger unambiguous range.

![Unambiguous Range Data](image)

**Figure 33.** Phase modulation sidebands at 1 GHz from the main tone.

It must be noted that difference in phase modulation frequency between adjacent pulses ($\nu_a$) should be kept large enough to ensure that the main beat tone can be distinguished clearly from the sidebands. A large $\nu_a$ and high repetition rate will increase the bandwidth requirement of the phase modulator, therefore in a real lidar system, design parameters such as the laser repetition rate, $\nu_a$, CFBG dispersion, and the phase modulator bandwidth will dictate the lidar performance in terms of the maximum unambiguous range, update rates, etc.
CHAPTER 5: CHIRPED PULSE LIDAR FOR SIMULTANEOUS VELOCITY AND RANGE MEASUREMENTS

Lidar systems can be used for distance and velocity measurements. One technique for obtaining velocity information is by simply recording the change in target position (Δx) as a function of time increments (Δt). Generally, this technique is more suitable for slowly moving targets. For faster moving targets, Doppler lidars are employed which rely on detecting the Doppler shift in the frequency of the received echo signal. This can be done by beating a received echo signal with a reference signal to obtain the beat frequency corresponding to the Doppler frequency shift. The chirped pulse lidar system offers velocity measurements using both the above mentioned techniques, allowing high resolution measurements of slow and fast moving targets.

5.1 Conceptual Overview

To add simultaneous velocimetry and distance measurement capability to the lidar system, a train of oppositely chirped stretched pulses is utilized. A schematic of the interference of oppositely chirped pulses is shown in Fig. 34.(a) One pulse train (echo signal) is Doppler-shifted in frequency and is also delayed in time relative to the reference pulse train. This results in the generation of a beat tone at frequency f_{up} in the up-chirped pulses, and another beat tone at frequency f_{down} in the down-chirped pulses as shown in Fig. 34.(b). The target distance is then calculated by \( d = \frac{f_{center}}{2S} \) where \( f_{center} = \frac{f_{up} + f_{down}}{2} \). The velocity is given by \( v = \Delta f \cdot \lambda / 4 \) where \( \Delta f = f_{down} - f_{up} \), and \( \lambda \) is the center wavelength. Since the observed frequency difference \( \Delta f \) is twice the actual Doppler shift in the echo signal, a factor of 2 has been included in the velocity calculation.
calculation to account for this [50]. If $f_{\text{down}} > f_{\text{up}}$, the target is moving towards the observer, and vice versa.

Figure 34. (a) The interference of oppositely chirped pulse trains. One pulse train is Doppler shifted and temporally delayed with respect to the other. (b) This results in the generation of a beat signal that contains distance and velocity information.

5.2 Lidar Setup Utilizing an Acousto-Optic Modulator (AOM) to Simulate Doppler Shifted Echo Signals

Figure 35. Lidar setup with an acousto-optic modulator (AOM) to simulate Doppler shifts.
The lidar setup consists of two parts. The first part generates a train of oppositely chirped pulses as shown in Fig. 35.(a). The pulses from the MLL are divided in two arms, each with a polarization controller (PC), circulator and CFBG (dispersion = 1651 ps/nm). The sign of dispersion of the two CFBGs is opposite. A fiber delay is introduced in the upper arm to interleave the up-chirped and down-chirped pulses in the time domain. Stretched pulses of ~10 ns duration with a -3 dB optical bandwidth of ~6 nm (~750 GHz), centered at \( \lambda = 1548 \) nm are observed, yielding a time bandwidth product of ~7500. An erbium doped fiber amplifier (EDFA) is used to amplify the pulses to an average power of 276 mW. Since the gain of the EDFA is not uniform across all wavelengths, the amplified pulses exhibit a stronger intensity at shorter wavelengths and this can be used to obtain the sign of the chirp (and the corresponding beat frequency).

The second part of the setup (Fig. 35.(b)) consists of the lidar interferometer. A directional coupler splits the signal in two arms. An AOM in the reference arm introduces a frequency shift of +100 MHz in the optical signal, which simulates a Doppler frequency shift generated by a target moving towards the observer. In the reference arm, a VOD is used to introduce delays in the target arm to simulate a target at a distance. The PC is used to match the polarizations of the two arms. A directional coupler combines the signal from the two arms resulting in optical interference. An RFSA is used to observe the beat signal after photodetection.
Fig. 36. Phase modulation sidebands at 1 GHz from the main tone.

Fig. 36 shows the observed RF spectrum when the VOD is used to simulate a fixed target distance of 2.6 mm, and an AOM is driven at 100 MHz to simulate a target moving at 77 m/s. Two beat notes are observed in the RF domain (at 1.22 GHz and 1.44 GHz) resulting in $\Delta f = 200$ MHz, and $f_{\text{center}} = 1.23$ GHz. The target distance is then given by $d = f_{\text{center}} / 2S = 2.6$ mm. A $\Delta f$ of 200 MHz indicates a velocity of $v = \sim 77$ m/s. When the VOD is used to introduce additional relative delays between the two interferometer arms, the two beat tones shift in the RF domain while maintaining a frequency difference ($\Delta f$) of 200 MHz.

5.3 Lidar Setup Using a Fast Moving Target

In the above experiment, a fast moving target was simulated in the laboratory using an AOM in the lidar interferometer. In this section, the setup is modified to incorporate a fast
moving target to obtain actual velocimetry and distance data. A schematic of the experimental setup is given in Fig. 37. The first part of the setup for generating oppositely chirped pulses is identical to that explained in section 5.2. The oppositely chirped pulse train is directed to a high power EDFA followed by a directional coupler that directs the pulse train into the two lidar interferometer arms.

