Forced Air Cooling of Volume Bragg Gratings for Spectral Beam Combination

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ABSTRACT

Volume Bragg gratings have been successfully used in spectral beam combining of high power fiber lasers with narrow channel separation and in four channel passive coherent beam combining of fiber lasers. Future application of beam combining with kilowatt level lasers requires a more detailed understanding of how to cool the gratings without hurting beam quality. Forced air cooling blown across both surfaces of the grating is both easy and cheap, but has been avoided in the past due to concerns of how the air density fluctuations will hurt beam quality. It is now shown that forced air cooling has no adverse effect on the M^2 parameter due to density fluctuations in the air, and can efficiently cool VBG's such that no degradation in beam quality is seen due to thermal distortions.

Volume Bragg gratings are routinely made with low absorption on the level of 10^{-4} cm^{-1}. To model grating operation for kilowatt level lasers, absorption of the studied grating was artificially increased by 140 times. Thus the use of 80 W fiber lasers enabled imitation of 11kW beams, and the effects of forced air cooling on the beam quality were measured. Without cooling, the M^2 parameter quickly degrades, and diffraction efficiency is hurt. Forced air cooling for a simulated 9 kW laser beam in resonance with the RBG improved the M^2 value from 2.0 to the nominal value of 1.1, and decreased the laser induced temperature increment from 71 to 14°C.

Keywords: Volume Bragg grating, spectral beam combining, air cooling, thermal

1. INTRODUCTION

Current commercially available fiber systems allow for CW output powers of several kilowatts from single mode fibers. Further power scaling is ultimately limited by nonlinearities in the fiber such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) due to the narrow linewidth and small area of the fiber. Further power scaling therefore revolves around combining the outputs of several fibers, such as spectral beam combining (SBC) or coherent beam combining (CBC).

Volume Bragg gratings (VBG's) have proven to be an effective means of high spectral density beam combining in high power laser systems. VBG's allow for near 100% diffraction efficiency into a single order without sensitivity to polarization, and have had previous success with 5 channel spectral beam combing (SBC) for a maximum combined power of over 679W, a channel separation of 250pm and a combined spectral bandwidth of 1nm[1]. Due to the single order, high diffraction efficiency of the VBG, the M^2 parameter of the combined beam remains low at 1.6 for the 679W combined beam. While successful, such systems are ultimately limited by thermal lensing caused by high power being transmitted through the VBG. Recent advances have allowed for SBC with multiplexed VBG's, such that a single piece of glass can hold several gratings inside[2]. In such configurations, less power needs to be transmitted through the glass and thermal lensing problems can be easier to mitigate. To further reduce thermal problems, an air cooling system was explored.

2. VOLUME BRAGG GRATINGS

Volume Bragg gratings are holographically recorded in a photosensitive glass known as photo-thermo-refractive glass (PTR). PTR is a multi-component silicate glass, doped with silver, cerium, and fluorine. It has good thermal properties, and has low absorption (10^{-4} cm^{-1}) in the visible to the near infrared (350nm – 2500nm). It is linearly photosensitive,

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allowing for holograms to be recorded[3] in the following process. Silver atoms are reduced by UV light, forming the atomic state Ag^0. Thermal treatment allows the silver atoms to react with cerium atoms, forming nucleation sites for growth of NaF crystals. The crystal growth then modulates the refractive index, allowing for refractive index changes up to 1000ppm (Δn is about 10^{-3}).

Theoretical models of VBG's are described by Kogelnik[4] and based on coupled wave theory (CWT). Later models for VBG's recorded in PTR glass have been developed[5].

Reflecting VBG's allow for a narrow spectral range to be diffracted into a single order without sensitivity to polarization. Diffraction efficiencies near 100% with spectral selectivity (FWHM) of less than 50pm can be recorded. The narrow spectral selectivity of the reflecting VBG allows for SBC with dense channel separation.

3. METHODOLOGY

To reduce thermal lensing effects seen in high power SBC with VBG's, air cooling was explored. A device was design to hold the VBG in place, and allow air to flow across the front and back surfaces (Figure 1Figure 1). A VBG was then recorded to be used in a single high power beam. With the beam incident on the VBG, both the temperature of the VBG was monitored and then M^2 of the beam was measured.

Thermal effects were characterized by measuring the temperature of the grating and by measuring the beam quality (M^2 parameter). While measuring the beam quality doesn't allow the individual aberrations to be isolated, or allow the amount of defocus in the system to be measured, we are only concerned with the combined impact the thermal aberrations will have on the ability to focus the beam to a small spot size.

