Thermal tuning of volume Bragg gratings for high power spectral beam combining

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ABSTRACT

A tabletop kW-level spectral beam combining (SBC) system using volume Bragg gratings (VBGs) recorded in photo-thermo-refractive (PTR) glass was presented at the last meeting [1]. Diffraction efficiency of VBGs close to 100% was demonstrated. However, 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 spectral beam combining achieving this condition at wavelengths with less than 0.25 nm separation. We present modeling of reflecting VBGs for high power SBC that takes into account laser spectral bandwidth, beam divergence, PTR-glass scattering losses, and grating non-uniformity. A method for optimization of VBG parameters for high-efficiency SBC with an arbitrary number of channels is developed. Another important aspect of spectral beam combiner design is maintaining high diffraction efficiency as the temperature of beam-combining VBGs changes during operation due to absorption of high power radiation. A new technique of thermal tuning of large aperture VBGs, designed to maintain high efficiency of beam combining without mechanical adjustment over a wide range of laser power, is developed. Finally, these tools are used to demonstrate a robust and portable 5-channel SBC system with near diffraction limited spectrally-combined output beam.

1. INTRODUCTION

Fundamental limits on the power than can propagate in an optical fiber such as non-linear and thermal effects lead to beam combining as a method to reach higher powers than an individual fiber emitter can accommodate. Spectral beam combining and coherent beam combining are the two major complimentary methods of beam combining in the effort to reach multi-kilowatt diffraction limited beams.

The focus of this research is on spectral beam combining by volume Bragg gratings recorded in photo-thermo-refractive glass. A 0.75 kW five channel SBC system with channel separation of 0.5 nm between adjacent wavelengths as well as a low power five channel dense SBC system with channel separation of 0.25 nm were previously reported [1][2]. The spectral separation between channels that can be achieved will ultimately determine how much power within a certain spectral range 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 delivery of high power laser beams. How many beams that can be combined within this window, and hence the highest power that can be combined will be determined by the achievable spectral separation. For this reason the goal of the current phase of research is to spectrally combine 5, 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.

To effectively combine high power beams with such a narrow spectral separation, very precise control of the VBG resonant wavelength must be implemented. VBGs with narrow spectral selectivity also have narrow angular selectivity. So tuning the VBGs by angle becomes a challenge and is impractical at high output powers. 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, can be controlled electronically. Therefore, once the beams are aligned to be collinear, no realignment is necessary to tune for peak efficiency. A thermal tuning method and novel thermal tuning apparatus is presented in order to achieve precise control of the VBG resonant wavelength and hence combining efficiency of a SBC system without mechanical tuning. With this tuning method, peak combining efficiency of a given system can be maintained from low to peak power operation without mechanical realignment.

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With the necessity of increasingly narrow spectral selectivity, it is also important to model VBGs and the effects of non-ideal beams in order to optimize the design of a SBC system. When designing VBGs to be used with non-plane wave beams, there is a competition between increasing peak diffraction efficiency at the resonant wavelength for the diffracting beam and decreasing diffraction efficiency at a nearby wavelength for a transmitting beam. Series 1 in Figure 1 shows the ideal diffraction efficiency spectrum for a VBG. Series 2 through 4 show the result of various non-ideal effects on the diffraction efficiency discussed in more detail below. The far right side of the plot shows the Bragg wavelength at which a beam would be diffracted, while the first minimum in series 1, located at -0.18 nm, shows the location of a possible wavelength at which a beam could be transmitted to combine with the diffracted beam. Without including non-ideal effects in the model, any optimization would produce unrealistic results. A VBG model that includes the three major non-ideal effects, as well as an optimization method are presented and discussed.

2. MODELING OF VOLUME BRAGG GRATINGS

There are three main effects that reduce the peak diffraction efficiency at the Bragg wavelength and raise the diffraction efficiency for the transmitted beams: laser beam divergence, spectral bandwidth, and inhomogeniety of the grating parameters across the aperture of the VBG.

Figure 1 shows the influence of these three effects on the difraction efficiency. The VBG modeled here has a thickness of 3.66 mm and a refractive index modulation of 420 ppm. Series 1 represents the monochromatic plane-wave diffraction by an ideal VBG. Series 2 is for a Gaussian beam with 2 mrad divergence. Series 3 includes 2 mrad divergence and 50 pm laser spectral bandwidth. Series 4 includes 2 mrad divergence, 50 pm bandwidth and 50 pm of resonant wavelength shift across the aperture. Understanding and minimizing these effects is important to designing an efficient system.

