High Power Spectral Beam Combining of Fiber Lasers with Ultra High Spectral Density by Thermal Tuning of Volume Bragg Gratings

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ABSTRACT:

Lasers that produce 100 kW level diffraction limited power will require beam combining due to fundamental thermal and nonlinear limitations on the power of single aperture lasers. Towards this goal, we present high power, high spectral density beam combining by volume Bragg gratings of five 150 W beams with a spectral separation of 0.25 nm between beams, the narrowest to date for high power. Within 1 nm, 750 W of total power is combined with greater than 90 % efficiency. Combined beam quality is discussed including the effect of unequal individual beam divergences on the combined beam quality. The individual input beams may have unique divergences as they enter the system, and the heated volume Bragg gratings (VBGs) may introduce very slight changes in divergence to each beam. These small differences in beam divergence between the beams will not degrade the M^2 of the individual beams, but the composite M^2 after combination can be adversely affected if the beams do not have equivalent divergence at the output of the system. Tolerances on beam divergence variation are analyzed and discussed. High power beams transmitting through or diffracting from a VBG can experience different distortions resulting from thermal effects induced in the VBGs. Each beam also experiences a different aberration, as no two beams pass through the same number of identical VBGs. These effects are studied with experiment compared to modeling. Possible methods of beam quality improvement are discussed.

Key Words: Spectral Beam Combining, Volume Bragg Gratings, High Power, High Radiance, High Energy, Fiber Lasers, Gaussian Beam Modeling, HEL, Holographic Optical Element (HOE)

1. INTRODUCTOIN:

High power lasers with diffraction limited beam quality are desired for many applications in defense and industry. For applications in which the beam must propagate for a distance, higher power is only beneficial if diffraction limited beam quality is maintained. The figure of merit for a beam used in such applications should be radiance or brightness which are considered here to be interchangeable. Radiance is defined as the power divided by the product of the solid angle in the far field and the unit area in the beam waist. The radiance for a radially symmetric Gaussian beam is given in Equation 1[1].

$$B = \frac{P}{\lambda^2 * (M^2)^2}. \qquad (1)$$

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A major goal of high radiance beams has been to reach 100 kW of diffraction limited power for short and mid ranged defense applications. It is probable that to reach such power levels beam combining will be required. Both passive and active coherent beam combining techniques have had moderate success in increasing laser beam radiance, but the requirements on high speed phase control of active coherent beam combining architectures makes the approach complex, and costly.

The focus of this research is on passive spectral beam combining by volume Bragg gratings (VBGs) recorded in photo-thermo-refractive glass. 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. The unique, unmatched properties of VBGs allow achieving this condition at wavelengths with less than 0.25 nm separation. The spectral separation between channels that can be achieved will ultimately determine how much power can be combined by this method. There is a 50 nm transparency window in the atmosphere in the near infrared which can be used for free space high power beams. We report spectral beam combining of five, 150 W beams with a 0.25 nm separation between channels, achieving a total power of 0.75 kW within a 1 nm wavelength range. Combining of two high power beams with spectral separation of 0.25 nm was reported at last year's meeting[2]. Here we report the first demonstration to date of 750 W of power combined within 1 nm with greater than 90% efficiency. The measured beam quality of the combined beam will be discussed in a later section.

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

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 [3]. A complete theoretical model for VBGs based on Kogelnik's coupled wave theory has been developed[4,5].

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 [6-8]. 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.

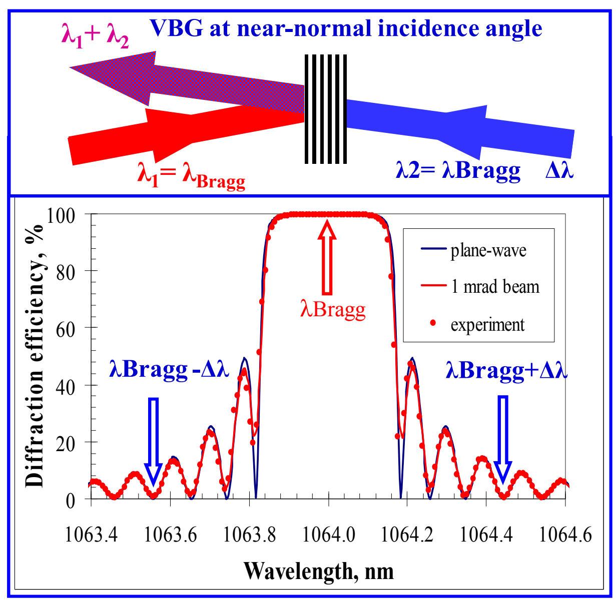

Figure 1: Spectral beam combining by a reflecting VBG (top) which has a central maximum and a series of zeros in diffraction efficiency spectrum (bottom)

