Scaling the spectral beam combining channels in a multiplexed volume Bragg grating

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Abstract: In order to generate high power laser radiation it is often necessary to combine multiple lasers into a single beam. The recent advances in high power spectral beam combining using multiplexed volume Bragg gratings recorded in photo-thermo-refractive glass are presented. The focus is on using multiple gratings recorded within the same volume to lower the complexity of the combining system. Combining of 420 W with 96% efficiency using a monolithic, multiplexed double grating recorded in PTR glass is demonstrated. A multiplexed quadruple grating that maintains high efficiency and good beam quality is demonstrated to pave a way for further scaling of combining channels.

OCIS codes: (140.3298) Laser beam combining; (050.7330) Volume gratings.

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1. Introduction

Continuous wave near infrared fiber laser sources are commercially available with power levels of many kilowatts. Scaling fiber laser systems beyond these power levels is limited by thermal and nonlinear effects. There has been much interest in the use of spectral beam combining (SBC) and coherent beam combining (CBC) to combine multiple high power laser beams into a single high power beam to bypass these limitations and create a compact high-power laser system with a narrow spectral linewidth and good beam quality [1]. In CBC, several lasers of the same wavelength are spatially combined such that all the lasers are locked in phase. In SBC, multiple channels of different wavelengths are superimposed spatially using a dispersive element such as a volume Bragg grating [2, 3]. The primary advantage of SBC over CBC is the reduced complexity since the phase of the individual beams does not need to be monitored or controlled. The disadvantage of SBC is that the spectrum of the combined beam is broadened with respect to the individual input beams. To overcome this disadvantage, it is necessary to use very narrow spectrally selective beam combining devices to produce an output beam with minimum spectral bandwidth. The development of a five-channel SBC system using four single reflective Bragg gratings (RBGs) was recently reported which realizes these conditions [4]. The system had channel separation of 0.25 nm between adjacent wavelengths with a total combined power of 0.75 kW within a 1 nm spectral range and an M^2 of 1.6. This extremely high power-spectral density (0.75 kW/nm) combining was accomplished with >90% combining efficiency due to the ability of PTR VBGs to diffract light into a single order with high efficiency within a narrow spectral band. To achieve these results a thermal tuning scheme was implemented to control the resonant condition of each grating and to manage thermal distortions. Scaling such a system to a larger number of combining channels will also scale the complexity of the thermal control system. The goal of the current work is to demonstrate recent advances that have been made towards realizing this system using a single diffractive optical element. This will allow us to achieve a combining system with lower complexity and better robustness due to fewer components for alignment and fewer thermal controls. While similar work in wavelength division demultiplexing for optical telecommunications has been shown using multiple superimposed RBGs [5], this paper presents the first experimental demonstration of SBC using a multiplexed volume Bragg grating at high power levels of hundreds of Watts.

The recording medium for the diffractive optics used in these experiments is a Na_2O-ZnO-Al_2O_3-SiO_2 glass doped with silver, cerium, and fluorine called photo-thermo-refractive (PTR) glass. PTR glass is a photosensitive material for high optical quality, low loss phase hologram recording. It is well suited to applications in high power laser systems due to the low absorption losses and high damage threshold, making it an excellent material for use in high power SBC experiments. Refractive index change is induced by a multi-step process as described in [6]. The first step is the exposure of the glass sample to UV radiation in the range of 280 nm to 350 nm. This exposure results in photo-reduction of silver ions Ag^+ to atomic state Ag^0. This stage is similar to the formation of a latent image in a conventional photo film and no significant changes in the optical properties of the PTR glass occur. The next step in the process is a thermal development. A number of silver containing clusters arise in the exposed regions of the glass after aging at elevated temperatures, due to increased mobility of Ag^0 atoms. These silver containing clusters serve as the nucleation centers for NaF nanocrystal precipitation inside of the glass matrix. Interaction of those nanocrystals with the surrounding glass matrix causes a localized decrease of refractive index. Refractive index change (Δn) of about 10^{-3} (1000 ppm) can be achieved using this process.