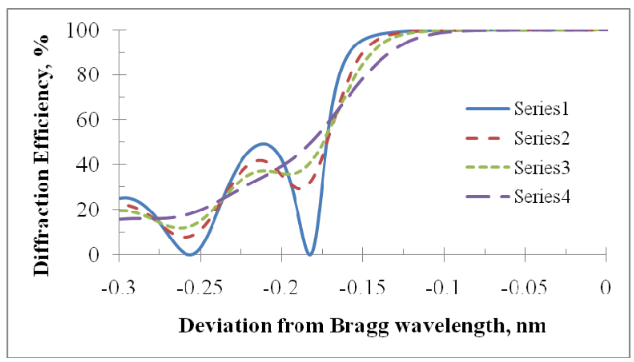

Figure 1: Modeling of VBG diffraction efficiency versus detuning from Bragg wavelength.

To include these effects in the VBG diffraction efficiency profile, the ideal plane wave diffraction efficiency spectrum is first calculated using the following equation that results from Kogelnik's theory of coupled waves [3]. For the method used here we begin with the diffraction efficiency as a function of spectral detuning, and Bragg angle. Angular detuning is considered to be zero here, and is introduced later through convolution.

$$\boldsymbol{\eta(\Delta\lambda)} = \left(\mathbf{1} + \frac{\mathbf{1} - \left(\frac{\lambda_0 f^2 \Delta\lambda}{2 n_{av} \delta n}\right)}{sinh^2\left(\left(\frac{2\pi n_{av} t \delta n}{\lambda_0 f}\right)^2 - \left(\frac{\pi f t \Delta\lambda}{\lambda_0}\right)^2\right)^{\frac{1}{2}}} \right)^{-1} \tag{1}$$

Where λ_0 is the resonant wavelength at normal incidence of the VBG, $\Delta\lambda$ is a small variation from the resonant wavelength, f is the grating frequency, n_{av} is the average refractive index, and δn is the refractive index modulation amplitude. The grating spatial frequency, f, and the incident beam angle can be related by the Bragg condition given here.

$$\frac{\lambda_0}{n_{av}|\cos(\theta_m{}^*)|} = \frac{2}{f} \tag{2}$$

Where $\theta_m{}^*$ is the Bragg angle inside the medium. Combining equations *(1)* and *(2)*, it is clear that the diffraction efficiency, η, of a given VBG can is a function of wavelength, $\Delta\lambda$, and Bragg angle, $\theta_m{}^*$. The notation for the diffraction efficiency then becomes $\eta(\Delta\lambda,\ \theta_m{}^*)$.

Finite divergence and finite spectral content must be taken into account for spectral beam combining optimization. To accomplish this, the profile of the input beam in angle space is convolved with the diffraction efficiency. Let

$$\boldsymbol{G_\lambda(\Delta\lambda, w) = e^{-2\left(\frac{\Delta\lambda-\lambda_0}{w}\right)^2}} \qquad (3)$$

represent the input beam in spectral space with a Gaussian spectral profile, and

$$\boldsymbol{G_\theta(\theta, b) = e^{-2\left(\frac{\theta-\theta_0}{b}\right)^2}} \qquad (4)$$

represent the input beam in angle space with a gaussian divergence profile, where w is the spectral width, $\boldsymbol{\theta}_0$ is incident beam angle, and b is the divergence (FWe^{-2}M).

To include the effects of a finite beam divergence, the diffraction efficiency spectrum is calculated for each angle within a range of interest, producing a two dimensional diffraction efficiency array. In this array, one index represents wavelength change while the other represents angle change. To include the effects of a divergent beam, *(4)* is multiplied to each row in angle space. Then the area under each row is divided by the area under the curve generated by *(4)*. The resulting one dimensional array is the diffraction efficiency in wavelength space including the effects of a finite beam divergence, $\boldsymbol{\eta_{d\theta}}(\Delta\lambda)$. This operation effectively convolves *(4)* and *(1)* in angle space.

The effects of a beam with a finite spectral bandwidth may be included by convolving the result with $G_\lambda(\lambda, w)$.

$$\boldsymbol{\eta_{d\lambda,d\theta}(\Delta\lambda) = (G_\lambda * \eta_{d\theta})}(\Delta\lambda) \qquad (5)$$

Finally, the variations in VBG Bragg wavelength across the beam aperture can be included in the model by the same mathematical method. If the shift in Bragg wavelength as a function of a lateral coordinate is assumed to be nearly linear, and the beam is Gaussian, equation *(5)* can be used again to account for this shift, where w is now the spectral shift in Bragg wavelength across the beam aperture.