Two VBG's were recorded and tested in the air cooling system. One VBG was recorded low absorption and with high diffraction efficiency of more than 99%, a normal incidence resonance near 1065nm, and a FWHM of 300pm. The performance of this VBG was then tested in a 1KW fiber amplifier. A second VBG was recorded with high absorption ($140 * 10^{-4}$ cm^{-1}), a diffraction efficiency of near 95%, a normal incident resonance near 1065nm, and a FWHM of 150PM. The high absorption of the second VBG allows for the heating effects of a 11kW beam to be simulated using only a 80W laser.

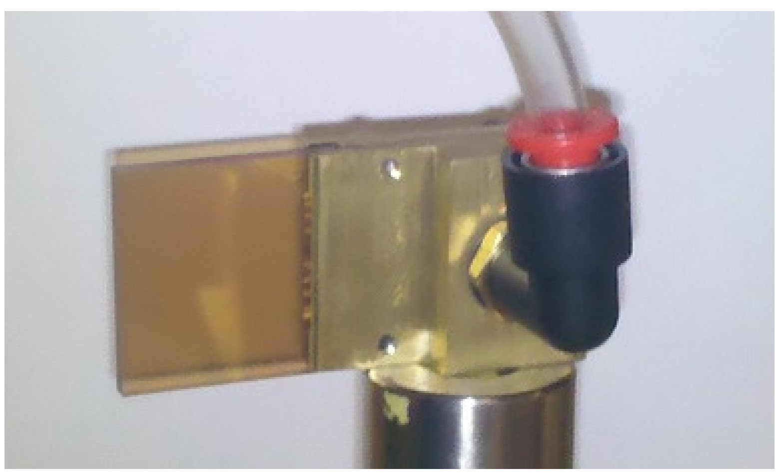

Figure 1: Image of the air cooling system with a high absorption VBG attached. Normal VBG's have an absorption of approximately 10^{-4} cm^{-1} and are clear. The absorption of this VBG was artificially increased by 140 times to allow for the simulation of 11kW beams.

4. EXPERIMENT

4.1 High Power

To test the effectiveness of VBG's, a series of experiments were performed in collaboration with Nufern. A low absorption VBG was recorded to be characterized in a high power laser and compare the performance with and without the air cooling. To fully understand the limits of the air cooling, the VBG was tested in two configurations: the reflecting and the transmitting configuration. The reflecting configuration is designed to show how much power can be diffracted by the VBG, while the transmitting configuration is designed to show the limits of SBC using a transmitted beam through the VBG. In the reflecting configuration, the VBG is tuned to be in resonance with the laser, diffracting all of the power.

The VBG was recorded with 99% diffraction efficiency, a normal incidence resonance centered at 1065nm and a spectral bandwidth (FWHM) of 300pm. The performance of the VBG was characterized in a 1KW fiber amplifier and compared to the performance using the air cooling system. The wavelength of the fiber amplifier was centered at 1064nm and was resolution limited to have a spectral bandwidth of less than 50pm, significantly less than that of the VBG. The beam was fiber delivered and collimated to a diameter of approximately 3.5mm. The nominal M^2 parameter of the beam was measured to be <1.1 through the full power range of the amplifier.

In the reflecting configuration, it was found that maintaining an air flow of 1.8SCFM (standard cubic feet per minute) allowed the beam to maintain an M^2 of less than 1.1 through the full power range (Figure 2). No degradation in beam quality was seen due to the turbulence of the air flow, and minimal heating of the VBG was seen at full power. At 907W incident on the VBG, the temperature of the VBG was seen to be 22°C, near room temperature. M^2 results are shown in Table 1.