Photo-exposure of PTR to an interference pattern results in the recording of a periodic refractive index modulation which can be used as a volume phase grating. Reflecting Bragg gratings recorded in this fashion can be designed and characterized using Kogelnik's coupled wave theory [7]. When designed for SBC, RBGs recorded in PTR glass reflect light within a narrow spectral bandwidth (on the order of 100 pm) with efficiency >99%. SBC is achieved by designing the resonant wavelength of reflection for each grating such that it will reflect only a single laser channel and transmit all other laser channels. In this way a cascade of RBGs is able to insert individual laser channels into the combined beam as shown in [4].

2. Three channel high power beam combining

To achieve beam combining with a single diffractive element, it is necessary to multiplex several mutually aligned RBGs within the same glass volume such that each laser channel is properly redirected into a single, common output. The first step towards this goal was to record two RBGs in a PTR glass plate and prove that the high power beam combining results achieved with multiple individual gratings can be transitioned into a single, multiplexed grating. The geometry for combining with a double grating is shown in Fig. 1. This device

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combines two channels reflected from the multiplexed RBG and a third out of resonance channel transmitted though the device.

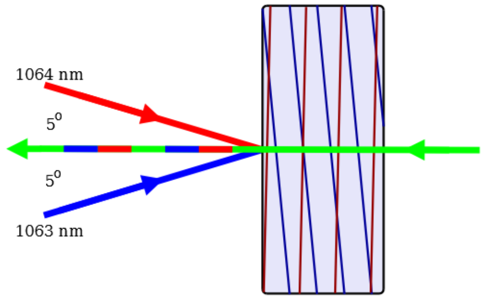

Fig. 1. Schematic of three beam combining by means of a 2x RBG where two beams are diffracted while a third out of resonance beam is transmitted.

The 2x RBG was designed for two lasers with central wavelengths of 1064.86 nm and 1063.54 nm, and each having a 200 pm tuning range. The grating was designed such that each laser beam is incident at 5° in air with respect to the surface normal and is reflected parallel to the surface normal. The difference between Bragg wavelengths of the two gratings was required to be accurate within the tuning range of the lasers (± 100 pm) at the Bragg angle of 5°. Fine spectral tuning of gratings was produced by temperature control with a thermo-electric cooler (TEC). For RBGs in PTR glass with resonant wavelengths in the vicinity of 1 μm, the resonant wavelength changes with heating at a rate of 10 pm/K [8].

In spectral beam combining, the diffraction efficiency of each individual grating relative to others is not a critical design parameter because each grating is designed for a different resonant wavelength and there is no degeneracy between gratings. Therefore, the goal was to generate gratings with efficiency >99%. Any inequality of grating efficiency beyond this would only result in a widening of the reflection bandwidth by tens of picometers. Since the spacing of the wavelength channels is >1 nm, this level of widening is insignificant.

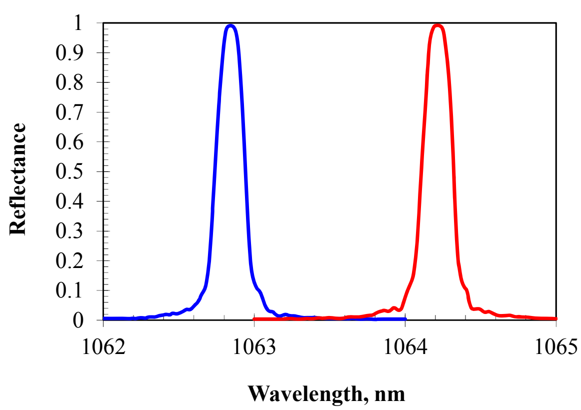

Fig. 2. The reflection spectra of the two individual gratings of a 2x RBG. Measurement is produced by probing with a low power tunable laser along the combining arm (central arrow in Fig. 1) and power meters placed in input arms (top and bottom arrows in Fig. 1). Efficiency of each grating is >99% with bandwidth (FWHM) of 215 pm ± 10 pm.