A third convolution is necessary to incorporate all three effects into the model simultaneously. Equation *(6)* results from performing a second wavelength convolution on equation *(5)*.

$$\boldsymbol{\eta_{d\lambda_B,d\lambda,d\theta}(\Delta\lambda) = \left(G_\lambda * \eta_{d\lambda,d\theta}\right)(\Delta\lambda)} \qquad (6)$$

Equation *(6)* gives the VBG diffraction efficiency as a function of wavelength detuning and Bragg angle, including the effects from beam divergence, beam spectral bandwidth, and a Bragg wavelength shift across the beam aperture.

3. OPTIMIZATION OF VBG PARAMETERS FOR SPECTRAL BEAM COMBINING

A method for optimizing a spectral beam combining system with an arbitrary number of channels has been developed. In the previous section, modeling the diffraction efficiency spectrum for a single grating was discussed. The results of this modeling are used to optimize a single VBG for SBC. For a given number of laser beams, each with finite divergence and bandwidth, with a given spectral separation, starting wavelength, and a possible range of grating thickness and refractive index modulation, a grating configuration is found to achieve maximum efficiency. The finite divergence and bandwidth of the beams are major parameters that drive the optimization, and must be accounted for. Otherwise, ideal models could be used and no optimization would be necessary.

In a SBC system, there are as many VBGs as beams minus one. In this case, optimization must be performed for each VBG. The first VBG in the SBC system will only interact with two beams, the diffracted beam at the VBG resonant wavelength, and the transmitted beam at some specified distance from the resonant wavelength. The next VBG in the system will interact with three beams, the diffracted beam at the VBG resonant wavelength, and the two beams from the first VBG which will both transmit through the second VBG. This continues until the desired number of beams is combined. Optimization is performed iteratively for each successive VBG in the system. The output of each iteration, which is the ratio of the power incident on the optimized VBG to the power that will arrive at the next VBG for each beam, is used as the input for the next iteration. The final result of the optimization is the necessary refractive index modulation and thickness for each VBG in the system to obtain peak combining efficiency.

Figure 2 shows an example of the resulting data from an optimization calculation for a 5-channel combining system with a spectral separation between channels of 0.25 nm around 1064 nm, and beam divergence of 1 mrad. The two peaks in combining efficiency are associated with using the 2^{nd} or 3^{rd} minimum of diffraction efficiency curve for a transmitted beam. The results show a significant performance advantage in using the 3^{rd} minimum, but the advantage diminishes with each successive minimum. By including scattering losses associated with grating parameters: thickness and refractive index modulation, we are able to identify an absolute maximum configuration, usually using a high order zero.

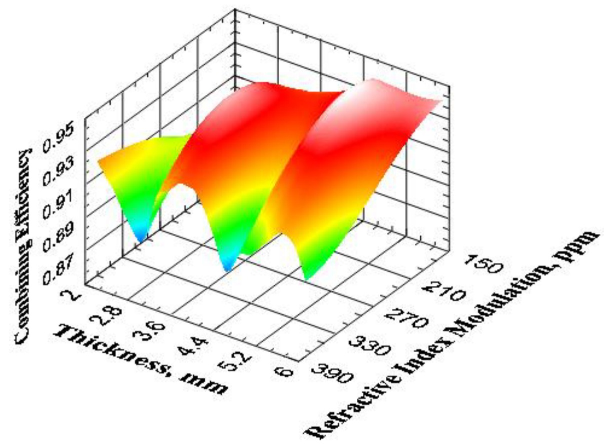

Figure 2: Efficiency of 5-channel SBC as a function of VBG thickness and refractive index modulation

The ideal diffraction efficiency for each of the four VBGs whose parameters were determined by the optimization procedure is shown in Figure 3. This system was designed such that each laser would interact with every VBG whose Bragg wavelength is less than or equal to that of the laser. Every VBG in Figure 3 has less than 1% diffraction efficiency at wavelengths corresponding to the Bragg condition of higher-wavelength VBGs.

4. THERMAL TUNING OF VOLUME BRAGG GRATINGS

We have developed a thermal tuning technique for maintaining high efficiency of beam combining throughout the power range of the system. VBGs are recorded in PTR glass which has a small but finite absorption. It means that the glass is heated under high power laser radiation, which causes glass expansion and hence 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 novel heating aperatus. As laser power is increased, the VBG temperature is lowered, and combining efficiency is maintained without need for mechanical adjustment.