The target arm consists of a circulator that directs the pulses to a fiber launcher. The optical pulses are launched to probe a single tooth on a 1 mm thick plastic disc with a radius of 6 cm, located about 20 cm away. Its outer surface is machined to form small teeth that are covered with retro-reflecting tape to ensure easy collection of the echo signal without the need for careful optical alignment. The disc is mounted on a Dremel rotary tool and can be spun at thousands of revolutions per minute (RPMs). A metal enclosure is made around the disc for safety considerations.

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**Figure 37. Lidar schematic.** (a) Setup for generation of temporally stretched, oppositely chirped pulses. (b) lidar interferometer setup. PC, Polarization Controller; CFBG, Chirped Fiber Bragg Grating; VOD, Variable Optical Delay; EDFA, Erbium Doped Fiber Amplifier.
The reference arm uses the reflection from the facet of the FC/PC fiber connector as the reference signal. The VOD is tuned and the disc is manually rotated slightly to adjust the position of the teeth such that the lidar interferometer arms are equal in terms of their optical path lengths (i.e. beat tone is centered at DC) when the laser beam probes a single tooth at normal incidence. This position of the target is referred to as the mean target position in the remainder of this paper.

When the target disc spinning, an average echo signal power of 22.5 µW is observed at the input of the directional coupler. The average reference signal power is 0.75 mW. For simultaneous velocity and distance measurements, the target disc is spun at thousands of revolutions per minute resulting in an echo signal that is Doppler down-shifted in frequency because the teeth on the disc are moving along the direction of the probing beam. A directional coupler directs the optical interference signal to a 15 GHz photodetector resulting in coherent detection. Since the RFSA has a finite sweep time that results in blurring of the beat frequency due to target motion, an 8 GHz real-time oscilloscope is used to acquire a photodetected waveform of 40 µs duration. Fourier transforms of different segments (of 1 µs duration) in the acquired pulse train are taken to observe Doppler splitting, and also to record the shift in the beat signals with time (Fig. 38).
5.4 Simultaneous, Velocity and Distance Measurements using a Fast Moving Target

The Fourier transform of a 1 µs segment (3 µs – 4 µs) of a 40 µs acquired pulse train is observed to reveal Doppler splitting of the beat frequency, with RF tones at 0.68 GHz and 0.80 GHz (Fig. 39) resulting in $f_{\text{center}} = 0.74$ GHz, and $\Delta f = 0.12$ GHz, and the velocity of the target is therefore $v = \Delta f \cdot \lambda / 4 = 46.5$ m/s at a target distance of $d = f_{\text{center}} / 2S = 1.48$ mm from the mean position. It must be noted that the beat notes shown in Fig. 38 are not single tones, but an envelope structure over an array of narrow lines separated by 20 MHz (corresponding to the PRF of the MLL). For more accurate measurements, the ‘center of mass’ of the beat envelope can be determined or a MLL with a lower PRF can be used.
Ranging and Velocimetry Data at $v = 46.5$ m/s

Figure 39. A 1 µs time window is used to take Fourier transforms (F.T) of different segments of the acquired pulse train to observe the shift in beat tones with time.

To further confirm the lidar performance, the target velocity is doubled and the experiment is repeated. A Fourier transform of a 1 µs segment (from 12 – 13 µs) of the acquired pulse train is observed to reveal an $f_{\text{center}}$ of ~1 GHz and $\Delta f = 0.24$ GHz. This corresponds to a target distance of $d = f_{\text{center}} / 2S = 2$ mm from the mean position and a velocity of $v = \Delta f \cdot \lambda / 4 = 94$ m/s. A dynamic range of at least 25 dB is observed. A similar analysis of another 1 µs segment (from 39 – 40 µs) of the acquired pulse train reveals that the beat frequencies have shifted, as can be seen in Fig. 40.(a). A value of $f_{\text{center}} = 2.28$ GHz corresponding to a new target distance of $d = 4.56$ mm (from the mean position) is observed. The width of each of the two tones is less than 150 MHz, resulting in a range resolution of < 0.4 mm. A beat note separation of $\Delta f = 0.24$ GHz is maintained, indicating an unchanged velocity of 94
m/s. Separate Fourier transforms of the up and down-chirped pulses in the acquired pulse train reveal \( f_{\text{down}} > f_{\text{up}} \), indicating motion of the target away from the observer. The distance and velocity of the target at different times are given in Fig. 40.(b).

Figure 40. (a) Observed beat notes at different times. (b) Target distance and velocity at different times.
The pulse repetition rate of the MLL is 20 MHz, therefore in the frequency domain the beat signal envelope consists of tones that are separated by 20 MHz. This can introduce errors in the measurement of the exact position of the beat signal peak. Moreover, the FWHM ($\Delta f_{\text{FWHM}}$) of the beat note envelope in Fig. 40.(a) is observed to be < 60 MHz resulting in a velocity resolution of $\Delta v_{\text{res}} = \Delta f_{\text{FWHM}} \cdot \lambda / 4 = 23.2 \text{ m/s}$, or +/- ~11.6 m/s. For a target moving at a velocity of ~94 m/s, this implies an error of +/- ~12%, but the percentage error reduces as the target speed increases.