The multiplexed RBG was produced with a thickness of 5.5 mm and aperture of 8.5 mm x 25 mm. The resonant wavelengths are 1062.91 nm and 1064.14 nm and each individual grating has a refractive index modulation of 230 ppm. The multiplexed RBG for these experiments was tested by probing with a low power tunable laser illuminating the grating along the combined arm depicted in Fig. 1 as the central arrow. The power of the transmitted

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light and the light reflected into each of the input arms of Fig. 1 (top and bottom arrows) were measured as the wavelength was swept through the range of interest. The reflection spectra of both combining channels of the device are shown in Fig. 2. Both gratings recorded in the same volume of PTR glass can be excited by the same laser beam and they have high diffraction efficiency while their spectra do not overlap. This feature enables efficient redirection of input beams and prevents leakage between the channels. Such a device works as a wavelength division multiplexer if illuminated along the top and bottom arrows in Fig. 1 or as a demultiplexer if illuminated along the central arrow in Fig. 1.

An important design requirement for high power beam combining is achieving low absorption in the combining element. While PTR glass has extremely low absorption in the near infrared, even absorption of a fraction of a percent of 100 W can lead to significant heating of the element. This heating causes distortions of the combined beam and results in an increased M^2 typically due to thermal focusing of the combined beam [9]. This can be mitigated by recording devices with very low absorption and controlled in the final system by using the aforementioned TEC to maintain a constant temperature. The level of allowable absorption losses was required to be <0.1% through the entire device. This requirement was based on previous experience with SBC using single PTR RBGs. The measured attenuation, resulting from internal absorption through the thickness of 5.5 mm, is 0.05% yielding an absorption coefficient of 4×10^{-4} using a base 10 logarithm. This low level of absorption means that thermal load is minimal and the combining efficiency is not negatively impacted by losses. The combination of high reflection efficiency and low losses of this multiplexed grating make it well suited for high power beam combining.

After characterization at low power, the 2x RBG was mounted in a copper housing and connected to a TEC in Fig. 3 for use as a combiner at power levels of several hundreds of Watts. The beam quality of the input lasers was characterized using a commercially available M^2 meter. The two lasers that were used to reflect off of the 2x RBG had M^2 of 1.05 along both axes and the third laser used for transmission through combiner had M^2 of 1.13 in the x direction and 1.16 in the y direction. The x direction is shown in Fig. 3 and corresponds to the plane of reflection by the RBG.

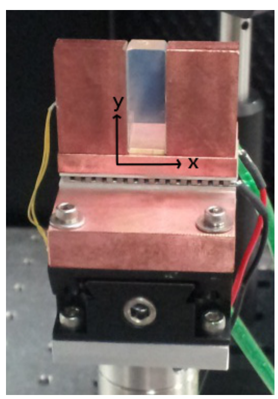

Fig. 3. The housing for thermally controlling the multiplexed RBG during high power beam combining experiments.

The first experiment was done in a reflection only geometry without any laser being transmitted through the combiner. The total combined power was 282 W out of a total incident power of 285 W, giving a 99% combining efficiency. The beam quality was preserved with an M^2 of the combined beam being 1.15 in the x direction and 1.08 in the y direction. Throughout the experiment, the 2x RBG was kept at a constant temperature using the TEC. Just as heating of the RBG can be used to tune the resonant wavelength to a desired value, unwanted heating due to absorption of the high power radiation will cause the grating period to change and go out of resonance, destroying the combining. At the power levels considered in this combining configuration, no heating was observed and the TEC did not need to be adjusted to keep the RBG in resonance.

Next, the transmitted laser emitting at 1063.3 nm was added to the setup to demonstrate combining of three channels as depicted in Fig. 1. The wavelength of this laser was chosen to be out of resonance with both of the multiplexed gratings. This three channel setup gave a total combined power of 420 W out of 438 W for a combining efficiency of 96%. Heating of the grating due to the introduction of the third laser was observed and required that the TEC be adjusted by 8 K in order to bring the grating back into resonance. A slight degradation of the combined beam quality compared to the incident beam quality was observed due to this heating. The M^2 was measured to be 1.38 in the *x* direction and 1.20 in the *y* direction. The beam size was 3-4 mm, making these results particularly significant in that the grating was able to produce such beam quality while handling power densities on the order of several thousand Watts per square centimeter. A summary of these results is compiled in Table 1.