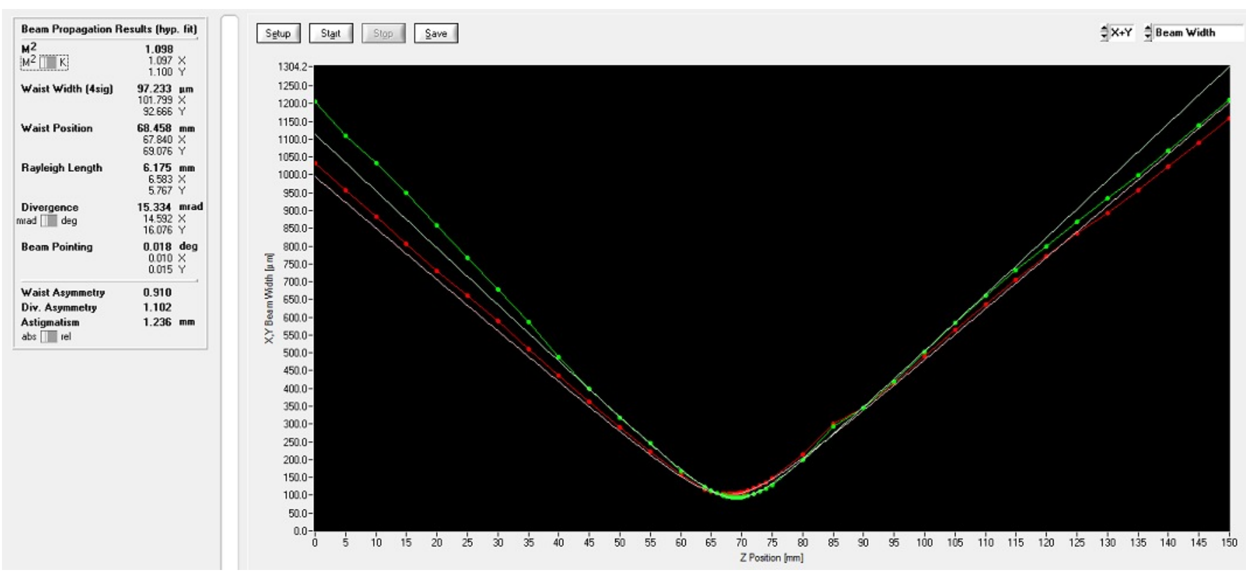

Figure 2: M^2 of the 907W beam after diffraction by the VBG air cooled with a 1.8SCFM flow rate. M^2 parameter remains below 1.1.

The air flow was then modulated to understand the minimum necessary to maintain high performance of the VBG. Reduction of the air flow showed higher temperatures in the VBG, but the temperatures were not high enough to hurt the M^2 of the beam. However, as the temperature of the VBG increased, thermal expansion inside the VBG caused the Bragg period to change and shifted the resonance of the VBG. This effect was seen at 0.6SCFM, where the resonance conditions changed, resulting in a reduction of diffraction efficiency for the used alignment. Results are shown in Table 2.

In the transmitting geometry, the beam interacts with a larger volume of the VBG, and more absorption is expected, leading to more thermal distortions. However, high beam quality could similarly be maintained at maximum power with only 1.8SCFM of air flow (Table 1). A higher temperature was observed, but at only 28°C, the VBG temperature was still very close to room temperature.

Again, the air flow was modulated. Through the full range of the modulation, no reduction of M^2 was seen. Reducing the air flow to 0.6SCFM showed the temperature increase to 36°C, which was not enough significantly distort the beam (Table 2).

Table 1: Effect of power level on beam quality with the low absorption grating using a flow rate of 1.8SCFM. High beam quality is maintained over the full power range of the laser using a flow rate of 1.8SCFM in both the transmitting and reflection geometry.

Incident Power (W)	M2 (Reflected, x/y)	M2 (Transmitted, x/y)
474	1.05/1.09	1.10/1.14
657	1.07/1.11	1.10/1.12
907	1.08/1.13	1.13/1.11

Table 2: Temperature results with air cooling using 907W incident on the grating and a low absorption grating. (*)At 907W, VBG diffraction efficiency dropped below 90% due Bragg wavelength temperature shift, power was reduced to 657W to maintain high diffraction efficiency.

Air Flow (SCFM)	Temperature (°C, Reflecting)	Temperature (°C, Transmitting)
0.6	23.9(*)	36.0
1.2	22.2	31.0
1.8	22.0	28.5

4.2 High Power Projections

Results using the low-absorption VBG in the 1KW amplifier were promising, and showed that air cooling was an efficient method of managing small thermal effects in high power beams. However, there was not enough data to understand the limits of such cooling methods for more drastic thermal effects in higher power beams. Without access to higher power lasers, a VBG with 140 times larger absorption was recorded to simulate the effects of high power beams using only 80W lasers. Such experiments allow simulation of power levels up to 11KW.

