High Brightness Spectral Beam Combination of High-Power Vertical-External-Cavity Surface-Emitting Lasers

Yushi Kaneda, Li Fan, Ta-Chen Hsu, Nasser Peyghambarian, Mahmoud Fallahi, Armis R. Zakharian, Jörg Hader, Jerome V. Moloney, Wolfgang Stoltz, Stephan Koch, Robert Bedford, Armen Sevian, and Leonid Glebov

***Abstract*—High brightness spectral beam combination of two high-power vertical-external-cavity surface-emitting laser (VECSEL) using volume Bragg grating in a photo-thermo-refractive (PTR) glass is demonstrated. High efficiency beam combination in excess of 90% is achieved, providing an efficient method for power scaling of diffraction limited beam. The beam quality of each starting lasers was 1.68 and 1.35, and that of combined beam was 1.9. Scaling opportunities based on the parameters of VECSELs and PTR Bragg gratings are discussed.**

***Index Terms*—Semiconductor laser, spectral combination, vertical-external-cavity surface-emitting laser (VECSEL), volume Bragg grating (VBG).**

THERE HAS been significant interest in ways to increase the brightness of the laser output beam to multiple kilowatts levels. Semiconductor lasers are capable of providing high brightness, compactness, wavelength tailoring capability, and possibility of wavelength tuning. However, the difficulty is to reach very high brightness, such as kilowatt-level power in near-diffraction-limited beam. One of the approaches toward the objective is to combine the output of multiple laser elements. Spectral beam combination allows simple and efficient power scaling. Compared to an alternative approach, namely a single laser giving diffraction-limited output with kilowatts of output power, such a combination scheme can operate in soft-failure mode, allowing the whole system to continue to work when some of the laser elements fail. Further, the heat dissipation requirement can be relieved as the sources of the heat can be distributed. Unlike spatial beam combination, spectral beam combination allows relative preservation of the source laser beam qualities [1], [2].

For spectral combination schemes, a highly wavelength-dependent combination device and tunable laser sources are necessary. Volume Bragg gratings (VBGs) in photo-thermo-refractive (PTR) glass have narrow diffraction bandwidth combined with high diffraction efficiency, low losses and tolerance to high power laser radiation [3]. These gratings were effectively used for spectral radiation combination of high-power fiber lasers [4] where efficient combination of two 100-W beams exceeded 90%. Compared to conventional surface diffraction gratings, VBG allows the diffraction angle and wavelength to be independently tailored, giving flexibility in configuration when cascading for multiple elements to increase the number of channels. VBG devices can also be used to control the operating wavelength of the vertical-external-cavity surface-emitting lasers (VECSELs). We did not perform such experiments as the VBGs did not have proper antireflection (AR) coatings. In this report, we demonstrate the spectral beam combination of two tunable VECSELs, using a VBG made of PTR glass and discuss the scaling of combined power based on the results.

We used a tunable VECSEL laser using a gain medium similar to what is described elsewhere [5]. The "z-cavity" is folded at the VECSEL chip to double-pass the gain and increase the efficiency. The fold by a concave mirror (ROC $=$ 75 mm) yields flexibility in the resonator mode size by adjusting the distance between the flat-HR end mirror. The resonator mode size is estimated to be 190-μm radius in tangential (horizontal) and 210-μm radius in sagittal (vertical) orientation. The VECSEL chip was pumped with an 808-nm, 23-W, fiber-coupled diode bar, emitting from a 100-μm diameter, NA $=$ 0.22 fiber. The output facet of the fiber was imaged onto the VECSEL chip. Without the birefringent filter, the laser had a threshold pump power of 3.1 W with a heatsink temperature of 10 °C. The spatial mode of the laser output was TEM_{00} and the lasing wavelength was 971.9 nm in this condition. A 2-mm-thick quartz birefringent filter was inserted to allow the wavelength of the laser to be tuned. Using a combination of heat-sink temperature and modification of pump power, it was possible to tune from 960 to 981 nm and maintain a spectral width around 0.22∼0.25 nm. For this particular device, the maximum output power is slightly greater than 4 W.