Table 1. Summary of beam combining results at high power

	Power, W	Combining Efficiency	M^2,x	M^2,y
Incident Beam 1	135	-	1.05	1.05
Incident Beam 2	150	-	1.05	1.05
Incident Beam 3	143	-	1.13	1.16
Beam 1 and 2 Combined	282	99%	1.15	1.08
All Beams Combined	420	96%	1.38	1.20

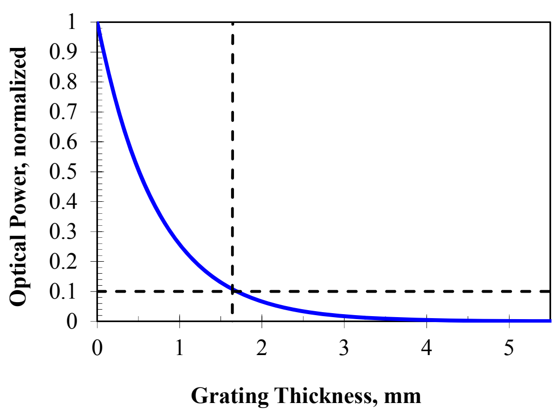

Fig. 4. Distribution of power inside of a volume reflecting grating along direction of beam propagation. The 5.5-mm-thick grating with 230 ppm refractive index modulation is designed to produce a reflectance of 99.8% at 1064 nm. This simulation shows that 90% of the power is localized within the first quarter of the grating.

In order to understand why the addition of the transmitted beam causes such significant heating, it is necessary to discuss the mechanism of reflection by a volume reflecting grating. Following [10], the power distribution throughout the thickness of a reflecting grating at Bragg resonance was calculated for the gratings used in these experiments as shown in Fig. 4. The distribution includes the contributions of both forward and back propagating modes for the grating and was normalized to the maximum power occurring at the incident face. It is clear that 90% of the optical power only encounters the first quarter of the grating. The conclusion that can be drawn is that the effective optical path of the reflected beams is much less than the thickness of a grating with high diffraction efficiency. This means that total absorption of a beam reflected by a volume Bragg grating is less than the value predicted by the absorption coefficient and thickness of the optical element. For a highly transparent PTR glass, the power density of a transmitted beam is evenly distributed in the volume of the grating. Therefore, a transmitted beam contributes much more significantly to the heating of the device. This result is significant for beam combining experiments because it demonstrates that implementing a reflection-only geometry is more desirable for heat management and results in an improved combined beam quality. Therefore the use of a single multiplexed VBG for beam combining, not only reduces the number of thermal controls that were used in [9], but it also provides a combining geometry that inherently produces fewer thermal degradations. The difference in volume occupied by the transmitted and reflected beams also provides an explanation for the degradation of M^2 when the transmitting beam is introduced. The increase in M^2 can be due to the introduction of aberrations such as defocus. The reflected and transmitted beams occupy different volumes of this thermal lens and experience different levels of defocus. While defocus alone does not increase M^2 of a single beam, combining beams with different levels of divergence results in an increase of M^2 in the output [4]. Simple divergence mismatch can be compensated for by adjusting the incident beam defocus to counteract the thermal lens. Further detriment to beam quality occurs from higher order aberrations which will affect the M^2 of single beams interacting with the heated VBG. Such effects have been quantified in [11]. At much higher optical power densities, or for VBGs with higher levels of absorption, the analysis of thermal effects from transmitted and reflected beams requires more in depth analysis techniques [12]. At such levels, the reflecting beam can introduce chirp of the grating period which produces a nonlinear degradation to the spectral response of a VBG. In the current work the product of $\alpha_{abs}I_0$ is <5W/cm^3 and is many times below the power limits discussed in [12]. When considering much higher $\alpha_{abs}I_0$ products, introducing a transmitted beam instead of a reflected may be useful in avoiding the onset of these nonlinear thermal effects.

3. Scaling the number of multiplexed gratings

With successful demonstration of beam combining using a 2x multiplexed grating at high power levels, the next step is to demonstrate scalability of such a system. A new multiplexed grating was designed to combine four laser channels in a reflection geometry. The device and design angles are shown in Fig. 5. The device which was recorded had a thickness of 6.5 mm and aperture of 25 mm x 6.5 mm. The refractive index modulation of each individual grating is 130 ppm ± 15 ppm. The performance was tested by probing the common arm of Fig. 5 with a low power (1.5 mW) tunable laser and measuring the splitting efficiency in each of the input arms of Fig. 5. The relative diffraction efficiency spectra of each grating are shown in Fig. 6. This characterization shows that scaling of the number of multiplexed gratings recorded in PTR glass to four can occur while maintaining high efficiency.