3. THERMAL TUNING OF VBGS FOR HIGH POWER SPECTRAL BEAM COMBINING:

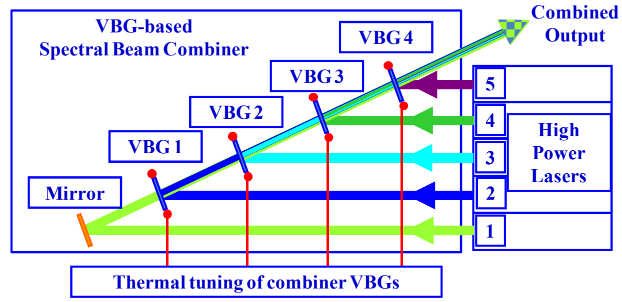

Figure 2: Linear geometry of spectral beam combining

Each beam in the SBC system will experience interaction with a different combination of VBGs as shown in Figure 2. The first beam transmits through four VBGs, while the second beam diffracts from one VBG and transmits through three, etc. Furthermore, each VBG is under a different thermal load. The first VBG experiences 150 W of power transmitting through it, and 150 W of power diffracting from it. While the second VBG experiences 300 W of power transmitting through it, as well as the same 150 W of diffracted power, etc. This is important because PTR glass has a small but finite absorption. It means that the glass is heated under high power laser radiation, which causes glass expansion and refractive index change resulting in Bragg wavelength shift and thermal lensing. It is clear that each VBG experiences different heating conditions and therefore have a different Bragg wavelength shift. This shift is corrected by thermal tuning.

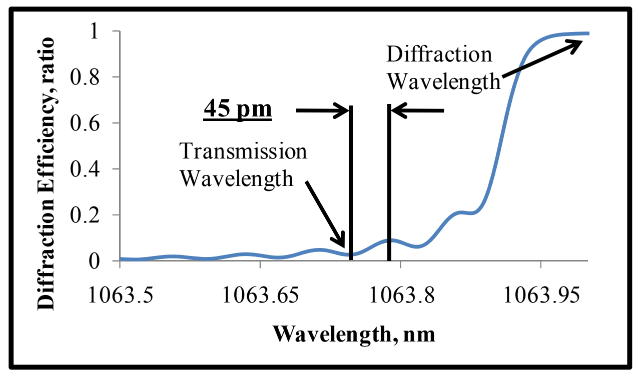

Figure 3: The tail of a diffraction efficiency spectrum illustrating sensitivity of losses for a transmitting beam to offset of wavelength

The most recent results are achieved through use of a novel VBG thermal tuning technique presented at last year's meeting. This technique has been developed to be used in this experiment due to the high precision requirements of SBC with only 0.25 nm spectral separation between beams. Utilizing thermal tuning rather than angular mechanical tuning allows precise positioning of the VBG Bragg wavelength as well as the minima in the Bragg reflection spectrum. The last problem is crucial for the transmitting beams whose wavelengths must coincide with minima in diffraction efficiency. Figure 3 shows the calculated diffraction efficiency spectrum for a VBG with parameters consistent with those used in the SBC system, thickness of 4.78 mm, refractive index modulation of 211 ppm, and approximately 65 pm of Bragg wavelength shift across the beam aperture of 6 mm. The desired transmission wavelength is the third minimum of the VBG's efficiency spectrum and is 0.25 nm from the Bragg wavelength. The beam is assumed to be monochromatic and have diffraction-limited divergence.

The wavelengths at which beams are to be transmitted and diffracted are highlighted in Figure 3. It is important to note that in the area of the side lobes, the distance between nearest maxima and minima of reflection efficiency is only 0.045 nm. A wavelength offset of this value would reduce transmittance of the grating by 7 %. The diffracting beam would also experience a reduction in efficiency for a 0.045 nm tuning error, but there would only be a reduction in efficiency of around 2 %. Maintaining very precise control of the Bragg wavelength is important for the diffracting beam but critical for the transmitting beam.