It must be noted that in the oppositely chirped pulse lidar system discussed in this chapter, two identical CFBGs, each with a dispersion of 1651 ps/nm were used. However, the GDR profiles of the two gratings are different. Due to this, the shapes of the Doppler shifted beat notes ($f_{\text{up}}$ and $f_{\text{down}}$) do not look identical, as evident in Fig. 40 (a). The setup can be modified to achieve Doppler shifted beat notes with identical widths and profiles [25]. Also, the GDR can be removed by using spectral phase modulation, and is discussed in the next chapter.

5.3 Velocity and Distance Measurements of a Slow Moving Target

For slowly moving targets, the velocity is measured by calculating the distance travelled by the target over a finite time duration. For instance, in the data shown in Fig. 40 (b), the target travels a total distance of $\Delta x = 4.5 \text{ mm} - 0.9 \text{ mm} = 3.6 \text{ mm}$, over a duration of $\Delta t = 39 \mu s$, resulting in a velocity of $v = \Delta x / \Delta t = 92 \text{ m/s}$ in a direction away from the observer. This is in very close agreement with the target velocity calculated using the Doppler shift (94 m/s). The error in Doppler velocity measurements can be reduced by using a CFBG with lower group delay ripple as discussed in the next section.
CHAPTER 6: SPECTRAL PHASE AND AMPLITUDE MODULATION FOR TWO FOLD INCREASE IN LIDAR RANGE RESOLUTION

The range resolution of a lidar is given by c/2B where c is the speed of light and B is the bandwidth of the lidar signal. The lidar system presented has an optical bandwidth (B) of about ~750 GHz, therefore a range resolution of ~200 µm should be theoretically possible. However, a maximum resolution of < 400 µm is observed at small relative pulse delays. This is due to the group delay ripple (GDR) of the CFBGs, as shown in Fig. 24 (a). Moreover, the CFBGs used in this setup have a dispersion that is linear with respect to wavelength. Therefore they generate stretched pulses that do not have a perfectly linear chirp in the optical frequency domain, resulting in a broadening of the beat signal. In addition to this, the optical spectrum of the chirped pulses originating from the CFBG based chirped pulse source does not have an ideal rectangular shape. In the wavelength to time mapping regime, the shape of the temporal intensity profile of the pulses resembles the shape of the optical spectrum. Thus, fluctuations in the spectral amplitude are mapped on to the temporal intensity profile of the pulses. This undesirable amplitude modulation on the pulses results in a broadening of the observed RF beat frequency envelope. In this chapter, an analysis of these impairments is provided, followed by a spectral phase and modulation technique that is used to overcome these impairments, resulting in a two fold increase in the lidar range resolution.

6.1 Compensation of Group Delay Ripple

For fiber optic communication systems, compensation of group delay of up to +/- 60 ps/nm was demonstrated by using a dispersion trimming wavelength selective switch [99]. Conway, et al. successfully demonstrated the removal of spectral phase ripple in CFBGs using a
digital post processing algorithm in the electronic domain. In this section, we demonstrate a technique that utilizes spectral phase tailoring in the optical domain to achieve GDR-free operation of a CFBG system while maintaining a dispersion of 1651 ps/nm across the C-band. Moreover, to experimentally demonstrate the benefit of GDR compensation on the performance of a system, the CFBG is used in a lidar setup to generate temporally stretched, frequency chirped pulses from a mode-locked laser. With spectral phase tailoring, the GDR of the CFBG is removed resulting in two fold improvement in the lidar range resolution. This approach can be used to achieve range resolution of a few hundred micrometers in a long range (> 10 km) chirped lidar configuration and also for doubling the resolution of chirped pulse, Doppler velocity measurements [26, 27]. Moreover, the development of a GDR free CFBG system is expected to improve the performance of many other systems that rely on optical dispersion or linearly chirped, time-stretched architectures such as photonic analog to digital conversion (ADC) technology, optical frequency domain reflectometry, serial time encoded amplified imaging, microwave signal analysis, and pulse shaping [10, 25, 28, 29, 31, 33, 44, 101].

6.1.1 Simulation Results that Confirm the Effect of GDR on Lidar

To confirm the effect of the GDR and the non-linear optical frequency chirp of the CFBG, a simulation was performed using the dispersion profile of one the CFBGs (as supplied by the manufacturer). A square shaped input optical spectrum from 1550 nm to 1556 nm was assumed and a pulse train with only up-chirped pulses was considered. The results obtained for different simulated target distances are given in Fig. 41. It is evident that the beat signal width increases as the relative difference between the interfering pulses increases. This reduces the range resolution of the system and also imposes a limit on the smallest target velocity that can be
measured using the Doppler shift. If the full width at half maximum (FWHM) of each Doppler shifted tone is 60 MHz, then the minimum resolvable velocity (-3 dB down) is ~23.2 m/s. This limitation does not apply for velocity measurements that are made by calculating the displacement of the target over small time durations, as discussed in chapter 5. In the past, there has been some effort in minimizing the effect of GDR by electronic post processing [91, 100, 102]. In the next section, a novel approach that removes the GDR from the pulses *directly in the optical domain* is presented.

Figure 41. Simulation results at different target distances confirm the broadening of the RF beat tones.

