Active Coherent Superposition of Five Fiber Amplifiers at 670W using Multiplexed Volume Bragg Gratings

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ABSTRACT

We present an experimental study on active coherent combining of five Yb (Ytterbium)-doped fiber laser amplifiers that employs multiplexed volume Bragg gratings (MVBGs), reporting a combining efficiency of 82% and near-diffraction limited beam quality at a combined input power of 380 W, and 70% combining efficiency with equal beam quality at 670 W input power.

Keywords: Fiber laser, Volume gratings, Laser beam combination

1. INTRODUCTION

Beam combining techniques using gratings for high power fiber laser arrays have recently shown advancement in both coherent and incoherent beam combining schemes. Coherently, diffractive optical element (DOE), complex surface gratings, has demonstrated its capability in scalability in quantity and power handling [1, 2]. On the other hand, incoherent beam combining has achieved near 10 kW combined output using multilayer dielectric gratings [3]. As the individual fiber laser element reaches higher output power, the requirements for beam combining scheme and/or gratings element become more stringent. Gratings design criteria such as angle and power of diffraction, absorption, and bandwidth are the primary contribution to the combining efficiency. Furthermore, a stable phase locking scheme is required for coherent beam combining techniques. Common phase locking scheme involves stochastic parallel gradient descent algorithm (SPGD) [4] or locking of optical coherence by single-detector electronic frequency tagging (LOCSET) [5] is widely used and both schemes have shown significant successes on phase locking for coherent beam combination [6, 7]. In the context of this article, the coherent beam combining phase locking scheme is implemented using self-referenced LOCSET.

To exploit alternative approach for coherent beam combination, we conducted an experimental study using multiplexed volume Bragg gratings (MVBGs) [8]. In principle, there are two differences between surface gratings and holographic volume gratings when it comes to coherent beam combination. First is the order of diffractions, for surface gratings, the order of diffraction increases as more channels added to the beam combining system. The volume gratings uses the zeroth order diffraction for each input beam so more inscribed gratings are required for additional channels added to the combining system. The other difference is apparent: surface versus volume. The sophisticated gratings are etched on the surface for the surface gratings to split equally either on transmission or reflection. In order to reduce the loss through the combiner, reflective scheme for high power beam combining is often implemented [2]. However, in the scheme of passive coherent beam combining, it is more convenient to use transmissive Dammann surface gratings [9]. As for the holographic volume gratings, the inscriptions can be orientated to produce both transmissive and reflective gratings, however since the gratings are imbedded inside the volume of photo-thermal-refractive (PTR) glass [10], there exists intrinsic absorption through the glass regardless of the beam combining geometry. Nevertheless, both high density spectral beam combining and passive coherent coupling of fiber lasers have been demonstrated with high-efficiency MVBGs [11, 12].

Previously we have shown concept demonstration of active coherent beam combining with five fiber lasers using MVBGs and LOCSET up to 300 W of input power at 67% combining efficiency [8]. However, during the experiment, the MVBGs heated to 115°C at the highest input power level. In the same experiment, 82% combining

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efficiency was achieved with 80 W of input power and we observed little heating on the MVBGs. The result showed direct linkage between MVBGs heating and the combining efficiency and we suspected the cause of the heating was at the interface between the anti-reflective (AR) coating and the PTR glass. In this paper, we present a follow-up experimental study with recoated MVBGs.

2. MVBGS DESIGN AND EXPERIMENTAL SETUP

To combined five lasers using MVBGs, four sets of Bragg gratings were inscribed in a single PTR glass such that at near normal incident the input splits equally into five outputs under optimal Bragg condition. In the beam combining scenario, the MVBGs overlaps five input beams at different input angles in both near and far field and the combining takes effect when coherence is enforced on the selected output. The details of phase locking scheme will not be discussed in this article. For simplicity and safety of high power fiber laser amplifiers, we selected transmissive MVBGs as the beam combining element. OptiGrate Inc. fabricated the holographic element using their advanced gratings recording technique involves Michelson interferometer and UV lasers. The parameters for two transmissive MVBGs used in the experiments are shown in Table 1 & 2. The design parameters for MVBGs #2 take the input angle into account for more balanced diffraction efficiency at the desired input angle. Figure 1. shows the beam profiles of the split beams with input beam incident normal to the MVBGs. The split beams shows no degradation in beam quality at low input power. The AR coating has been reapplied for MVBGs #1 since our previously reported experiment.