The experimental setup is shown in Figure 4. The high power laser produces a 6 mm, 160 W beam, while the low power tunable laser produces a 6 mm, ~10 mW beam with close to diffraction limit divergence. Heating to the grating may be caused by both the high power laser beam and the external heating apparatus. The diffraction efficiency spectra are measured with the tunable low power laser under various heating conditions.

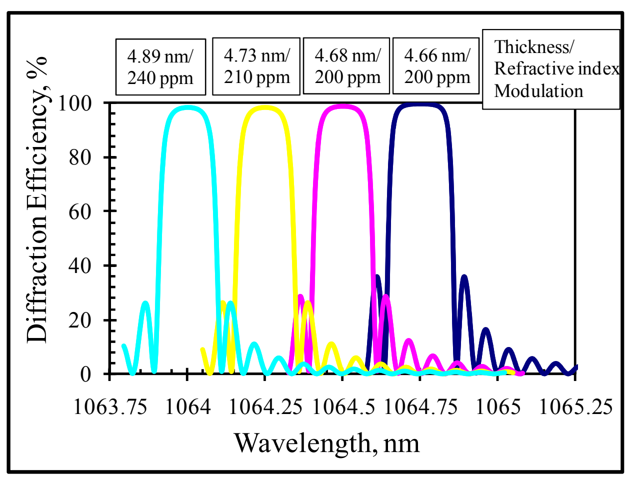

Figure 3: Diffraction efficiency spectra of VBGs for an optimized system

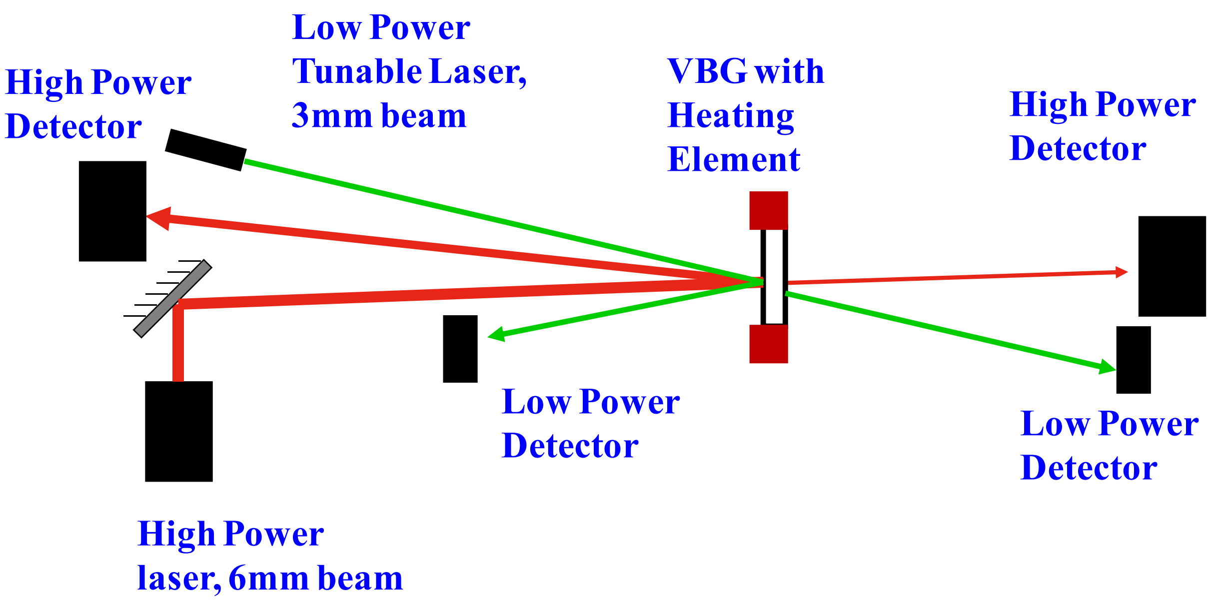

Figure 4: Experimental setup for diffraction efficiency spectra measurement in VBGs exposed to high power laser radiation

Figure 5 shows the VBG diffraction efficiency spectrum for three different cases. Diffraction efficiency spectrum of grating at room temperature with no illumination by a high powwer radiation is shown by blue dots. Next the heater temperature is set to 70˚ C, and the VBG is aligned with a low power beam. The dashed line in Figure 5 shows the diffraction efficiency for this condition. Next the high power beam is turned on, and the heater temperature is lowered until peak diffraction efficiency is recovered to its previous position. The diffraction efficiency of a probe beam produced by a VBG under exposure to the high power beam is measured and determined to be equal to that of the low power beam. The solid line shows the diffraction efficiency spectrum of the VBG with the high power beam turned on and the heater temperature set to 55˚ C. The two curves overlap, demonstrating the conservation of resonance wavelength from low to high laser power.