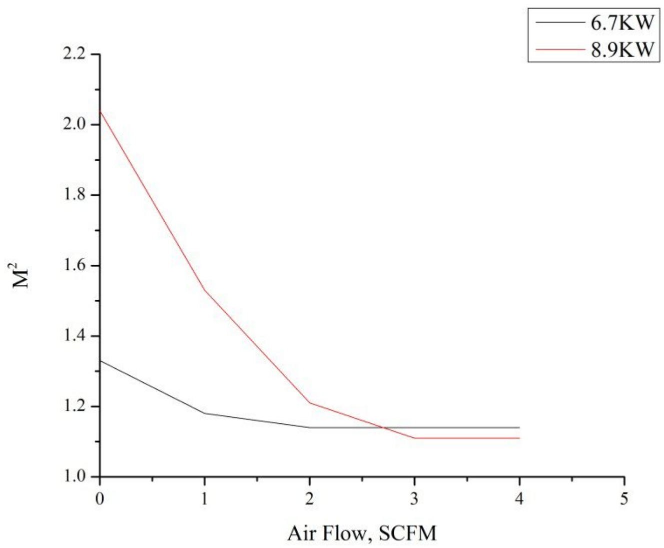

Figure 3: Degradation of M^2 due to thermal effects for the beam being diffracted by a high absorption VBG. High air flow can remove nearly all beam quality distortions even for the 8.9KW simulated beam.

With such a high absorption VBG, large thermal distortions could be easily induced in the VBG. Measurements of the diffracted beam quality are shown in Figure 3. Testing in the reflecting geometry showed that with no air flow, the M^2 parameter was increased to 2.04 for an 8.9KW simulated beam, and up to 1.33 for a 6.7KW beam. Increasing the air flow to a maximum of 5SCFM could remove all thermal distortions and return the M^2 parameter to a nominal value of 1.1. For the 8.9KW beam, and air flow of more than 3SCFM was needed to maintain high beam quality. While, for the 6.7KW beam, only an air flow of 2SCFM was needed to maintain the high beam quality.

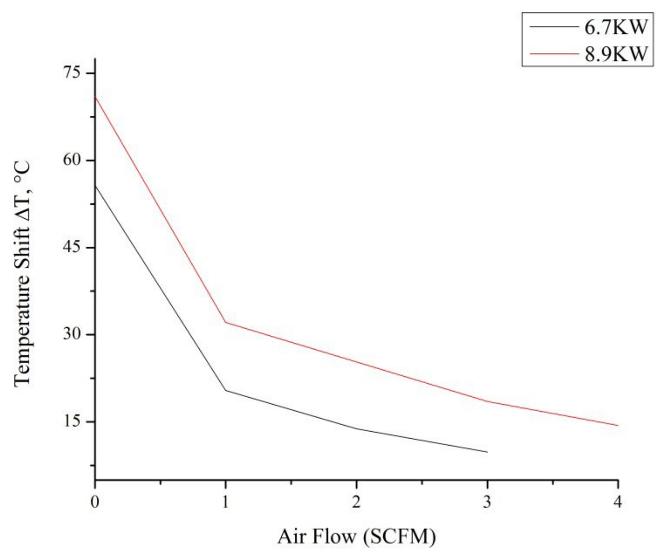

Figure 4: Temperature shift of the VBG relative to room temperature (near 20°C) for a beam diffracted by the high absorption grating. A relatively low air flow can remove nearly all of the heat.

Studying the temperature of the VBG (Figure 4). shows that high temperatures in the VBG are necessary to cause these large distortions in the diffracted beam. Without cooling, the VBG is heated to more than 73°C above room temperature, where the M^2 is only increased to 2.04. As was seen with the 1KW tests, a relatively low air flow of 1SCFM removes most of the heat. Higher airflow produces diminishing results, and at 3SCFM the VBG is cooled to 19°C above room temperature, where the M^2 parameter returns to a nominal value of 1.1. From this, it is seen that near 19°C of heating is acceptable without impacting beam quality.

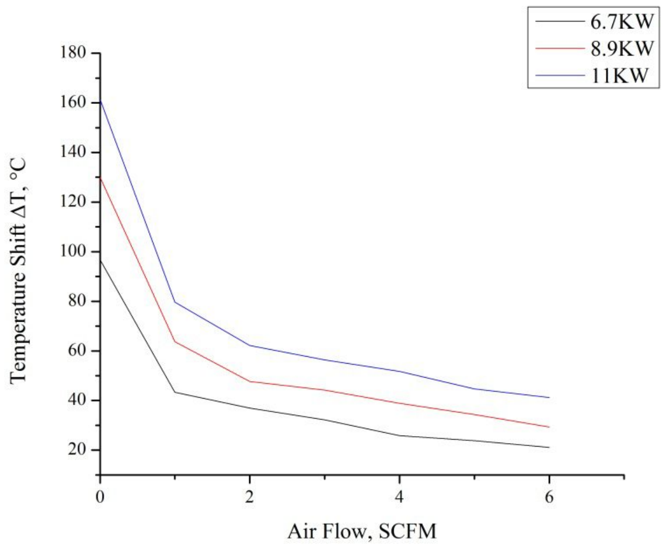

Figure 5: Temperature shift of the VBG relative to room temperature. High temperatures of more than 100°C above room temperatures are seen with no air flow, with less than 1SCFM of air flow required to remove most of the heating.