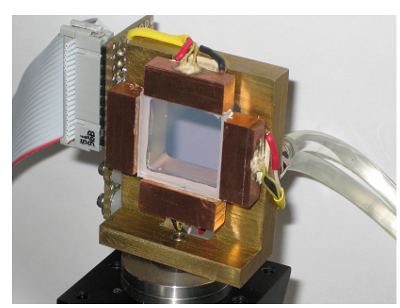

Figure 4: VBG thermal tuning apparatus

A significant benefit of the thermal tuning technique is maintaining high efficiency of beam combining throughout the power range of the system. As discussed above, PTR glass heating under high power laser radiation causes Bragg wavelength shift. Therefore, when the system is aligned to operate with high efficiency at low power it must be re-aligned for high power beams to produce high combining efficiency. Using the new thermal-tuning technique, initial alignment is performed while heating the VBGs with a thermal tuning aperatus, shown in Figure 4. As laser power is increased, the VBG temperature is lowered, and combining efficiency is maintained without need for machanical adjustment. This method was discussed in detail in a paper in last year meeting[2].

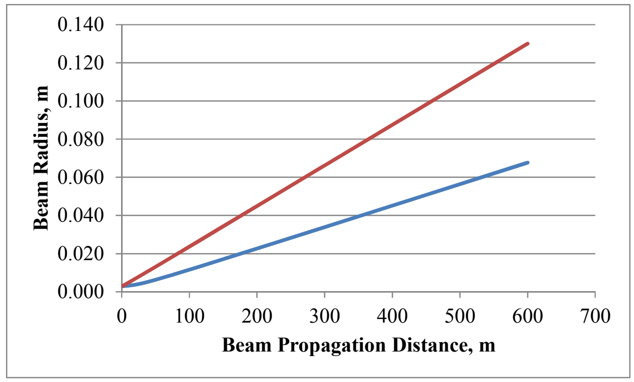

Figure 5: Beam radius vs propagation distance for two beams with a divergence difference of 0.100 mrad

4. MODELING THE BEAM QUALITY OF SPECTRALLY COMBINED BEAMS:

Laser induced heating of the VBGs also introduce very slight changes in divergence to each beam, and these changes will be unique for each beam. These small differences in beam divergence will not degrade the M^2 of the individual beams, but, if left without compensation, the composite M^2 after combination can be adversely affected if the beams do not have equivalent divergence at the output of the system.

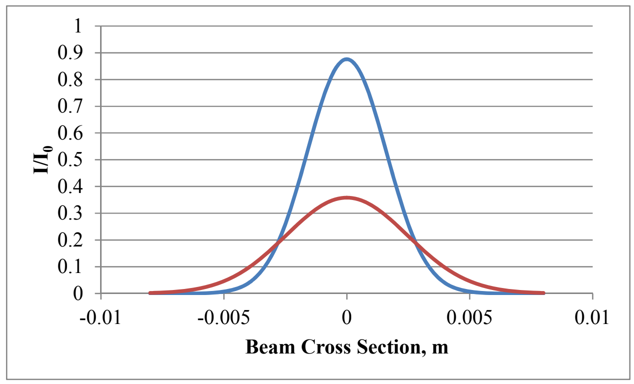

Figure 6: Cross section of two beams with 0.100 mrad divergence difference after 10 m propagation

To illustrate the effect divergence difference between beams can have on beam quality, two collinear beams with slightly different divergences are modeled and the combined beam quality is calculated. Figure 5 shows the beam $\frac{1}{e^2}$ size as a function of propagation distance from the aperture for two beams with different divergences (half angle), $\theta_1 = 0.1129$ mrad, and $\theta_2 = 0.2129$ mrad, but each with diffraction-limited beam quality, M2 = 1. The aperture size is 3 mm for both beams at z = 0.

In order to determine the combined beam quality factor M^2, the intensities of each beam must be summed at two points in the far field. The divergence can then be calculated from the beam size at each point. The beam quality factor can then be determined by dividing this divergence by the divergence of an ideal Gaussian beam with the same aperture size. Figure 6 shows the relative intensity of each beam as a function of beam radius after 10 meters of propagation. Even though the areas under these curves are identical, the peak power of the higher divergence beam has significantly reduced at this point, but the combined beam quality, $M^2 = 1.25$, has not yet been reduced to an unusable level.