Table 1. Transmissive MVBGs #1 specifications. The MVGs is designed to operate at 1064 nm and 0°, ±5°, ±10° input angles.

Grating	I	II	III	IV
Wavelength (nm)	1064	1064	1064	1064
Grating period (um)	6.13	12.21	12.24	6.14
Tilt (deg)	-3.38	-1.71	1.65	3.32
Input angle (deg)	-0.04	-0.04	-0.04	-0.04
Output angle (deg)	-10.20	-5.04	4.94	9.93
Measured diffraction efficiency at 1064 nm (%)	24.3	22.5	20.1	23.6
Thickness (mm)	4.11			
Material loss (%)	1			
Reflectivity per surface at 1064 nm (%)	<0.2			
Flatness at 633 nm	0.19λ:0.16λ			
Grating dimensions (mm)	25 x 25			

Table 2. Transmissive MVBGs #2 specifications. MVBGs #2 provides more strict parameters on angular position of the gratings.

Grating	I	II	III	IV
Wavelength (nm)	1064	1064	1064	1064
Grating period (um)	6.35	6.36	12.61	12.67
Tilt (deg)	3.24	-3.19	1.63	-1.58

Input angle (deg)	0.03	0.03	0.03	0.03
Output angle (deg)	9.65	-9.57	4.85	-4.76
Measured diffraction efficiency at 1064 nm and 0.03 deg input angle (%)	18.8	16.8	20.7	20
Transmission at 0.03 deg input angle (%)	23.3			
Thickness (mm)	4.3			
Material loss (%)	0.5			
Reflectivity per surface at 1064 nm (%)	<0.3			
Flatness at 633 nm	0.14λ:0.13λ			
Grating dimensions (mm)	22 x 22			

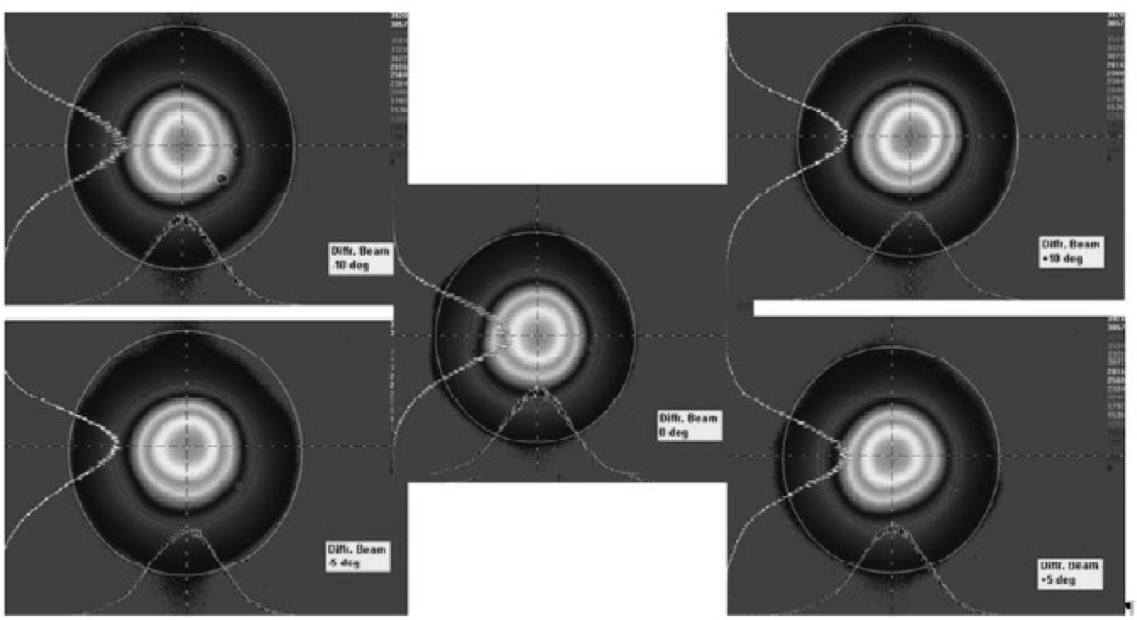

Figure 1. Output beam profiles of split beams with input incident near normal to the transmissive MVBGs.