Using this thermal tuning aparatus, the laser heats the glass from the center while the glass temperature is controlled from the edge. Without the use of thermal control, the temperature at the edge of a VBG under high power laser radiation is much cooler than the temperature at the peak of radiation. This thermal gradient produces a gradient in the Bragg wavelength of the VBG which can reduce combining efficiency. By heating the edge of the greating while high power radiation heats the center, the combined thermal gradient will be smaller than it would be without thermal control.

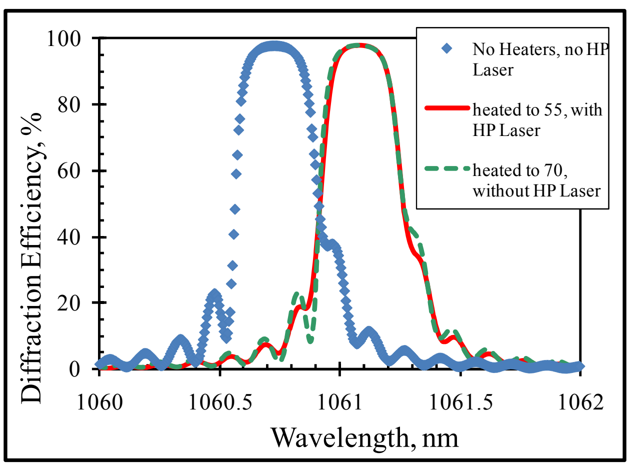

Figure 5: Diffraction efficiency under various heating conditions

The experimental setup in Figure 4 is modified by replacing the low power output colimator which produces a 6 mm beam with one which produces a 3 mm beam. With a smaller test beam, different parts of the VBG can be probed more accuratly.

Figure 6 shows the Bragg wavelength shift as a result of heating across the grating aperture while the VBG is under various heating conditions. The Bragg wavelength shift is the difference between the Bragg wavelenth of the VBG at room temperature and under some external heating.

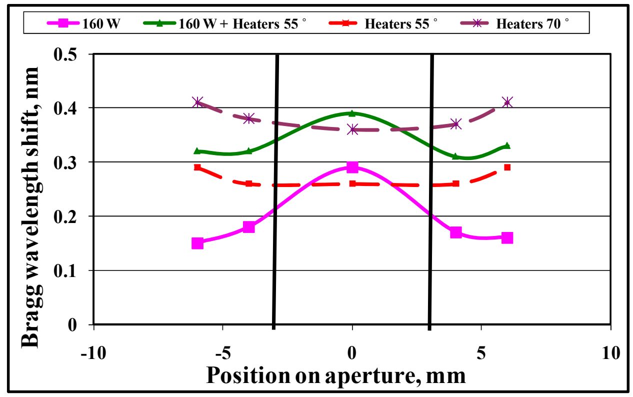

Figure 6: Bragg wavelength profile across the aperture under various heating conditions

The lower solid pink line shows the Bragg shift as a result of heating from only the laser source. Next the grating is pre-heated to a desirable starting temperature. The upper dashed line shows the Bragg wavelength profile while being heated from the edge to 70°C. When the laser radiation is turned on, the VBG edge temperature is reduced to 55°C. The Bragg wavelength profile that results from both high power laser radiation and heating at the edge is shown by the upper solid line (green). The Bragg wavelength gradient between the center and the edge of the VBG is significantly reduced in this case. Also, the resulting central Bragg wavelength is very near the intended central Bragg wavelength, and therefore diffraction efficiency is maintained without angle tuning the grating or spectrally tuning the laser.

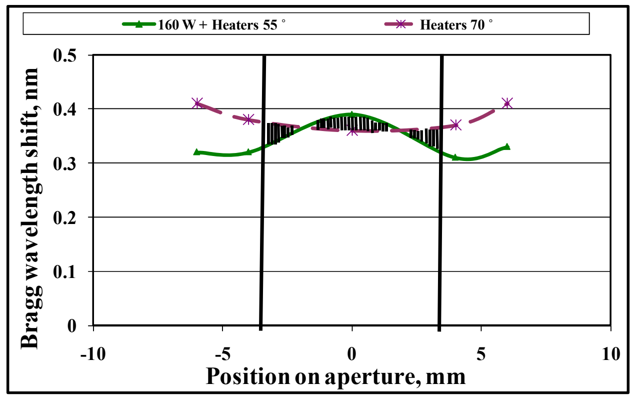

Figure 7: Profiles of deviation from initial Bragg wavelength for external heating to 70°C and a combination of external heating to 55°C and 160 laser radiation

