Multiplexed Volume Bragg Gratings for Spectral Beam Combining of High Power Fiber Lasers

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ABSTRACT

The recent development of kW fiber laser sources makes the concept of laser systems operating at power levels from tens of kilowatts up to 100-kilowatt levels a reality. The use of volume Bragg gratings for spectral beam combining is one approach to achieve that goal. To make such systems compact, lower the complexity and minimize the induced thermal distortions we propose and demonstrate the use of special volume Bragg elements which have several Bragg gratings written inside as combining optical components. The multiplexed volume Bragg gratings (MVBGs) were recorded in photo-thermo refractive glass and three beams with total power of 420 W were successfully combined using one MVBG. The combining efficiency was 97% and there was no significant beam quality degradation. The results demonstrated that the approach of using multiplexed volume Bragg gratings for spectral beam combining is an excellent extension to the current state of the art combining techniques. Especially valuable is the capability to reduce the number of optical elements in the system and while being able to manage the expected thermal load when kilowatt level sources are used for beam combining.

Key Words: Spectral Beam Combining, Volume Bragg Gratings, Multiplexed Volume Bragg Gratings, High Power, Fiber Lasers

1. INTRODUCTOIN

Compact high-power lasers with good beam quality and narrow line-widths are desired for a great number of applications. Today, 1 μm ytterbium-doped LMA fiber laser sources with several kilowatts of CW power in both single and multi-mode regimes are commercially available. However, further scaling to higher power levels is fundamentally limited due to the onset of thermal and nonlinear effects in the fiber. Spectral beam combining (SBC) and coherent beam combining (CBC) are the two major complimentary methods of beam combining in the effort to reach multi-kilowatt diffraction limited beams. In spectral beam combining, outputs from an array of sources operating at different wavelengths are superimposed spatially by means of filters or dispersive elements to form a beam with combined power. Spectral beam combining is commonly implemented using either surface diffraction gratings or volume Bragg gratings (VBGs) [1, 2]. VBGs have the advantage of being modular and can be easily scaled when high channel numbers are desired. The focus of the research presented in this paper is on spectral beam combining by volume Bragg gratings recorded in photo-thermo-refractive glass.

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2. VOLUME BRAGG GRATINGS IN PHOTO-THERMO-REFRACTIVE GLASS

Photo-thermo-refractive (PTR) glass is a relatively new photosensitive material for phase hologram recording. It combines high sensitivity achieved due to two-step process and high optical quality resulting from extensive experience accumulated in optical glass technology. PTR glass is a Na_2O-ZnO-Al_2O_3-SiO_2 glass doped with silver (Ag), cerium (Ce), and fluorine (F). It is transparent from 350 nm to 2500 nm. The chain of processes, which occurs in these glasses and produces refractive index variation, is as follows[3]. The first step is the exposure of the glass sample to UV radiation, somewhere in the range from 280 nm to 350 nm. A number of commercially available lasers with a long length of coherence can be used for such exposure. 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 at it. 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 crystal growth. Interaction of those nanocrystals with the surrounding glass matrix causes the decrease of refractive index. Refractive index change Δn about 10^{-3} (1000 ppm) can be achieved using the above described process.

Reflecting VBGs in photo-thermo-refractive (PTR) glass are simple holograms with planar surfaces of periodic refractive index modulation, recorded by interference of collimated laser beams. Their design and operation are based on Kogelnik's coupled wave theory in thick holograms [4]. A complete theoretical model for VBGs based on Kogelnik's coupled wave theory has been developed and applied to grating recorded in PTR [5, 6].