The experimental setup for active coherent beam combining of five fiber laser amplifiers is shown in Figure 2. The Yb-doped fiber laser amplifiers are arranged in master oscillator power amplifier (MOPA) configuration with 10 kHz narrow linewidth non-planar ring oscillator (NPRO) as the common seed source at wavelength of 1064 nm. Each fiber amplifier has three stages amplification, where first stage amplifies 10 mW to 200 mW, second stage amplifies previous stage to 5 W, and third stage amplification outputs up to 150 W. Since coherent beam combining requires each of the input beams to have the same polarization, the linearly polarized light from the NPRO seed source is polarization maintained using polarization maintaining (PM) fibers throughout the entire fiber amplifier system. To mitigate any backward amplification such as reflection from the output facet or nonlinear effect stimulated Brillouin scattering (SBS), each amplification stage is implemented with fiber pigtailed optical isolator to prevent catastrophic damage to the amplifier system. An external high power free space isolator is in place at the output of each fiber amplifier to prevent scattering light from entering the amplifier.

Each input beam is aligned to the MVBGs with a pair of turning mirrors. The optical alignment starts with P3 incident on the MVBGs at near normal angle and the MVBGs is adjusted so the spit beams have close to equal powers. The center split beam is passed through the beam block and sampled at the wedge to align with the Spiricon beam profiler and LOCSET. Majority of the power passes through the wedge and is measured with the power meter. The rest of the laser beams are aligned to P3 on the beam profiler in both near and far field to ensure greater than 90% spatial overlaps. Every laser is polarization controlled using a set of half-wave plate, polarizer, and half-wave plate to achieve the same linear polarization in the beam combining system. Phase adjustment is controlled using lithium niobate ($LiNbO_3$) modulator at modulation frequency of 100 MHz. At 150 W of output power, each fiber amplifier is enhanced with SBS mitigation technique involving linewidth broadening. The enhancement technique is outside the scope of this article and will not be part of the discussion.

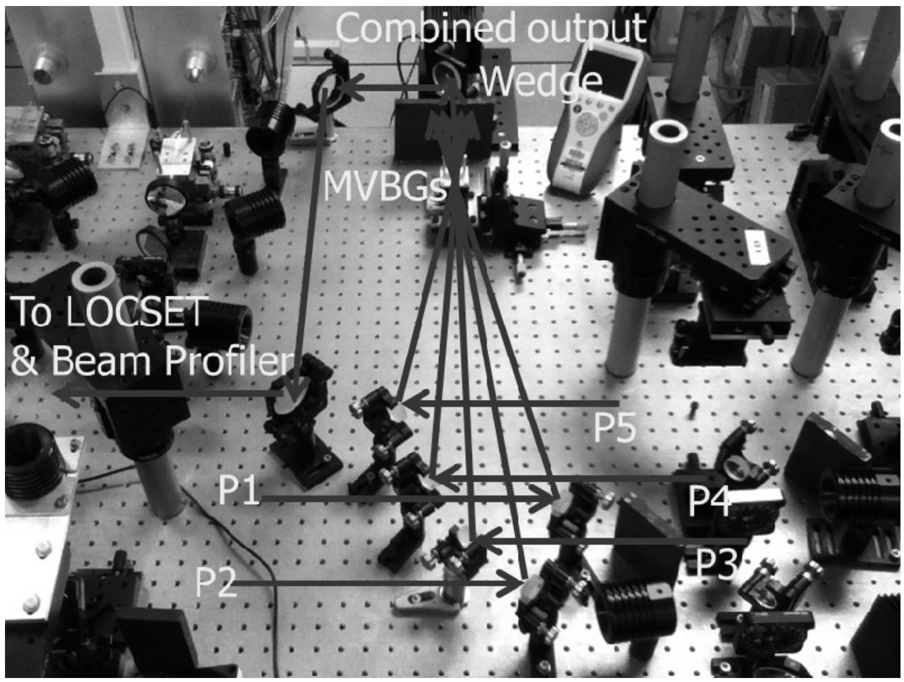

Figure 2. MVBGs active coherent beam combining experimental setup. P1~P5 represents 5 input beams from fiber MOPA laser array. P1 is used as the reference beam for self-referenced LOCSET to control the phase modulator and minimize the phase error between P2~P4 and P1. M1~M5 are the steering mirrors for aligning each input lasers to the multiplexed VBGs. The loss ports are blocked after the MVBGs. The small percentage of combined output is sampled using the wedge as feedback mechanism for phase locking.