The temperature of 55° C was found by lowering the temperature from 70° C until peak diffraction efficiency was restored. However, this temperature returned the central Bragg wavelength to just above the origional Bragg wavelength associated with heating to 70°C without the high power laser. This is a result of the Gaussian-like thermal profile the beam produces. The average deviation from this central wavelength from the edge of the beam to the center is minimized to achieve peak diffractin efficiency. Figure 7 illustrates this effect.

The beam quality of the test beam was measured to determine any effect the thermal tuning apparatus may have. Table 1 below shows the peak diffraction efficiency and M^2 under various heating conditions. It is clear from these results that the thermal tuning method does not deteriorate beam quality. The first three rows are the results of changing the VBG edge temperature without any high power radiation, while the final two rows show the results with high power radiation at two different VBG edge temperatures. In all cases, $M^2 \leq 1.12$, and diffraction efficiency was near 98%. For the case of using a high power beam without any thermal control of the VBG, row four, the diffraction efficiency dropped down to 97.7%. This is the case associated with the highest thermal gradient across the aperture of the beam. The final case, row five, using high power radiation and thermal controll of the VBG, reduces the thermal gradient and returnes the diffraction efficiency to 98%.

Incident optical power	Edge Temperature	Diffraction Efficiency	Test Beam M2
0 W	~25° (heater off)	98.0%	1.12
0 W	70° (heater on)	98.0%	1.09
0 W	55° (heater on)	98.0%	1.10
160 W	~37° (heater off)	97.7%	1.12
160 W	55° (heater on)	98.0%	1.09

Table 1: Diffraction efficiency and M^2 under various heating conditions

5. SPECTRAL BEAM COMBINING BY THERMAL TUNING OF VOLUME BRAGG GRATINGS

This thermal tuning technique, described in detail in section 4, can be used in spectral beam combining to keep the gratings in resonance from low power up to the full power of a given SBC system. Formerly, a SBC system would be alligned such that peak combining efficiency is achieved only after the VBGs heat up under high power laser radiation and reach thermal equilibrium. In this case, any fine tuning of the system would require angular adjustments to the VBGs while maintaining full input laser power. Angle tuning a VBG while kW-level radiation is incident on the grating is impractical. Thermal tuning eliminates the need for mechanical tuning and may be electronically controlled with proper feedback. Mechanical allignmnet is used only to make each beam co-linear, while thermal tuning is used to maintain peak combining efficiency throughout the power range of the system.

Figure 8 shows the experimental setup for 2 channel high power spectral beam combining. One VBG with thermal tuning is used to combine two high power lasers. Figure 9 shows the optimal VBG edge temperature as a function of power level. The combining efficiency for each data point is also given. From 10 W to over 300 W, beam combining efficiency was maintained within 0.5% of the low power combining efficiency. No angular tuning was required to maintain combining efficiency.