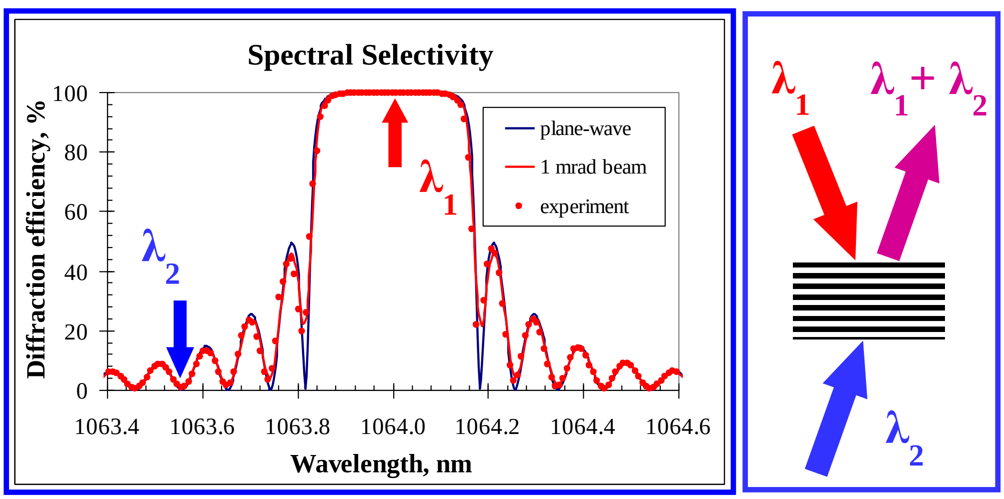

Figure 1: Spectral beam combining by a reflecting VBG (right) which has a central maximum and a series of zeros in diffraction efficiency spectrum (left)

Reflecting Bragg gratings used in a beam combining system are frequency (or wavelength) selective filters. They are not angularly dispersive, but reflect a beam at some angle for only a narrow range of wavelengths. This eliminates the added beam dispersion usually associated with SBC by surface gratings. The properties of these gratings, such as reflection spectrum bandwidth, angle, and wavelength, can be tailored to fit the desired system. Diffraction efficiency of VBGs close to 100% has been demonstrated [7-9]. When using VBGs for spectral beam combining, it is important to ensure high diffraction efficiency for the diffracted beam and low diffraction efficiency for the transmitted beams simultaneously. Figure 1 illustrates this concept for the reflecting configuration.

3. REFLECTING VBGS FOR HIGH POWER SPECTRAL BEAM COMBINING

At the SPIE Photonics West conference in 2011, we reported the development of a five-channel SBC system using reflective VBGs [10]. 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. Figure 2 shows the design of the setup. To effectively combine high power beams with such a narrow spectral separation, very precise control of the VBG resonant wavelength had to be implemented. The most common method of tuning the resonant wavelength is by angular tuning of the VBG. However, due to the narrow angular selectivity of the VBG, mechanical tuning becomes a challenge and is impractical at high output powers.

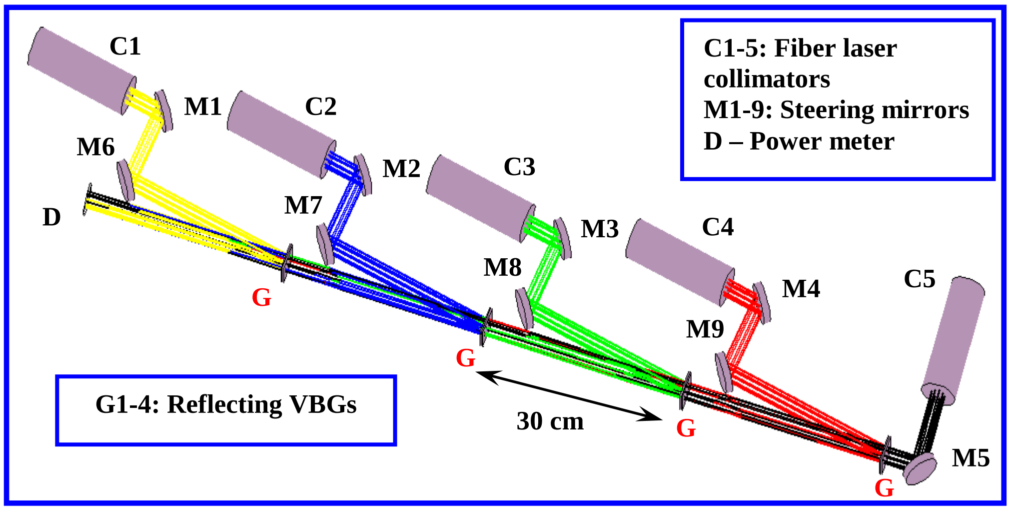

Figure 2: 5-channel spectral beam combining scheme implemented by using reflecting VBGs

We developed a thermal tuning technique for maintaining high efficiency of beam combining throughout the power range of the system (Fig. 3). By changing the temperature of the VBG, the glass expands or contracts, changing the period of the VBG and hence the resonant Bragg wavelength. This thermal method of tuning the resonant wavelength has much greater resolution than angle tuning and, once implemented, could be controlled electronically via thermo-electric coolers (TECs). With this tuning method, we were able to maintain peak combining efficiency of the system from low to peak power operation without mechanical realignment. As a result using thermal tuning and precise alignment, we successfully achieved beam quality M^2 of the combined beam of 1.6 for 5 channels and total combined power of approximately 755 W.