This value was calculated using the second moment beam radius in the far field at two different points in z and comparing the divergence of the combined beams with the divergence of an ideal diffraction limited beam. The intensity profile of each beam in the far field is calculated using Equation 2 below, P is the power; z, the propagation distance from the aperture; z_r, the Raleigh length; w(z), the beam radius at some distance z; and λ, the wavelength.

$$I = \frac{P}{1+\left(\frac{z}{z_r}\right)^2} e^{-2\left(\frac{r^2}{w^2(z)}\right)} \tag{2}$$

where,

$$z_r = \frac{\pi {w_0}^2}{\lambda}$$

and,

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_r}\right)^2}$$

After each beam profile is generated in the far field, they are summed incoherently to provide the profile of the combined beam. For a Gaussian beam of any divergence, the divergences calculated by the $\frac{1}{e^2}$ beam width or by calculating based on the second moment, σ^2, beam width are identical. However, in this case, two Gaussian beams with different divergences are summed and the result is not a Gaussian shape. The second moment method of calculating the beam divergence must be employed.

The beam radius, w, of a given intensity profile can be calculated by finding the variance as described in Equation 3.

$$w_{combined} = \sqrt{2\sigma^2(z)} = \sqrt{2 * \frac{\int_0^{2\pi}\int_0^{\infty} r^2 I_{combined}(r,z) r dr dz}{\int_0^{2\pi}\int_0^{\infty} I_{combined}(r,z) r dr dz}} \tag{3}$$

The same calculation is made for a perfect Gaussian beam at the same points in z. The half angle divergences are calculated for each and are compared to determine the combined beam quality as given in equation 4.

$$M_\sigma^2 = \frac{\phi\sigma_{combined}}{\phi\sigma_{gaussian}} = \frac{\left(\sqrt{2\sigma^2(z_2)} - \sqrt{2\sigma^2(z_1)}\right)_{combined}}{\left(\sqrt{2\sigma^2(z_2)} - \sqrt{2\sigma^2(z_1)}\right)_{gaussian}} \tag{4}$$

Figure 7 shows the relative radiance as a function of the M^2 beam quality factor for different quantities of combined beams. The relative radiance is calculated as the combined beam radiance, determined by use of equation 1, divided by the radiance of an individual ideal Gaussian Beam of the same size. From the plot, it can be seen that for two beams with an $M^2 = 1.25$, the increase in radiance is about 30 %. Ideally the radiance would increase by 100 % for each beam that is combined which can be seen in the plot for $M^2 = 1$. If the divergence difference between the two beams is reduced to 0.050 mrad, the combined beam propagation factor is improved to $M^2 = 1.16$ which gives about a 50 % increase over the single beam radiance. To achieve a 90 % increase in radiance by combining two beams, the necessary difference in divergence between the beams that must be maintained is less than 0.010 mrad, which corresponds to $M^2 = 1.03$

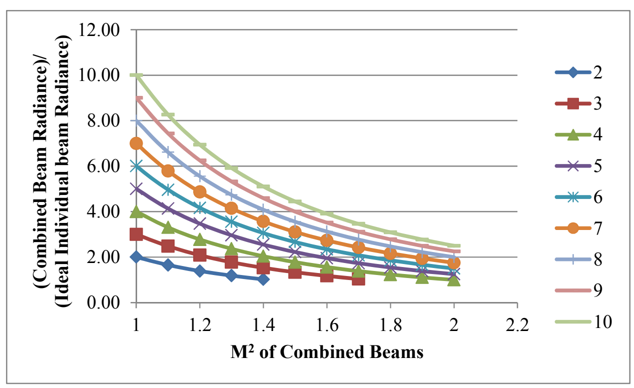

Figure 7: Relative Radiance in a combined beam vs M^2 for individual beams.

5. DIVERGENCE MATCHING OF SPECTRALLY COMBINED BEAMS:

It is clear that to effectively increase the radiance of spectrally combined beams, the divergence of each beam must be tightly controlled. The results are slightly different for five beams due to the fact that a smaller portion of the power will be located in the lowest or highest divergence case. Figure 8 shows the beam $\frac{1}{e^2}$ size as a function of propagation distance from the aperture for five beams with different divergences, 0.113 mrad, 0.138 mrad, 0.163 mrad, 0.188 mrad, and 0.213 mrad, for a total difference in divergence equal to that of the two beam case, 0.100 mrad. Figure 9 shows the intensity cross-section of the five beams after 10 meters of propagation. The combined beam quality factor for all five beams is calculated to be $M^2 = 1.34$. Table 1 summarizes the findings for both the two and five beam cases.