In the transmitting geometry, even higher temperatures are seen with worse beam quality degradation. Temperatures of the VBG are plotted in Figure 5, and M^2 as a function of air flow is shown in Figure 6. Again a small amount of air flow is necessary to remove most of the heating, while higher air flow pushes the temperature to some steady state above room temperature. Room temperature air flow alone is not enough to return the VBG to room temperature, and not all thermal distortions are removed for the 11KW beam. With 11KW of simulated power and a maximum air flow of 6SCFM, the VBG temperature can be reduced to 41°C above room temperature and M^2 can be reduced to 1.39. Only the 6.7KW beam could be sufficiently cooled to remove the thermal distortions and restore the M^2 to a level of 1.15 at a VBG temperature of 21°C above room temperature.

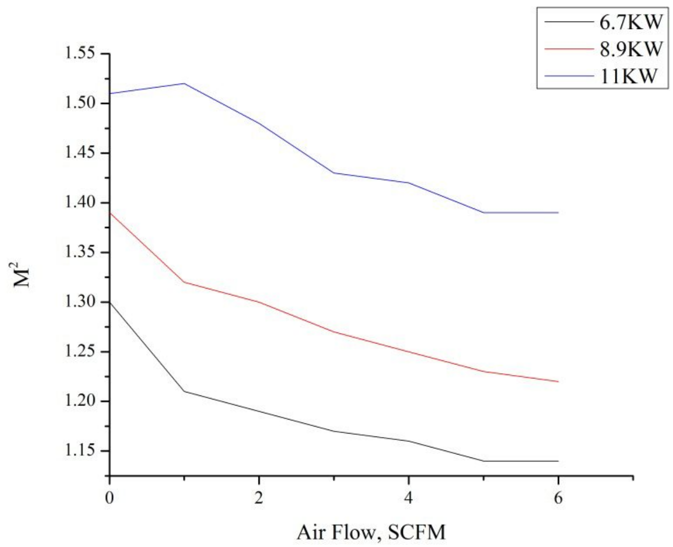

Figure 6: M^2 of the beam after transmission through the high absorption VBG.

5. MODELING

To further understand the air cooling, we built models of the VBG and air cooling in Comsol. A model of the brass holder and of the VBG was built for Comsol. This model allows the distribution of the air flow to be recreated, and to insure that using a low power laser with high absorption glass is the same as using a high power laser with normal absorption glass.

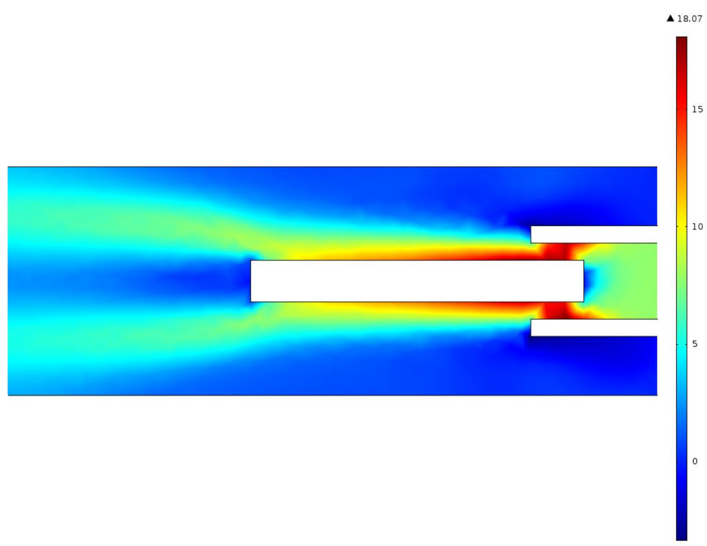

Figure 7: Y component of the velocity of the air for 1SCFM air flow modeled for a 6.7KW beam. Near the surface, air flow reaches speeds near 18m/s.