### 6.1.2 Compensation of Group Delay Ripple using Spectral Phase Modulation

To demonstrate GDR compensation, a CFBG with a dispersion of 1651ps/nm across the C band is considered. The GDR of the CFBG is less than +/- 50 ps and is given in Fig.42. The noise in the linearity of the chirped pulses (due to GDR) can be compensated by modulating the
The schematic of the spectral pulse shaper is shown in Fig. 43 where a diffraction grating is used to angularly disperse the light while directing it towards a liquid crystal on silicon (LCOS) based pixel array. The phase modulation imparted by each pixel in the LCOS array can be controlled by varying the voltage dependent phase retardation. The frequency setting resolution of the programmable filter control of the spectral pulse shaper is < 1 GHz, and the frequency setting accuracy is < +/- 5 GHz. The LCOS pixel array can be programmed along its horizontal axis to introduce a phase modulation across the optical spectrum. Since a linear spectral phase change corresponds to a shift in the temporal position of a pulse, this concept is
used to program the spectral waveshaper to generate a group delay which is equal and opposite to the GDR of the CFBG. This results in a train of temporally stretched pulses that exhibit a ripple free chirp profile.

![Spectral processor schematic](image)

Figure 43. Spectral processor schematic (adapted from [99]).

To investigate the effect of GDR compensation on the performance of a system, a chirped pulse lidar setup (shown in Fig. 44) is considered. A chirped pulse source generates pulses at a repetition rate of 20 MHz with a -3 dB bandwidth of ~ 7 nm centered at ~1554 nm. The optical bandwidth of 7 nm (~ 860 GHz) is sufficient to perform sub-millimeter range resolution. The pulses are directed to a CFBG using a circulator, where they experience a dispersion of 1651 ps/nm, resulting in chirped pulses with temporal durations of ~ 11.5 ns (23% duty cycle). The CFBG also imparts an undesirable noise in the chirp linearity due to its GDR shown in Fig. 42. The pulses are amplified in an erbium doped fiber amplifier (EDFA) where they experience
chirped pulse amplification (CPA) allowing easy generation of high power optical signals while the laser repetition rate of 20 MHz enables measurements with fast update rates.

The optical pulses are directed to a liquid crystal on silicon (LCOS) spectral pulse shaper which can be used to impart spectral amplitude and phase modulation on the optical signal. The optical spectra of the output from the spectral pulse shaper, with and without phase modulation are given in Fig. 44. A 4 dB loss is observed at ~1551 nm and ~1561 nm where the value of GDR is highest. This is due to an undesirable coupling between the phase and amplitude modulation capabilities of the LCOS spectral pulse shaper.

Figure 44. Experimental Setup. MLL, Mode-locked laser; PC, Polarization Controller; CIRC, Circulator; VOD, Variable Optical Delay; EDFA, Erbium Doped Fiber Amplifier; PD, Photodetector; RFSA, Radio Frequency Spectrum Analyzer.
An Erbium doped fiber amplifier (EDFA) is used to amplify the chirped pulses before directing them to a lidar interferometer where a variable optical delay (VOD) in the delay arm is used to simulate a target at a distance. A directional coupler combines the optical signals from the reference and delay arms and an RF beat signal is observed on the RF Spectrum Analyzer after photodetection with photodetector that has a bandwidth of 15 GHz. The VOD in the lidar interferometer is used to introduce path length differences between the pulses in the target and reference arms and the corresponding RF beat frequencies are recorded.

The interference of chirped pulses, with and without GDR can be visualized as is shown in Fig. 46. Due to the undesirable coupling between the amplitude and phase response of the spectral waveshaper, a matlab simulation is repeated using the GDR data and optical spectra given in Fig. 45. The GDR data (supplied by Proximion) was calculated by measuring the group delay with an optical vector analyzer (with a sample resolution of 2.5 pm), performing a polynomial fit and subtracting the raw group delay data from it. The modulation (+/- 3 ps) shown

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**Figure 45.** Output optical spectra from the spectral pulse shaper.
in the inset of Fig. 42 is close to the resolution limit of the measurement system and may be system noise. The simulation is performed by sorting the dispersed spectral components of an optical pulse on a time-axis after dispersion from a CFBG and interpolating the values at a temporal sampling rate of 0.25 ps. When two identical pulses with a small relative delay interfere, the difference in optical frequencies at each temporal location in the region of pulse overlap is calculated. The amplitude of the difference frequency (beat signal) generated at each temporal location is dependent on the amplitudes of the interfering spectral components. This is taken into account in the simulation by using the optical spectra shown in Fig. 45. The simulation code is given in Appendix D.

![Diagram](image)

**Figure 46.** Interference of chirped pulses (a) with GDR, (b) with GDR compensated.

With no GDR compensation, the simulation results are plotted in the form of a histogram with a 20 MHz bin size shown in Fig. 47. It is evident that the GDR plays a detrimental role in the lidar performance by broadening the observed beat signal envelope. This broadening becomes more dominant at larger target distances as the -3 dB width of the beat envelope changes from ~ 165 MHz at 2 mm distance to ~ 0.6 GHz at 18 mm. When GDR values of the CFBG are subtracted from the raw group delay data, it results in a group delay with effectively no ripple, and the corresponding simulated beat signals are given in Fig. 47 (a). It is evident that
the beat signal envelope maintains a narrower width as compared to the results obtained using data with GDR. The -3dB width of the beat signal envelope with GDR compensation at target distances of 2 mm and 18 mm are ~120 MHz and ~170 MHz respectively. Therefore, a slight broadening of the beat signal (and reduction of peak power) is still noticeable. This is because the GDR data is extracted from the raw group delay data by using a polynomial fit so when the GDR data is subtracted from the raw group delay data, a residual noise still remains. More accurate simulation results can be obtained if the GDR data is measured with higher resolution. Moreover, the CFBG is designed to impart a group delay that is linear in the wavelength domain but it does not map linearly in the optical frequency domain resulting in broadening of the beat note envelope. It must be noted that this simulation does not take into account any broadening in the RF frequency domain due to the limited temporal extent of the pulses.