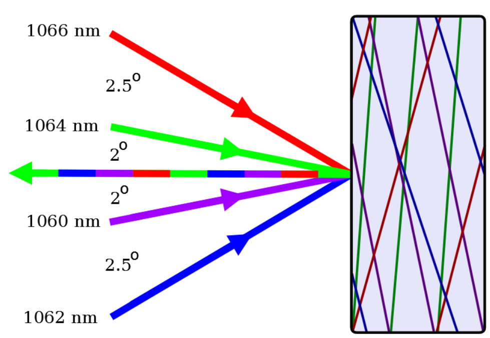

Fig. 5. A 4x multiplexed reflecting grating for spectral beam combining of four laser channels with wavelength separation of 2 nm.

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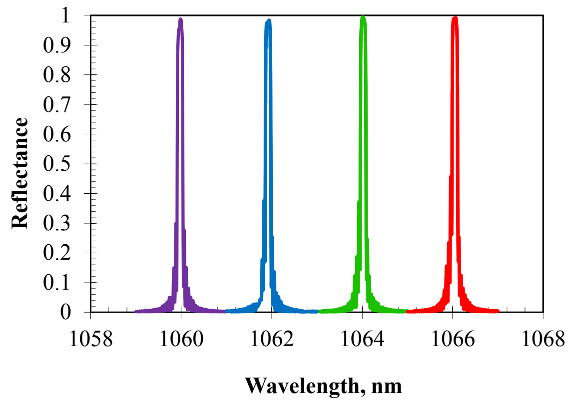

Fig. 6. The reflection spectra of the 4x multiplexed volume reflecting Bragg grating with thickness of 6.5 mm. Measurement is obtained by illumination by a tunable laser source along the direction of the central arrow in Fig. 5 and power meters placed in input arms (arrows marked with wavelengths in Fig. 5).

The quality of beams reflected from the 4x multiplexed RBG was characterized by M^2 measurements at low power to demonstrate that there are no inherent deformations being caused by increasing the number of gratings within the PTR glass sample. Using the same testing configuration that was used to measure the reflectance spectrum, the M^2 of each of the reflected beams was measured as the wavelength of the incident beam in the common arm was tuned to each of the reflection peaks shown in Fig. 6. The results are summarized in Table 2. Again, the x axis in these results refers to the plane of reflection from the RBG. No degradation of the beam quality is observed after reflection from the 4x RBG. These results show that homogeneity of the grating and subsequently the reflected beam quality is preserved in a multiplexed grating with an increased number of combining channels.

Table 2. M^2 of beams reflected from a 4x RBG

	Wavelength, nm	M^2, x	M^2, y
Incident Beam	1060-1066	1.13	1.20
Reflection from	1060	1.10	1.19
Multiplexed	1062	1.12	1.19
RBG	1064	1.07	1.22
	1066	1.10	1.23

From these low power tests, the scalability of multiplexed volume Bragg gratings recorded in PTR glass for applications in beam combining has been verified. Combined with results of high power combining with a 2x multiplexed grating, the pathway to combining more laser systems to achieve higher power beam combining with high efficiency is established.

4. Conclusions

The use of multiplexed reflecting Bragg gratings recorded in a single piece of photo-thermo-refractive glass for spectral beam combining is successfully demonstrated. A 5.5 mm thick double grating with channel separation of 1.3 nm produced diffraction efficiency exceeding 99% for each individual grating and high quality of diffracted beams exhibiting diffraction limited divergence (M^2 = 1.05). This monolithic device combined two beams with total power of 280 W and combining efficiency of 99% and three beams with total power of 420 W and combining efficiency of 96%. In this high power beam combining demonstration, the

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reflected and transmitted beams produced different thermal distortion effects due to the non-uniform distribution of optical power within the grating volume for a reflected beam. The use of a reflection only combining setup produces fewer thermal distortions resulting in more efficient high power beam combining and improved beam quality. A 4x multiplexed monolithic grating of thickness 6.5 mm was shown to maintain high efficiency exceeding 98% and caused no degradation of the incident beam's M^2 value. These positive results pave a way for further power scaling with spectral beam combining using volume Bragg gratings recorded in PTR glass.

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