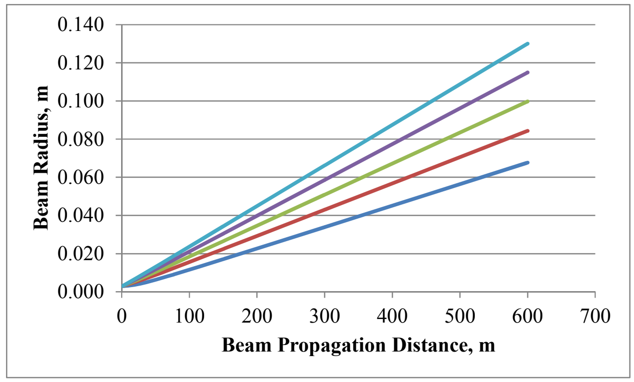

Figure 9: Beam radius vs propagation distance for five beams with a total divergence difference of 0.100 mrad

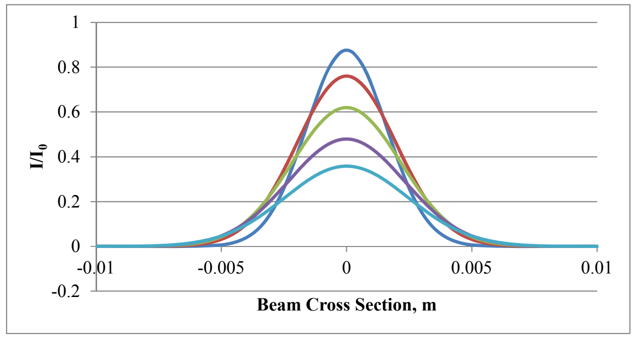

Figure 8: Cross section of five beams with 0.100 mrad total divergence difference after 10 m propagation

Such small differences in divergence are difficult to measure, and the divergence for each case would be different for different size beams. For this reason it is often better to sample the beam, focus it, and measure the focal spot error at the waist. For purely first order spherical aberrations, defocus, each beam will simply have a shifted waist with a different size. If the beam divergences were perfectly aligned, the waists would occur at the same location and would have the same radius.

The procedure to precisely align the beams should be to match the location of the beam waists in the focal spot after a lens, ideally in the same location as a diffraction-limited test beam. If this is achieved, any measurement of far field divergence will show equal, diffraction-limited divergence for all beams involved, and a combined $M^2 = 1$, assuming that the initial beams are diffraction-limited and no higher order aberrations are added in the beam combining optics. Note that an error in focal spot of up to ½ of a Raleigh length does not cause significant degradation of the beam quality factor or relative radiance.

6. IDEAL ALIGNMENT OF NON-IDEAL BEAMS:

In the previous section, tolerances on beam divergence differences for ideal diffraction-limited beams where $M^2 = 1$ for each beam were discussed. In most high power cases the beam quality of each beam will not be ideal, and in the case of VBG-based spectral beam combining, each beam experiences a different set of distortions due to the fact that each beam transmits through a different set of VBGs that are each being heated by different optical power loads. The beam that transmits through all VBGs will have higher distortions than the final beam which only diffracts from a single VBG.

In this case, it is impossible for a beam with $M^2 > 1$ to be adjusted to have diffraction-limited divergence. By definition, the minimum divergence for that beam would be increased by a factor of its M^2. $M^2 = \frac{\phi_{beam}}{\phi_{ideal-gaussian}}$. If the far field divergence is measured for each beam, the only way to give the beams equal divergence would be to increase the divergence of the beams with better beam quality which would result in a shifting of the beam waists in the focal spot and the resulting beam quality would be reduced. In the case of ideal beams of different divergence, the divergence could be measured directly, and each beam adjusted to be equal; but in the case of non-ideal beams the best case is not when the divergences are equal, but when each beam has the smallest possible divergence.

A clear method to achieve this is to ensure the beam waists in the focus are aligned together. The beam radius at the waist will be a different size for each beam that has a unique beam quality, but the waist locations should be aligned to the location of the ideal Gaussian beam waist. This insures that the divergence for each beam is as close to ideal as possible and the combined beam quality is best in this case.