Figure 47. RF beat tone envelopes due to interference of chirped pulses with and without GDR, at various target distances. (a) simulation results (b) experimental results.
The experimentally observed beat signal envelope without GDR compensation, at different target distances is given in Fig. 47 (b). At a target distance of 18 mm, the -3 dB, -10 dB, and -15 dB widths of the RF beat signal envelope are 300 MHz, 720 MHz, and 1040 MHz, respectively. A range resolution of \( R = \frac{300 \text{ MHz}}{500 \text{ MHz/mm}} = 0.6 \text{ mm} \) is observed. The experimentally observed RF beat signal envelopes with GDR compensation are also shown where the -3 dB, -10 dB, and -15 dB widths of the beat signal have been successfully reduced by a factor of \(~2\) to 160 MHz, 360 MHz, and 460 MHz, respectively, indicating a successful compensation of the ripple in the group delay, and an improved range resolution of \( R = \frac{160 \text{ MHz}}{500 \text{ MHz/mm}} = 320 \mu\text{m} \). A signal to noise ratio (SNR) of 20 dB is observed.

### 6.2. Spectral Phase and Amplitude Modulation for Two-fold Improvement in Lidar Range Resolution

As mentioned earlier, the optical spectrum of the chirped pulses originating from the CFBG based chirped pulse source does not have an ideal rectangular shape. In the wavelength to time mapping regime, the shape of the temporal intensity profile of the pulses resembles the shape of the optical spectrum. Thus, fluctuations in the spectral amplitude are mapped on to the temporal intensity profile of the pulses. This undesirable amplitude modulation on the pulses results in a broadening of the observed RF beat frequency envelope. In this section, the spectral waveshaper is used to simultaneously modulate the spectral phase and amplitude of the chirped pulses to improve the lidar performance.

The experimental setup shown in Fig. 44 is used and the experiment is repeated. As mentioned in chapter 2, the CFBG is not polarization maintaining, therefore spectral filtering due to polarization occurs at the polarizer. The polarization controller is used to optimize the shape
and bandwidth of the output optical spectrum from the chirped pulse source. The optical spectra observed at the output of the spectral pulse shaper under different conditions are given in Fig. 49. The optical spectrum without any spectral modulation shows a significant amplitude ripple. This is further worsened by the ~4 dB loss at the wavelengths of ~1551 nm and 1561 nm. To obtain pulses with Gaussian intensity profiles with phase modulation for GDR compensation and minimal amplitude noise, the transmission function of the waveshaper is modified and the optical spectrum (shown in blue) is observed. The FWHM of the optical spectrum of at least 5 nm with an amplitude ripple of < 1dB is achieved.

![Optical Spectra](image)

**Figure 48.** Optical spectra of the output from the spectral waveshaper

The results obtained by using the different configurations of the spectral waveshaper are given in Fig. 49.(a). The -10 dB widths of the beat signal envelopes (with no spectral modulation) are 550 MHz, 750 MHz, and 770 MHz at (one way) target distances of 15 mm, 20
mm and 24 mm respectively. The range resolution at these target distances is calculated to be 380 µm, 660 µm and 540 µm respectively. When spectral phase modulation (for GDR compensation) is applied, the beat envelope widths are reduced to 305 MHz, 430 MHz, and 770 MHz. When both spectral phase and amplitude modulation are applied, the -10 dB beat widths are further reduced to 240 MHz, 350 MHz, and 425 MHz respectively. This is approximately a two-fold reduction in the beat widths. The range resolution at these target distances is calculated to be 284 µm, 360 µm and 350 µm.

![Figure 49. Experimentally observed beat frequency envelopes](image)

On careful observation, it is observed that the power of the beat frequency envelope is reduced when amplitude modulation is applied to the pulses. This is due higher losses at certain wavelengths that are introduced to generate a Gaussian shape using the spectral waveshaper, (as shown in the optical spectra in Fig. 48). Moreover, it is also noticed that the -15 dB widths of the beat signal envelopes experience a slight increase when amplitude modulation is applied.
This may be due to an undesirable coupling between the amplitude and phase shaping capabilities of the spectral waveshaper.

In conclusion, we have demonstrated a spectral phase modulation technique for removing the group delay ripple (< 50 ps) of a chirped fiber Bragg grating directly in the optical domain thus removing the need for electronic post-processing. In our experiment, spectral amplitude modulation was used to create Gaussian shaped pulses. It is also possible to use the spectral pulse shaper to introduce the required attenuation at other wavelengths to create a resultant flat spectral output (or any other shape) from the CFBG, followed by amplification in an EDFA. Simulation results and experimental data are provided to verify the improvement in a chirped pulse lidar system where a two-fold improvement in the range resolution (320 µm) is achieved with 20 dB SNR. The GDR compensation can be improved further by performing a high resolution measurement of the GDR of the CFBG and by using a spectral waveshaper with better frequency setting resolution and accuracy. In addition to this, an iterative feedback algorithm to tailor the spectral phase modulation based on feedback from an optical vector analyzer may also be used to improve GDR compensation and the reduction in the amplitude modulation. The GDR compensation architecture presented in this paper can result in significant performance improvements in various other systems that involve chirped pulses from dispersive elements, such as photonic analog to digital conversion, optical frequency domain reflectometry, serial time encoded amplified imaging, microwave signal analysis, and pulse shaping.
CHAPTER 7: CONCLUSION