From this modeling several important facts were understood. Plots of the ycomponent of the velocity of the air (Figure 7) show that the air flow is turbulent. The turbulence improves the efficiency of the air cooling, allowing more air to come into contact with the surface of the glass, improving the efficiency of heat transport from the material. Peak temperatures at the center of the glass were measured in this model as a function of air flow and found to match closely to experimental predictions (Figure 9).

To understand why beam quality remained high, we studied the temperature distribution in the air (Figure 8). The temperature distribution most of the heat remains in the glass, while the ambient air is heated by only a few degrees. The relatively low air temperature results in only small density fluctuations, allowing phase distortions to remain minimal, having small impact on beam quality.

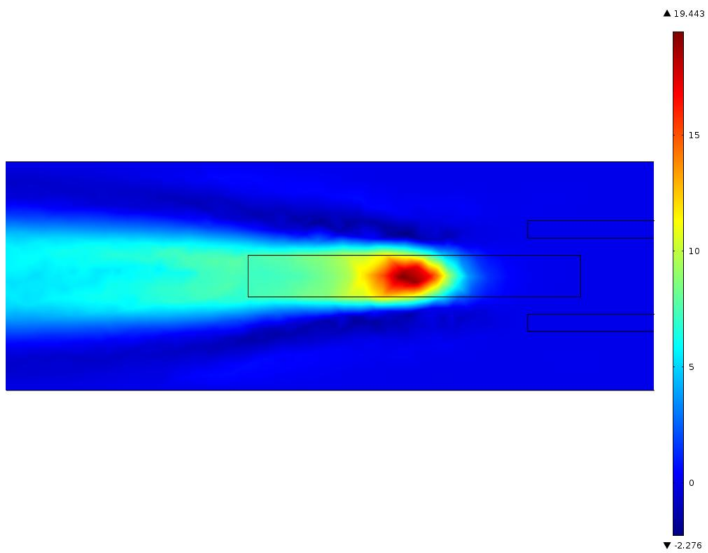

Figure 8: Temperature distribution of the air and the glass for a 6.7KW beam with 1SCFM of room temperature air flow. Surface temperatures are drastically reduced, although high temperatures are still seen deep in the glass.

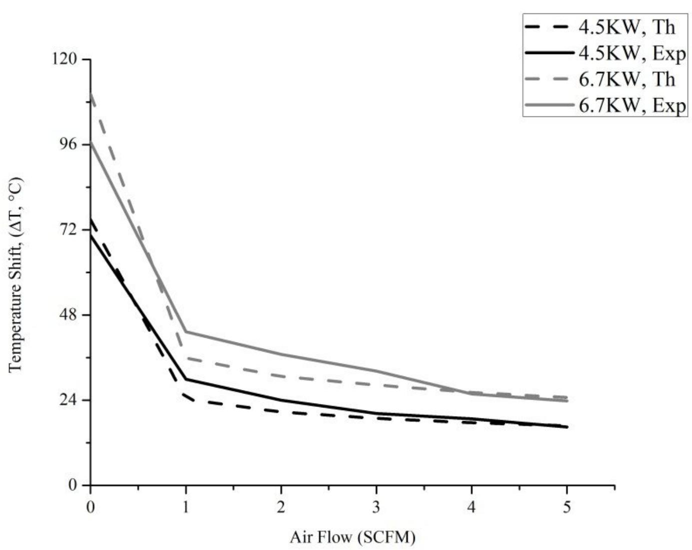

Figure 9: Temperature data comparing Comsol modeling to experimental data with the high absorption VBG.

6. CONCLUSION

These experiments have successfully shown that forced air cooling can be implemented with VBG's, successfully cooling them and preserving diffraction limited beam quality. Air cooling was once thought to add significant phase distortions to the beam, significantly hurting beam quality. These experimental results that beam quality is not negatively impacted by air cooling, and that air cooling can remove thermal distortions in the glass, restoring beam quality. Results from the high absorption VBG show that air cooling is sufficient to allow an 8.9KW, 6mm diameter beam to be diffracted by the VBG without loss of diffraction efficiency or degradation in the M^2 parameter. Further experiments have shown that a 6.7KW, 6mm diameter beam can be transmitted through the VBG and air cooled with a 5SCFM flow rate without loss of beam quality.

Current applications of VBG's have been used with high power SBC up to 1KW , both these models and experiments give hope that multiplexed VBG's can be used for SBC projects for high power applications above 10KW using simple air cooling to maintain high beam quality.

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