2-Beams			
Divergence Difference, mrad	0.100	0.050	0.010
Combined M^2	1.25	1.16	1.03
Focus Error/Raleigh Length	1.60	1.04	0.43
Relative Radiance	1.38	1.49	1.89
5-Beams			
Divergence Difference, mrad	0.100	0.050	0.010
Combined M^2	1.34	1.19	1.04
Focus Error/Raleigh Length	1.60	1.04	0.43
Relative Radiance	2.78	3.53	4.62

Table 1: Summary of beam propagation factor, divergence, Raleigh length, and radiance findings for two and five beam spectral beam combining

7. EXPERIMENTAL SETUP FOR DIVERGENCE MEASUREMENT OF SPECTRALLY COMBINED BEAMS

As discussed above, VBGs are recorded in PTR glass which has a small but finite absorption. This absorption causes each VBG to heat up and expand. The expansion induced by heating changes the Bragg wavelength and must be tuned by the previously discussed thermal tuning devices. The thermal tuning devices operate by cooling the edges of the VBG until the center of the VBG returns to the correct temperature and hence thickness to achieve the Bragg condition for the desired wavelength. This process can maintain the efficiency from low to high power operation, but, although the temperature in the center of the VBG is maintained, the temperature gradient across the aperture of the VBG causes the VBGs to behave like thermal lenses with a very long focal length.

Ideally, each laser in the system could be tuned individually while all other lasers are turned off. However, since the lensing and aberrations are caused by heating from all lasers, the alignment must be made while the system is at full power. This introduces a significant complication to the problem of aligning the beam divergences. All five lasers in the beam combining system should be propagating collinearly if properly aligned, and the spectral separation between beams is only 0.25 nm. A demultiplexer must be employed in order to separate each beam for measurement and alignment.

We developed a new approach where a thermally tuned VBG with selectivity narrower than 0.25 nm is used as the spectrally selective filter. Unlike the VBGs in the beam combining portion of the setup, this VBG can be tuned across the entire spectral range of the system, 1 nm, due to its high temperature range, from 5^{o} C to 130^{o} C. The high power combined beam is sampled down to a lower power and sent into the measurement setup. After a beam is selected and reflected from the demultiplexing VBG, it is sent through two alignment mirrors, and a beam sampler before being measured for waist size, divergence, and beam quality factor M^2. Figure 10 illustrates the experimental setup. The beam sampler sends a portion of the beam into an integrating sphere where the power and spectrum are analyzed to ensure that the proper beam has been selected.

Before sending the combined beam into the measurement setup, an ideal, low power, diffraction-limited Gaussian beam is sent into the Beam Map to determine the ideal focal spot for a perfect beam, $M^2 = 1$. The divergence of each of the five combined beams in the system can now be selected by the demultiplexing VBG, and adjusted until the focal spots are all in the same locations after the analyzing lens. In this way each beam will achieve the smallest divergence possible and the best combined beam quality can be reached.

This technique is used to align the divergence of five 150 W beams with a spectral separation between beams of 0.25 nm.

8. HIGH POWER SPECTRAL BEAM COMBINING OF FIBER LASERS WITH ULTRA HIGH SPECTRAL DENSITY:

Using thermally tuned VBGs in PTR glass we demonstrate kW-level ultra high density spectral beam combining, designed to be aligned at low power and temperature tuned for uninterrupted operation at any power up to the maximum. The result shows the highest powers spectral density to date, 0.75 kW/nm, of any spectral beam combining system.

Five 150 W beams were combined in the architecture shown in Figure 2. Efficiency of greater than 90 % was