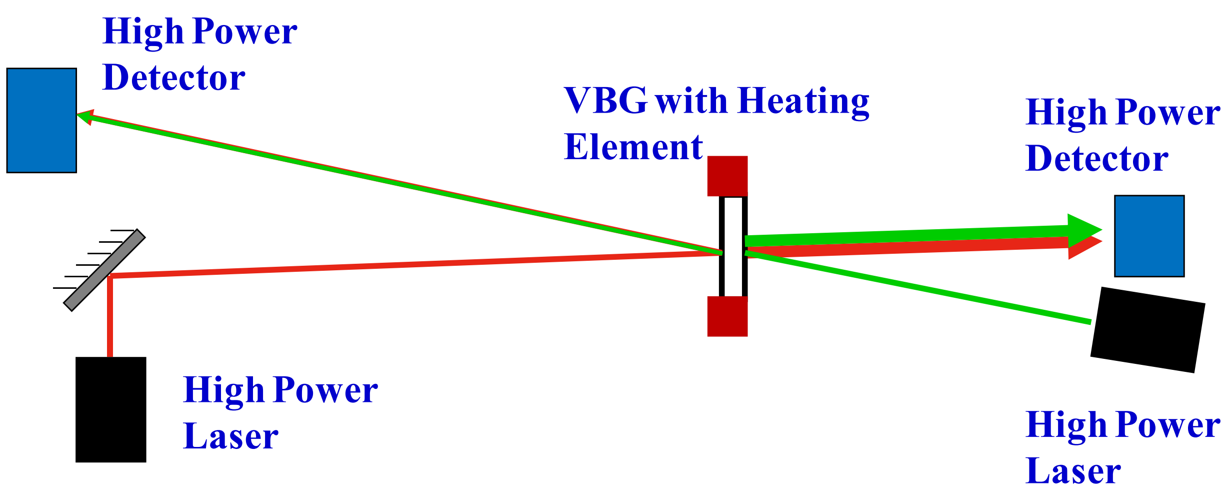

Figure 8: Two channel high power SBC experimental setup

The thermal tuning setup has been expanded to 5 channels, and low power tests have been finished. Total combining efficiency for 5 channels was greater than 90%, and combined beam $M^2 < 1.1$ has been demonstrated. Figure 10 shows the beam quality test results for 5 combined low power beams. The 5 channel results were done using high quality low power input beams. We will expand to 5 high quality, high power beams, and demonstrate 0.75 kW output with thermally tuned VBGs.

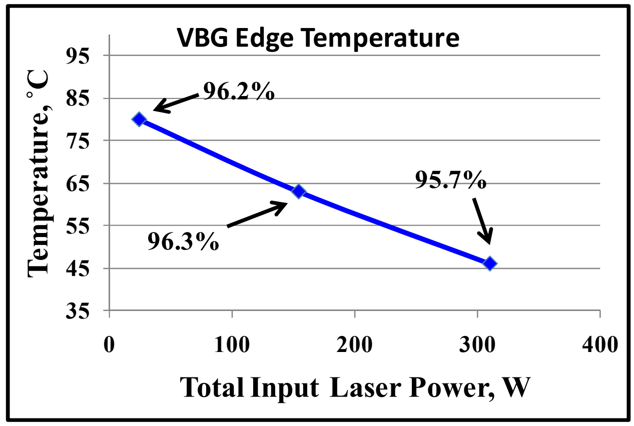

Figure 9: Two channel beam combining efficiency at different power levels and VBG edge temperatures

With electronicly controllable methods of tuning available, it becomes practical to create an automatically tuned beam combining system. Each VBG in the system has some diffraction loss that is transmitted through the grating rather than being reflected and combined. This lost power form each laser in the system can be measured to actively determine the diffraction efficiency of a given channel. An automated controller can then adjust either the VBG temperature or the laser wavelength to keep each channel in resonance without the need for mechanical adjustment. Figure 11 llustrates a concept for an automatically tuned beam combining system.