3. RESULTS AND CONCLUSION

Figure 3. shows the active coherent beam combining results for five fiber laser amplifiers using the transmissive MVBGs #1. The result shows greater than 80% combining efficiency achieved with total input power less than 400 W and 70% combining efficiency with 670 W of total input power. Measured beam quality (M^2) is 1.3 for input power less than 400 W and 1.6 at 670 W input. The reduced beam quality is mainly due to one of the fiber laser amplifier produces slightly worse beam quality at higher power. Replacing MVBGs #1 with #2 showed little to no change to both beam quality and combining efficiency. This indicates the diffraction power for individual gratings is not too sensitive for active coherent beam combining. Theoretically, greater than 90% combining efficiency is achievable with the transmissive MVBGs, however, degradation factors such as spatial overlapping on the MVBGs, collimation, polarization, and uneven power between input beams introduce losses for most if not all of the high power coherent beam combining techniques.

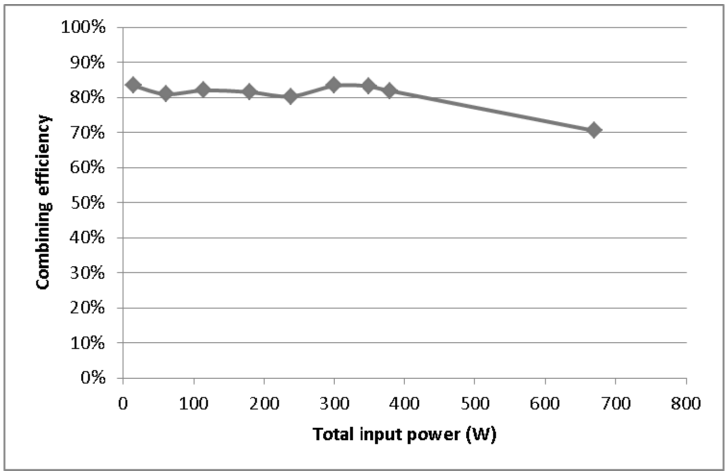

Figure 3. Combining efficiency vs total input power with recoated MVBGs #1. The combining efficiency remains stable up to 400W of input power. MVBGs #2 shows similar data trend.

The slight declination in combining efficiency for optical input power greater than 400 W is caused by heating in the MVBGs. Figure 4. shows a thermal image of the MVBGs with 0.6 kW incident power and beam diameter of 3 mm, where the maximum temperature of 44.3°C is detected within the MVBGs aperture. While at 400 W input power, the MVBGs stayed below 30°C, which means for a 1 cm diameter beam, the MVBGs can handle up to approximately 5.6 kW input power before heating starts to take effect in combining efficiency.

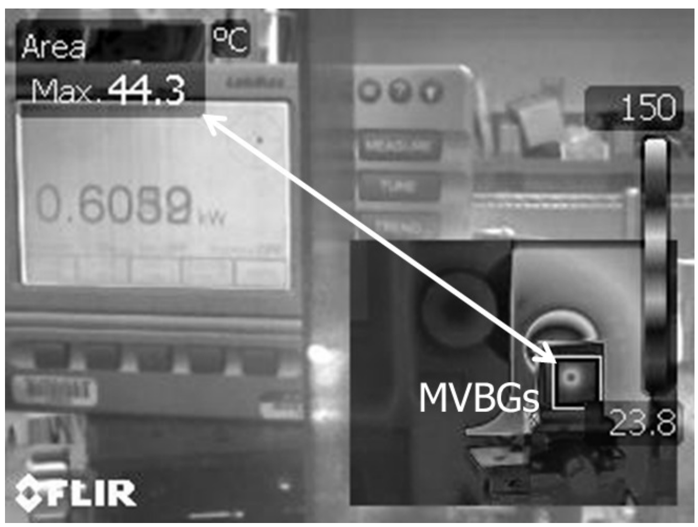

Figure 4. Thermal study of MVBGs heating at high input power of 0.6kW. The left corner shows the maximum temperature measured within the entire MVBGs aperture at 44.3°C.

In summary, we have performed an experimental study of transmissive MVBGs and achieved greater than 80% beam combining efficiency for less than 400 W of input power and 70% combining efficiency at our maximum input power 670 W. Comparing to our previous reported data, the recoated MVBGs showed excellent improvement in heating and combining efficiency at nearly twice the input power. The result clearly indicates the capability of MVBGs for coherent beam combining at high power. Passive coherent beam combining using reflective MVBGs has also shown promising results from Apurva et al. [12] at CREOL, University of Central Florida. Thus in the future, we plan to exploit beam combining schemes involving passive phase locking and MVBGs for high power and longer wavelength semiconductor lasers such as vertical external cavity surface emitting lasers (VECSELs) and quantum cascade lasers (QCLs).

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