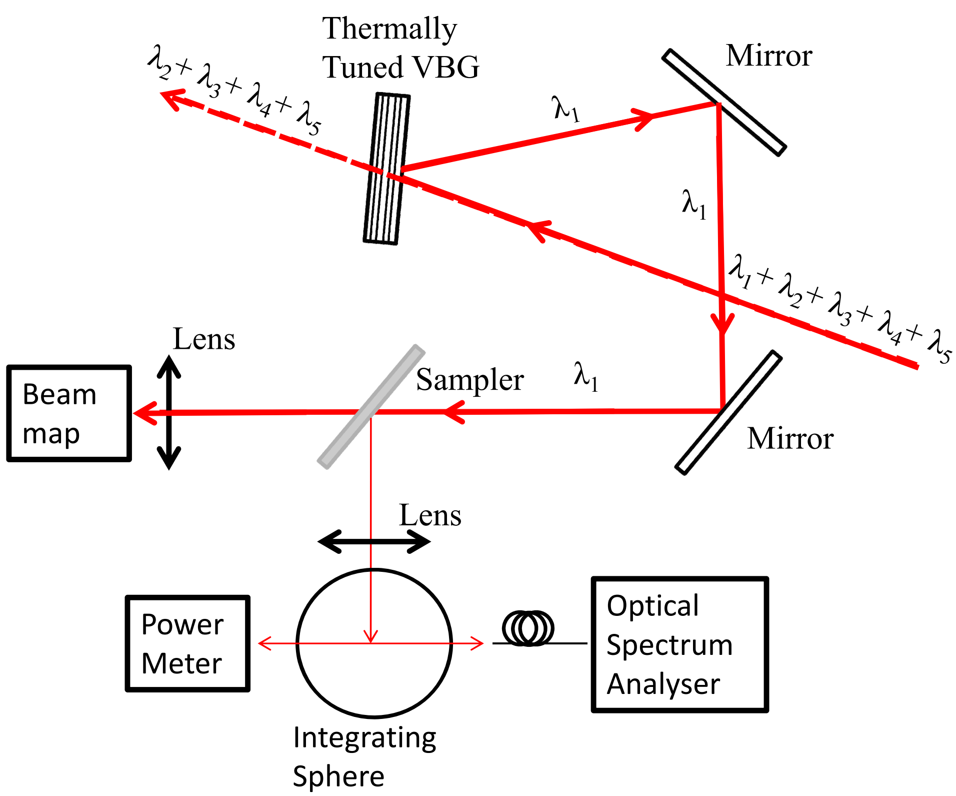

Figure 10: Demultiplexing and beam measurement experimental setup

maintained from 75 W to 750 W total power.

The VBGs used in this experiment have absorption in the range of α = 1-2x10^{-3} cm^{-1}. The relationship between the optical power absorbed int the VBG and the absorption coefficient is given by, $I_{abs} = I_0(1 - 10^{-\alpha L})$. The beams were first aligned to operate at 20 W each, 100 W total. The beam quality of each beam was measured after passing through the beam combining system and the measured M^2 value for beams one through five are 1.22, 1.23, 1.27, 1.08, and 1.05, and the combined beam quality was measured to be M^2 = 1.20, where beam one transmits through all VBGs and beam five is diffracted off of the final VBG and does not transmit through any. Figure 11 shows the combined beam quality measurement for the case of 100 W total power. From Figure 7, in the case of five beams with M^2 = 1.2, it can be see that this results in an increase of radiance over that of a unit beam of aproximately 3.5 times.

For the case of 750 W total power, the beam quality of each individual beam was measured while the system was operating at full power by using the demultiplexing measurement setup described above and shown in Figure 10. The individual beams, one through five, after passing through the system were found to have M^2 of 3.15, 2.82, 2.74, 1.77, and 1.36 respectively. The combined beam quality before alignment of the beam divergences was measured to be M^2 = 3.0, and after alignment of the beam divergences, the combined beam beam quality was reduced to the prevously stated value of M^2 = 2.1. From Figure 7, in the case of five beams with M2 = 2.09, it can be seen that this results in an increase of radiance over that of a unit beam of only 1.13 times.

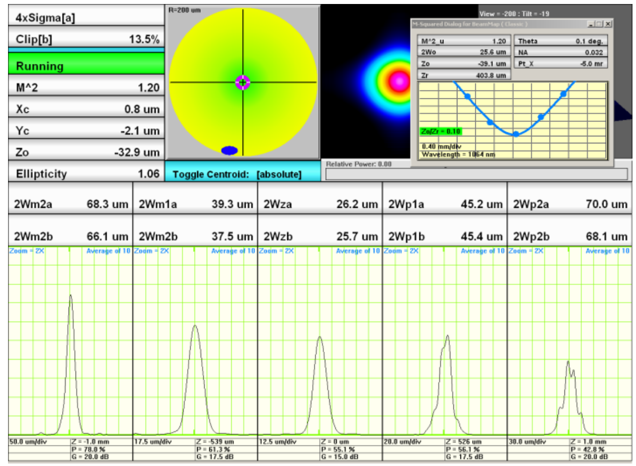

Figure 12: Quality of a combined beam in the five beam 100 W SBC system, 20 W each beam.