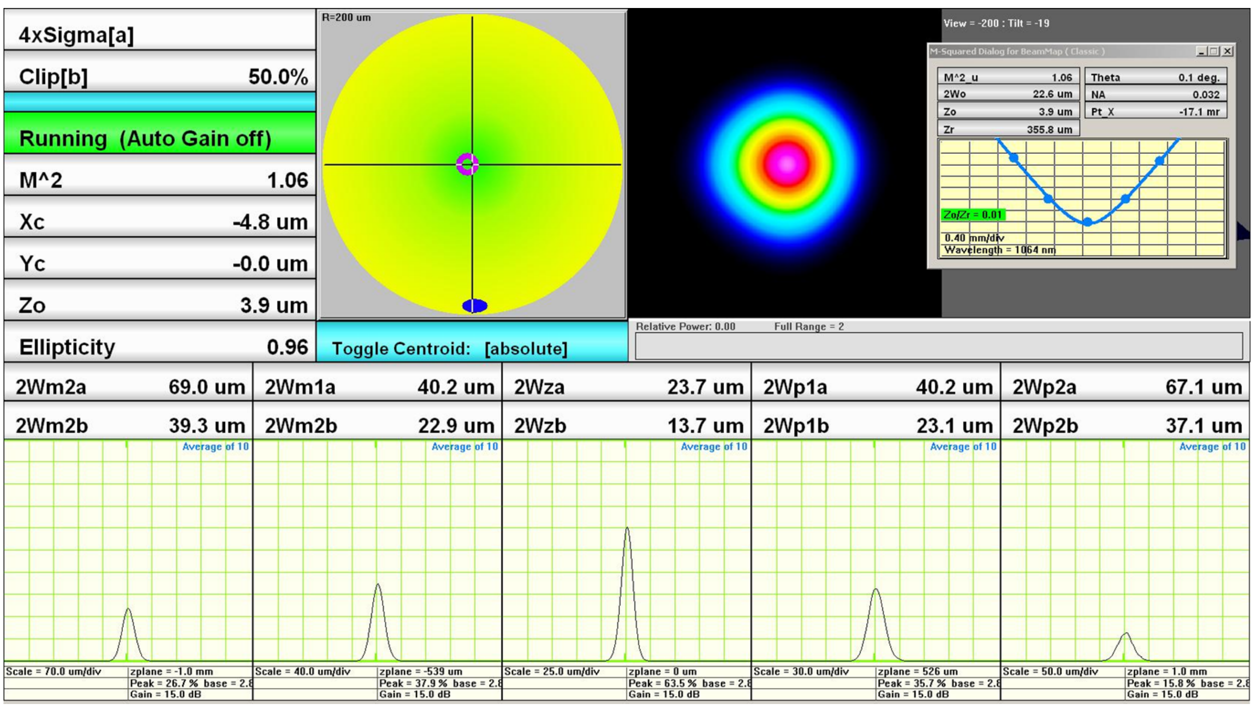

Figure 10: Five channel, combined low power beam quality, M^2=1.06

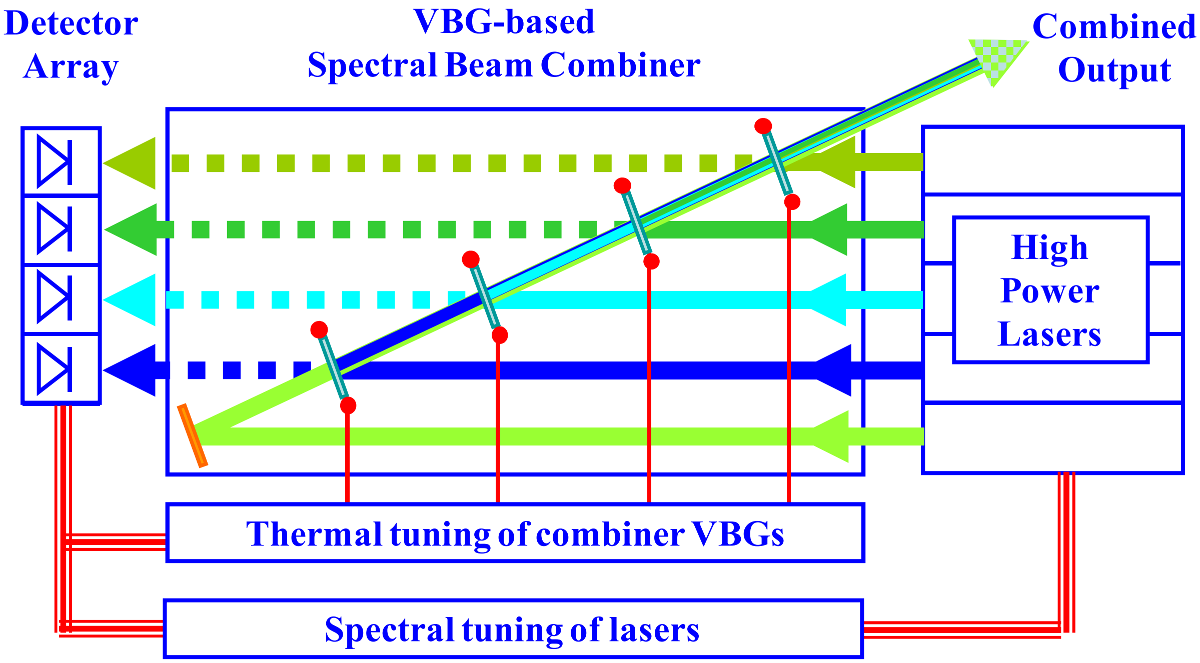

Figure 11: Concept for automated tuning of spectral beam combining system

6. CONCLUSIONS AND FUTURE EXPERIMENTS

Modeling of volume Bragg gratings, optimization of spectral beam combiner parameters, and temperature tuning of VBGs have enabled a demonstration of a robust and portable 5 channel SBC system. It could be aligned at low power and then thermally tuned for uninterrupted operation at any power up to the maximum. Two channel, thermall tuned, beam combining at 300 W output power, 96% efficiency and close to diffraction limit beam quality has been demonstrated. Five channel thermally tuned beam combining has been demonstrated using high quality low power beams, with combined beam $M2 < 1.1$. A five channel thermally controlled SBC system will be used in future experiments with five 150 W lasers with high beam quality, to demonstrate 0.75 kW five channel SBC with peak combining efficiency throughout the power range of the system and with near diffraction limited combined beam quality.

7. REFERENCES

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