This dissertation report presents a brief review of some common chirped pulse sources and their applications, followed by a brief summary of lidar ranging techniques including triangulation, pulsed time of flight, continuous wave, and frequency modulated continuous wave lidar. The performance advantages of using a chirped pulsed lidar over other approaches are discussed and verified by experiments. The salient features of the chirped pulse lidar are summarized below:

- In conventional TOF lidar systems, short pulses of < 6.7 ps duration are required for sub-millimeter range resolution. This limitation is removed in the chirped pulse architecture where temporally stretched pulses of durations in the nanoseconds regime are used to achieve sub-millimeter range resolution.
- Lidar measurements are performed with update rates of 20 MHz.
- The chirped pulse architecture enables amplification of optical signals to high power levels for long-distance ranging with minimal fiber non-linearities.
- Coherent detection at the receiver results in a signal to noise ratio of < 25 dB.
- The optical spectrum of a mode-locked laser consists of many axial modes resulting in an optical bandwidth of hundreds of GHz that is required for sub-millimeter range resolution. Moreover, the narrow linewidths (<3 kHz) of the individual axial modes result in a coherence length on the order of hundreds of kilometers, enabling long distance ranging with coherent detection at the receiver.
- A pulse tagging scheme based on phase modulation is demonstrated to achieve unambiguous range measurements.
• For targets moving at speeds greater than ~23.2 m/s, an oppositely chirped pulse train is employed to demonstrate simultaneous ranging and Doppler velocimetry measurements.
• For targets moving at speeds less than ~23.2 m/s, a velocimetry technique based on the measurement of the change in target position as a function of time is demonstrated.
• A spectral phase modulation technique for removing the group delay ripple (< 50 ps) of a chirped fiber Bragg grating directly in the optical domain is demonstrated.
• A spectral amplitude modulation technique is demonstrated to remove the ripple in the temporal intensity profile of the stretched pulses, resulting in narrower beat frequency envelopes. Gaussian shaped pulses are generated to achieve an improved lidar range resolution of 284 µm.
CHAPTER 8: FUTURE WORK

- A pulsed lidar architecture based on chirped pulses from a mode locked laser has been presented. The lidar system offers several benefits such as the ability to launch high power pulses with minimal non-linearities, fast update rates, long range operation with high range resolution, unambiguous ranging and Doppler velocity measurements. However, for real life applications, it is desirable to have all of the above features simultaneously. Therefore, in the future, it will be useful to investigate the realization of a system that may simultaneously offer a) high resolution b) unambiguous ranging, and c) simultaneous velocimetry and ranging d) group delay ripple compensation and pulse shaping.

- The detrimental effects of the group delay ripple (GDR) of the chirped fiber Bragg grating (CFBG) were confirmed with the help of simulations in chapter 5. The GDR results in a broadening of the beat signal resulting in an undesirable reduction of the range and velocity resolution of the lidar system. An alternative method for generating temporally stretched, frequency chirped pulses is by using dispersion compensating fiber (DCF). Ideally, for high resolution lidar measurements, pulses with a perfectly linear chirp in the optical frequency domain are required. Unfortunately, the DCF contains higher order dispersion terms that cause a deviation from an ideal linear chirp in the pulses. Digital post-processing techniques may be used to compensate for these effects. We believe this may be possible by acquiring the lidar beat signals in the time domain, and resampling them with a modified time base to compensate for higher order dispersion.
terms in the chirped signal. Taking a Fourier transform of such a signal with the modified
time base will result in narrower beat tones in the RF domain, which in turn, will provide
an improvement in range and velocity resolution.

- The criteria that we used for defining the resolution in range and velocity was the FWHM
  of the beat frequency envelope. However, due to imperfections in the dispersion of the
  pulses, the shape of the beat frequency envelope can exhibit an undesirable amplitude
  modulation on it, or it may not be symmetrical, therefore it may be beneficial to calculate
  the ‘center of mass’ of the beat envelope to obtain more accurate results.

- A spectral pulse shaper was used to remove the group delay ripple and the amplitude
  modulation noise from the temporally stretched, frequency chirped pulses. However,
  there is an undesirable coupling between the spectral phase and amplitude response of the
  spectral processor. An iterative algorithm including a feedback loop may be used to
  characterize and optimize the optical spectrum shape and the spectral phase profile of the
  chirped pulses to obtain better lidar performance.

- It may be possible to combine the chirped pulse lidar with other ranging techniques to
  obtain better performance. Techniques such as amplitude modulation, arbitrary waveform
  generation, pseudorandom noise modulation, etc may be incorporated in the existing
  setup to improve the performance of the system.
• The chirped fiber Bragg grating used in the experiments was linearly chirped in wavelength. Unfortunately, this results in a slightly non-linear chirp in the optical frequency domain, resulting in a broadening of the lidar beat frequency envelope. The spectral pulse shaper may be programmed to generate pulses with a linear chirp in optical frequency to improve lidar performance.

• The duty cycle of the stretched pulses was 20%. A mode-locked laser with higher bandwidth, or a CFBG with larger dispersion may be used to stretch the pulses to completely fill the pulse time period. It is also possible to stack two CFBGs in series to get a higher dispersion.

• The generation of chirped pulses with other temporal intensity profiles may be explored. For example, Lorentzian intensity profiles may be used to reduce the -3 dB width of the lidar beat frequency envelope. This is due to the smaller time-bandwidth product of Lorentzian profiles, as compared to Gaussian profiles.