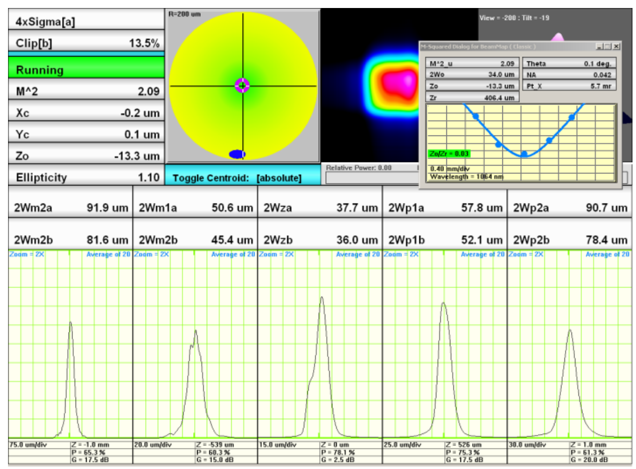

Figure 11: Combined beam quality of the five beam 750 W SBC system using interim VBGs

To confirm the beam combining model described above, as well as the measured result of M^2 = 2.1, the measured M^2 values for each beam were used as inputs to calculate the expected combined beam quality. The model shows that combining five beams with beam quality factors, M^2, of 3.15, 2.82, 2.74, 1.77, and 1.36, gives an expected combined beam quality of M^2 = 2.04. This calculated result is very close to the measured result of M^2 = 2.09 shown in Figure 12. It can be concluded that the beams a co-propagating and the beam divergences are well aligned. The model also confirms the low power result with the calculated combined beam quality factor M^2 = 1.17 being very close to the measured result of M^2 = 1.20.

Improvements in combined beam quality are expected in the very near future as the low absorption VBGs would replace the current VBGs.

9. CONCLUSIONS:

A model to describe the combined beam quality of multiple beams with unique divergences and initial beam qualities has been developed. It is concluded that the divergence of ideal diffraction-limited beams can vary up to the point at which the beam waists are shifted by ½ of a Raleigh length before significant degradation of beam quality or combined beam radiance occurs.

Volume Bragg grating thermal tuning devices were successfully employed to maintain diffraction efficiency above 90 % for the entire power range of a five beam 750 W spectral beam combining system with a spectral separation between beams of 0.25 nm, achieving, to the knowledge of the authors, the highest power spectral density of any spectral beam combining system to date of 0.75 kW/nm

The current results were achieved by the use of VBGs with high absorption 1-2x10^{-3} cm^{-1}. When new VBGs with an order of magnitude lower absorption, $\alpha = 1x10^{-4}$ cm^{-1}, the combined beam quality is expected to drasticaly improve.

A novel demultiplexing apparatus and beam measurement system has been demonstrated and successfully used to measure and align the divergence of all five spectrally combined beams. At low power operation, 100 W total, the combined beam quality was measured to be $M^2 = 1.20$. In the case of full power operation, 750 W total, the alignment of the beam divergences resulted in the improvement of combined beam quality from $M^2 = 3.0$ to $M^2 = 2.1$, The calculated result of $M^2 = 2.04$ matches reasonably well with the measured result.

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REFERENCES:

[1] Fan TY, “Laser beam combining for high-power, high-radiance sources,” IEEE J SEL TOP QUANT, 11(3), 567-577 (2005)

[2] Drachenberg D, Andrusyak O, Cohanoschi I, et al., “Thermal tuning of volume Bragg gratings for high power spectral beam combining,” Proceedings of the SPIE, Fiber Lasers VII: Technology, Systems, and Applications, 7580, 75801U-9 (2010)

[3] Kogelnik H, “Coupled wave theory for thick hologram gratings,” BELL SYST TECH J., 48, 2909-2947 (1969)

[4] Ciapurin I, Glebov L, Smirnov VI., “Modeling of phase volume diffractive gratings, part 1: transmitting sinusoidal uniform gratings,” OPT ENG,45(1), 015802-9 (2006)

[5] Ciapurin IV, “Modeling of Gaussian beam diffraction on volume Bragg gratings in PTR glass,” Proceedings of SPIE, 5742, 183-194 (2005)

[6] Andrusyak O, Ciapurin I, Smirnov V, Venus G, Glebov L. “Spectral beam combining of fiber lasers with increased channel density,” In: Proceedings of SPIE.Vol 6453, 64531L-64531L-7 (2005)

[7] Glebov L, “Volume Bragg Gratings for Spectral Beam Combining,” OSA Technical Digest, Conference on Lasers and Electro-Optics, Optical Society of America, CThX1 (2010)

[8] Andrusyak O, Smirnov V, Venus G, Glebov L, “Beam combining of lasers with high spectral density using volume Bragg gratings,” Optics Communications, 282(13), 2560-2563 (2009)