To make systems such as the one just described compact, lower their complexity and minimize the induced thermal distortions, we propose the use of special volume Bragg elements which have several Bragg gratings written inside as combining optical components. The properties of the PTR glass allow the recording of several VBGs in a single piece and therefore the complexity of the setup could be decreased proportional to the number of gratings recorded together. In the next section, we will describe and show the schematics of such a simplified beam combining system.

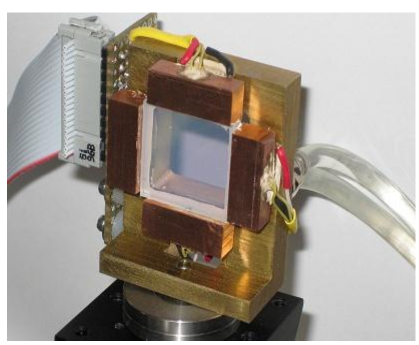

Figure 3: Thermal VBG tuning implementation

4. SPECTRAL BEAM COMBINING ARCHITECHTURE USING MULTIPLEXED VOLUME BRAGG GRATINGS

Figure 4 shows a spectral beam combining system capable of combining 5 laser beams which uses one PTR optical element containing 4 volume Bragg gratings. This system is fully analogous to the one described in the previous section but with the benefit of being more compact and simpler to align.

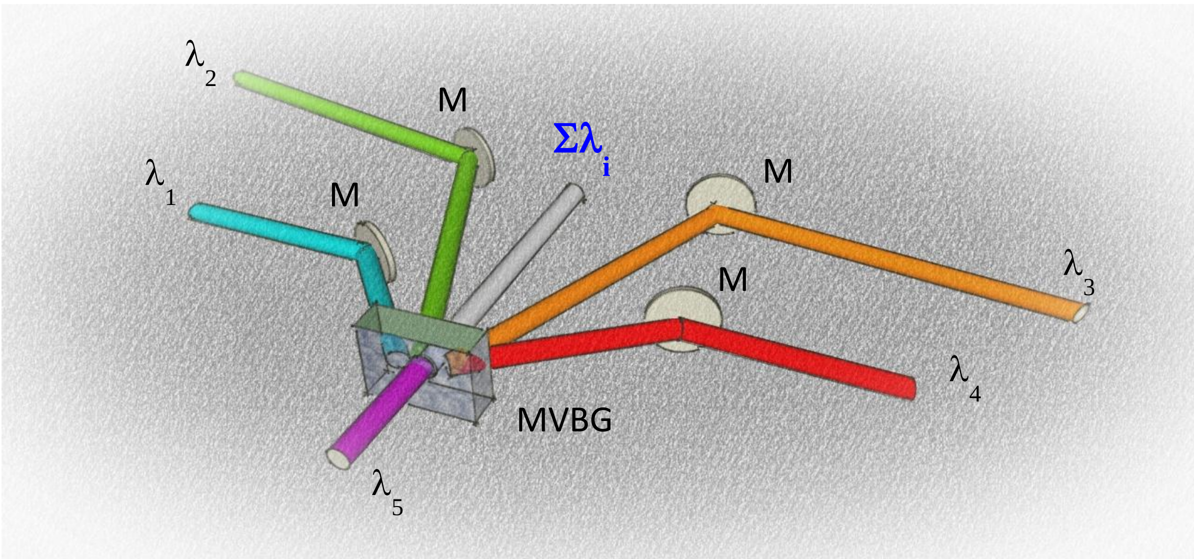

Figure 4: 5-channel spectral beam combining scheme implemented by using a single reflecting MVBG

To show the feasibility of this approach, we first designed and fabricated a double-multiplexed VBG, which can combine up to three beams as shown in Figure 5. Further development will scale the system to include more channels as depicted in Figure 4.