• Finally, it will be useful to test the lidar system in a lidar field test range to gather further insight into lidar performance and areas for improvement for operation in the field. The effect of atmospheric turbulence, heat gradients that effect the refractive index of air, attenuation, and scattering of the lidar signal should be studied in more detail to further propel the presented results towards the realization of a field deployable ranging system.
APPENDIX A: FREQUENCY RESOLVED OPTICAL GATING
Frequency resolved optical gating (FROG) is a technique used for the measurement of ultrashort pulses. It is used to measure the temporal intensity and phase profile of ultrashort pulses. Moreover, the spectral intensity and phase profile of the pulses is also obtained. This technique is superior to conventional SHG autocorrelation measurements which provide only limited temporal intensity information and no phase information [103, 104].

A FROG setup consists of two parts – an experimental optical setup, and an iterative phase-retrieval computer algorithm. A schematic of the FROG setup is given in Fig. 50. It consists of an input pulse train that is split into two beams using a 50/50 beam splitter. One beam is delayed with respect to the other by using two mirrors that are mounted on a motorized stage (Newport picomotor piezo linear actuator) that can be controlled by Labview computer interface.
(Appendix B). The peizo linear actuator allows the stage to be moved in increments of 30 nm. The two beams face three reflections each before becoming parallel to each other as they propagate towards a convex lens of 75 mm focal length. The two converging beams are focused on a BBO (Barium Borate) SHG Crystal of 1 mm thickness. The thickness of the crystal is chosen to ensure strong SHG signal generation (centered at 775 nm), while maintaining phase matching over a reasonably large optical bandwidth. Moreover, the group velocity dispersion caused by the SHG crystal is not sufficiently large to ensure accurate measurement of pulses of picosecond durations [47]. A convex lens of larger focal length may be used to reduce the incident angle of the two beams on the BBO crystal to achieve stronger SHG signal generation. Moreover, a polarizer and half-wave plates (not shown) are used to match the polarization of the interacting beams in the SHG crystal. In addition to this, the BBO crystal axis is aligned with the polarization of the incident signals to optimize the SHG generation. A second convex lens is used to collimate the SHG signal. A fiber coupler is used to direct the SHG signal to an Optical Spectrum Analyzer.

Before acquiring FROG data, the position of the delay stage is matched with the reference arm to get maximum SHG signal generation. The light polarization and BBO crystal axis are also aligned accordingly. Then the delay stage is manually moved backwards until the two beams are not temporally overlapping in the SHG crystal anymore. This delay value is recorded so that the computer Labview code can be used to introduce a total delay stage movement that is at least two times this value. This will be sufficient to accommodate the SHG spectra that are generated as pulses from the two arms slide across each other.
Since the pulses emitted by the Calmar laser have a fairly smooth profile, 128 steps of delay were considered sufficient and the corresponding 128 SHG optical spectra were recorded using the Labview code (Appendix B). Each delay step was 20 fs. The SHG spectra were recorded using 1001 points on the wavelength axis with a step size of 0.01502 nm, a center wavelength of 776 nm and a total span of 15 nm on the y-axis. If the temporal pulse shape and spectral characteristics are not well known, the FROG data may be acquired using a smaller delay step size with higher resolution on the optical spectrum analyzer. The individually recorded spectrum files are combined into one file in a format compatible with the FROG software by using the matlab code given in Appendix C.

A FROG software available from Femtosecond Technologies is used to process the FROG data to obtain the pulse characteristics. The FROG software uses a variety of different computational approaches to converge to an acceptable solution. The method of projections was observed to be very effective in SHG-FROG in particular. It uses the fact that the envelope of the SHG-FROG signal field can be represented by as \( E_{\text{sig}}(t,\tau) = E(t) E(t-\tau) \), where \( E(t) \) is the complex envelope of the pulse to be measured and \( \tau \) is the delay between the two beams. This is referred to as constraint 2 for the FROG Algorithm. Moreover, the intensity observed on the optical spectrum analyzer that yields the FROG trace is \( I_{\text{FROG}}(\omega,\tau) = |E_{\text{sig}}(\omega,\tau)|^2 \), referred to as constraint 1.

The FROG algorithm is based on using a trial solution for the Electric field, \( E_{\text{sig}}(t) \). The signal field \( E(t,\tau) \) is calculated from the trial field using the constraint 2, and its Fourier transform is taken to obtain the signal in the frequency domain, \( E_{\text{sig}}(\omega,\tau) \). The squared magnitude
of this field generates the FROG trace of the trial field \( E(t) \). The magnitude of this signal is constrained by replacing it with the magnitude of the experimentally observed FROG trace while the phase is left unchanged resulting in a signal \( E_{\text{sig}}(\omega, \tau) \). This forms the projection onto the set of signal fields that satisfy constraint 1. Taking the inverse Fourier Transform reveals a signal in the time domain \( E_{\text{sig}}(t, \tau) \). The method of projections is used to generate a new Electric field \( E(t) \) from \( E_{\text{sig}}(t, \tau) \). This is done by calculating a signal field that satisfies constraint 2 and but is as close as possible to \( E_{\text{sig}}(t, \tau) \). This algorithm is explained in detail in [47].