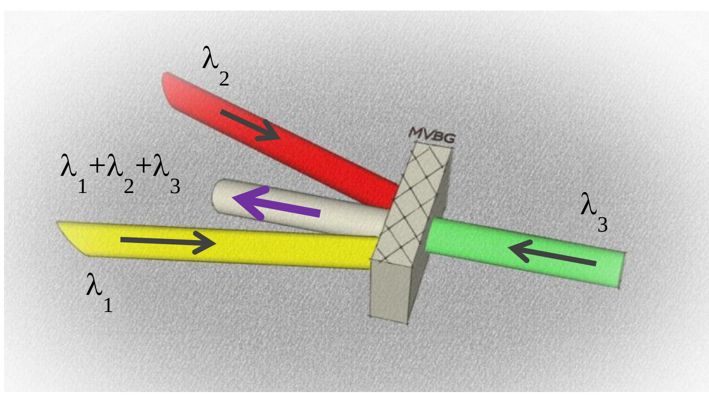

Figure 5: 3-channel spectral beam combining scheme implemented by using a single reflecting MVBG

5. HIGH POWER SPECTRAL BEAM COMBINING OF FIBER LASERS USING MBVG

The first experiments were done by combining two low-power fiber lasers using a double MVBG. Both laser beams were reflected by the volume gratings inside the PTR glass and correspond to λ_1 and λ_2 as shown in Figure 5. The initial beam quality parameter M^2 for both lasers was 1.05 and after the spectral combining, the M^2 of the output beam was 1.07. This promising result allowed us to move towards the design and fabrication of a double MVBG suitable for use at power levels on the order of hundreds of Watts. Such an optical element required high-optical quality glass that will introduce no beam distortions and has very low absorption coefficient. Using the already well-developed PTR glass technology, several MVBGs were recorded with suitable high-power parameters. Figure 6 shows the diffraction efficiency spectrum of a high-power double MVBG recorded in PTR glass used in the experiments described below. The two volume gratings had resonance frequencies approximately 1.4 nm apart and had spectral widths of about 200 pm. Their diffraction efficiency was 99% and matched well the initial design. We also performed a full efficiency characterization for each of gratings across their working aperture. The uniformity for aperture size of 13 x 17 mm was within 1%, which together with the measured absorption of 2×10^{-4} cm^{-1} made these gratings suitable for high power spectral beam combining.

The first experiments were done in "reflection only" configuration where two beams 3 - 4 mm in size (see Fig. 5 - λ_1 and λ_2) were reflected by the corresponding VBG. A total combined power of 282 W was achieved with combining efficiency of 99%. The M^2 of the combined beam was measured to be 1.15 in the 'X' and 1.08 in the 'Y' direction, which did not deviate substantially from the lasers' original M^2 of 1.05 for both lasers in each direction. Throughout the experiment, the MVBG was kept at a constant temperature using a thermo-electric element and copper housing around the glass (Fig.7). This approach allowed for retuning the VBGs into resonance in case there was any heating due to the lasers' radiation being absorbed. Any heating would cause the grating period to change and therefore go out of resonance for the operating wavelengths. We did not observe any heating issues and the MVBG temperature stayed constant. In conclusion, in this pure reflection configuration, where the power density on the MVBG was approximately 3 kW/cm^2, no beam quality degradation was observed.

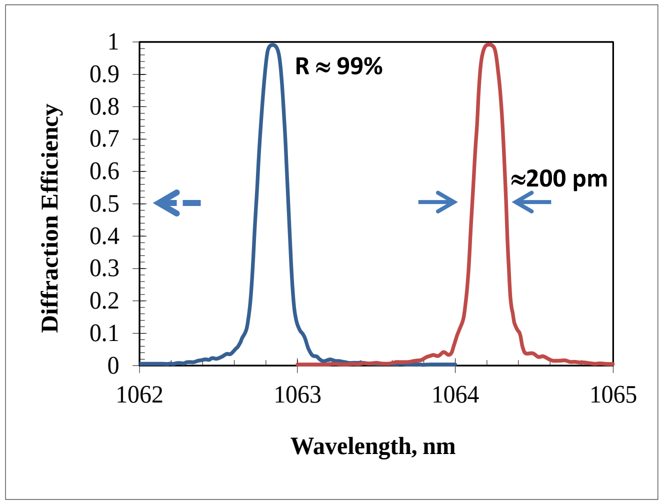

Figure 6: Double MVBG diffraction efficiency spectrum

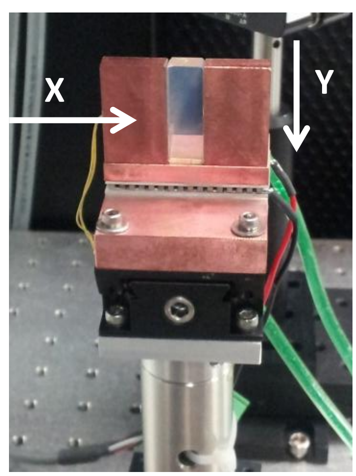

Figure 7: Double MVBG thermal stability control mounting

As a next step, we added a third laser beam to the combining setup. The wavelength of this laser was chosen to be out of resonance with the two gratings so it could be transmitted through the glass in order to be combined with the two reflected beams (see Fig. 5 - λ_3). With three incoming beams, the total combined power was 420 W, achieved with 96.5% combining efficiency. The M^2 of the combined beam was measured to be 1.38 in the 'X' and 1.20 in the 'Y' direction. It is evident, that there is a substantial deviation from the lasers' original M^2 of 1.05 for both reflected lasers (in both directions) and 1.13 and 1.16 for the X- and Y-directions of the transmitted laser. In order to keep the two gratings in resonance, the temperature of the MVBG was lowered by approximately 8° K. In the previous configuration, where only two reflected beams were combined, such thermal issue was not present. We can say with confidence that the worse M^2 and the change of the MVBG temperature set point are due to heating of the glass introduced by the transmitted laser beam. This conclusion is also supported by the difference in the combined beam M^2 in X- and Y- directions for the three-beam configuration. The laser beams' Gaussian power distribution centered in the middle of the MVBG and the different temperature at which the edges of the glass are kept to counteract the glass heating, creates a thermal gradient that is more pronounced in the X-direction due to the specifics of the VBG mounting. In the X-direction the glass is only 10 mm wide and the gradient is much higher when compared with the 25 mm size of the glass in the Y-direction and the lack of copper at the top of the glass. This leads to the definite conclusion, that the presence of a transmitted beam introduces extra heat into the glass via an absorption process, at levels sufficient to degrade the quality of the combined beam.

To explain why the two reflected beams did not follow the same law and deposit similar amounts of heat inside the glass we need to look at how the reflectivity of a VBG depends upon the thickness of the volume grating. Figure 8 shows a simulation of the dependence of reflectivity on the VBG thickness for a VBG with parameters matching the grating used in our experiments. The simulation shows that a VBG with 99 % reflectivity has thickness of approximately 6 mm but 90% of power is reflected within 50% of the volume grating thickness. This explains why in the case of combining two reflected beams no heating or any substantial M^2 degradation were observed. The reflected beams penetrated significantly less into the MVBG when compared to the case where the transmitted beam was also present and therefore much less of their power was absorbed and deposited as heat into the glass. In conclusion, the results presented here demonstrate that using MVBG for spectral beam combining in an architecture implementing only reflected beams is more desirable because it leads to a combined beam with little to no beam quality degradation.

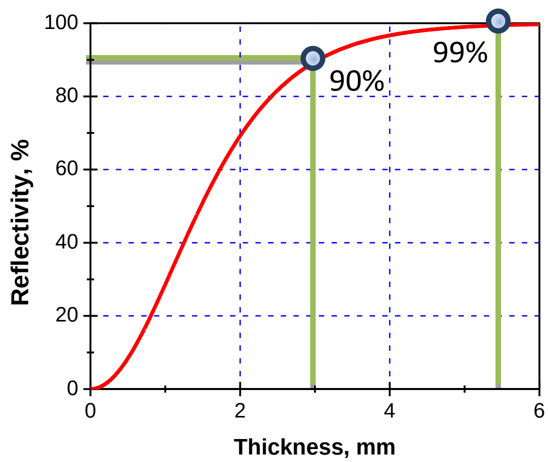

Figure 8: VBG reflectivity dependence on thickness

6. CONCLUSIONS

We propose and demonstrate in this paper, the use of special volume Bragg elements, which have several Bragg gratings written inside as combining optical components. The MVBGs were recorded in photo-thermo refractive glass and two different beam combining configurations were investigated. In the case of combining only two reflected beams, a total combined power of 282 W was achieved with 99 % combining efficiency and M^2 very close to the one of the individual beams. In the case of combining three beams, a total power of 420 W was reached with 96.5 % combining efficiency and average M^2 of 1.3. The beam degradation was attributed to heating of the glass introduced by the transmitting beam. In conclusion, the results demonstrated that the approach of using multiplexed volume Bragg gratings for spectral beam combining is excellent extension and alternative to the current state of the art combining techniques. Especially valuable is the capability to reduce the number of optical elements in the system while being able to manage the expected thermal load when kilowatt level sources are used for beam combining.

7. ACKNOWLEDGMENTS

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