Figure 51. Block diagram of FROG algorithm (adapted from [47])
APPENDIX B: LABVIEW CODE FOR FROG DATA ACQUISITION
Figure 52. Block diagram of Labview code for FROG data acquisition
APPENDIX C: MATLAB CODE FOR COMBINING OSA TRACES
clear all;

close all;

NumDataLines = 1001; %for example

ColNum = 2; %for example

for n = 1 : 1 : 256
    number = num2str(n);
    file = strcat('OSA_Labview_',number,'.txt')
    fmt = [ repmat('%*s ',1,ColNum-1), '%f %[^n]'
    fid = fopen(file, 'rt');

    data = textscan(fid, fmt, NumDataLines)
    Ex(:,n) = data;
    fclose(fid);
end

Ex;
for n = 1:1:256

    C(n,:) = [10.^(Ex{1,n})/10];

end

dlmwrite('C:\Users\Administrator\Desktop\FROG\DATA.txt',C,'delimiter','\t','newline','\pc')
APPENDIX D: MATLAB CODE FOR LIDAR SIMULATION
close all; clear all;

load Ripple.txt;

y = Ripple(:,1);

timeduration=10e-6

x=linspace(0,timeduration,length(y));  % this generates a vector which % has number of points = length of y, starting from 0, ending at % value of time duration

%figure(1);

dt = x(2) - x(1);

ff = linspace(-1/dt/2,1/dt/2,length(x));

FT2 = (fft(y));

FT3 = fftshift(FT2);

%j = 20*log10(abs(FT3));  % Log plot

%plot(ff,j);

k=0;
FT4 = FT3;

bah = size(FT3);

for i = (round(((bah(1,1))/2)+1*(bah(1,1)/2)):1:bah(1,1))
    FT4(i,1) = 0;
    k = k+1;
end

for i = 1:1:k
    FT4(i,1) = 0;
end

%figure (3);
%j = 20*log10(abs(FT4));
%plot(ff,j);
figure(4);

FT5 = fftshift(FT4);

FT6 = ifft(FT5);

plot (x,y, x, FT6, 'linewidth', 2) % green is the filtered wave

%axis([0 10^-8 -50 50])

load Rippledispersion.txt;

z = Rippledispersion(:,1);

load Ripplelambda.txt;

w = Ripplelambda(:,1);

%figure(5);

t = z - FT6;  % final times (ps)

%plot(w,t);

%dllmwrite('C:\Users\Administrator\Desktop\Data\RFSA Aquisition
%code\DATA.txt','C','delimiter','	','newline','pc')
% loading data from individual files (with no text inside them just
% numbers)

load t1.txt
OSAlambda = t1(:,1);  % t1 & t2 make the optical spectrum of the signal coming out of the
Finisar wavehaper in dB??

load t2.txt
OSApower = t2(:,1);

figure(3);

plot(OSAlambda, OSApower);

GDRlambda = real(w);  % t3 and t4 are fixed specs (redport) of the "CFBG-1" that I used
GDRtimeline = real(t);

yi = interp1(OSAlambda,OSApower,GDRlambda);  % finds power at each lambda in timeline
info(:,1) = [GDRtimeline];

info(:,2) = [(299792458000)./(GDRlambda)];  %Opt. Freq in MHz

info(:,3) = [yi];

% The five lines below are the user inputs

DELAY = 145; %in (relative delay between two pulses in ps). 100ps = 15mm one way
distance in air = 7500MHz

SpanStart = DELAY*0.15*500 - 1000 %MHz

SpanEnd = DELAY*0.15*500 + 1000 %MHz

StepSize = 20; %MHz ~75MHz means 1ps relative delay between %pulses; ~15MHz step size would work best with 15/75 = ~0.2ps

RES = StepSize/80;  %ps %I've rounded off 75MHZ to 80MHz

newtimeline = 31681:-RES:-27988; %in ps

newtimeline = newtimeline';
OP = interp1(GDRtimeline,info(:,3),newtimeline); %finds power at each point in the timeline

OF = interp1(GDRtimeline,info(:,2),newtimeline); %finds Opt. Freq at each point in the timeline

finalinfo(:,1) = newtimeline;

finalinfo(:,2) = OF; %Optical Freq.

finalinfo(:,3) = 10.^(OP./10); %converting Power from dB to linear

s = size(finalinfo)

nofdatapoints = s(1,1)

beat = zeros(nofdatapoints,2);

for i = 1:1:nofdatapoints-(round(DELAY/RES)) (%nofdatapoints-delay)
    j = i+(round(DELAY/RES));

    beat(i,1) = +finalinfo(i,2) - finalinfo(j,2); %saves beat frequencies in a column

    beat(i,2) = 2.* ((finalinfo(i,3) .* finalinfo(j,3)).^0.5); %saves beat powers in a column
end

min = SpanStart;

max = SpanStart + StepSize;

bin1(:,1) = SpanStart:StepSize:SpanEnd;  % a freq span

bin2 = zeros(((SpanEnd-SpanStart)/StepSize)+1,1);  % This is the total number of bins

for l = 1:1:((SpanEnd-SpanStart)/StepSize) % this is the loop that is incrementing the bin value

    for k = 1:1:nofdatapoints-(round(DELAY/RES))

        if min < beat(k,1)

            if beat(k,1)< max

                bin2(l,1)= bin2(l,1) + beat(k,2);

            end

        end

    end

end

end

min = min + StepSize;

max = max + StepSize;
end

figure(6)

[val, xout] = hist(beat(:,1),([SpanEnd - SpanStart]/StepSize));

subplot(2,1,1), plot(bin1,20*log10(bin2))

axis([SpanStart - 1000 SpanEnd+1000 -30 50])

subplot(2,1,2), plot(xout,20*log10(val))  \% bar  \% Simple histogram that does not take OSA Amplitude into account

axis([SpanStart-1000 SpanEnd+1000 20 100])
REFERENCES