The tunable output from the VECSEL was used for the spectral characterization of the VBG. The transmitting VBG was designed for an incident angle of 18° at 975 nm and had a narrow bandwidth so that another beam at the same angle at 5 nm apart from the Bragg wavelength would be totally transmitted. The VBG did not have an AR coating. The output

Manuscript received March 10, 2006; revised May 31, 2006. This work was supported by the Air Force Office of Scientific Research through an MRI Program F49620-02-1-0380 and by Deutsche Forschungsgemeinschaft.

Y. Kaneda, L. Fan, T.-C. Hsu, N. Peyghambarian, and M. Fallahi are with the College of Optical Sciences, The University of Arizona, Tucson, AZ 85721 USA (e-mail: ykaneda@optics.arizona.edu).

A. R. Zakharian, J. Hader, and J. V. Moloney are with Arizona Center for Mathematical Science, The University of Arizona, Tucson, AZ 85721 USA.

W. Stoltz and S. Koch are with the Material Science Center and Department of Physics, Philips Universität Marburg, 35032 Marburg, Germany.

R. Bedford is with the Air Force Research Laboratory, Wright-Patterson AFB, OH 45433 USA.

A. Sevian and L. Glebov are with the College of Optics and Photonics, CREOL and FPCE, University of Central Florida, Orlando, FL 32816 USA.

Digital Object Identifier 10.1109/LPT.2006.880758

Report Documentation Page

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **MAY 2006**	2. REPORT TYPE	3. DATES COVERED **00-05-2006 to 00-05-2006**
4. TITLE AND SUBTITLE **High Brightness Spectral Beam Combination of High-Power Vertical-External-Cavity Surface-Emitting Lasers**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Central Florida,College of Optics & Photonics/CREOL,PO Box 162700,Orlando,FL,32816-2700**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**3**	

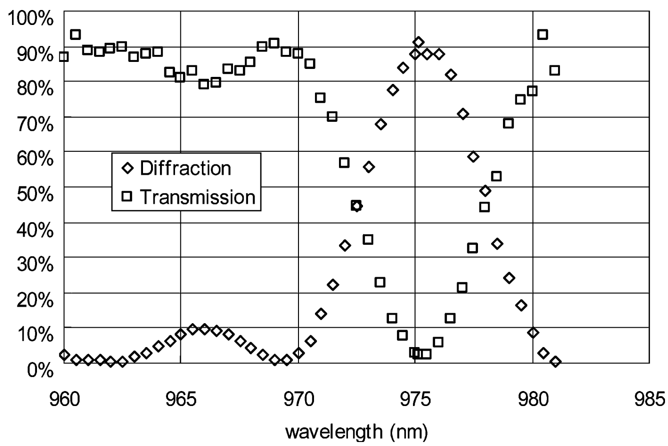

Fig. 1. Diffraction and transmission spectrum.

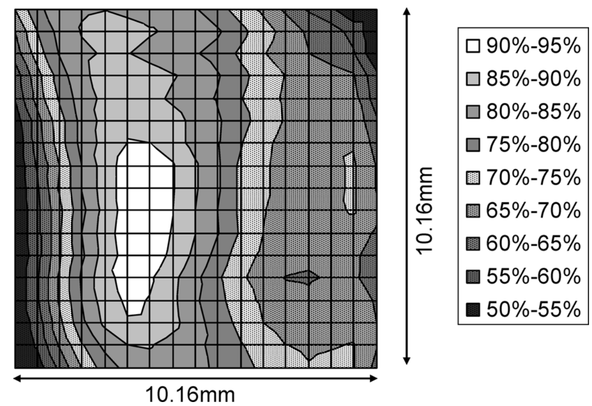

Fig. 2. Diffraction efficiency mapping of the VBG.

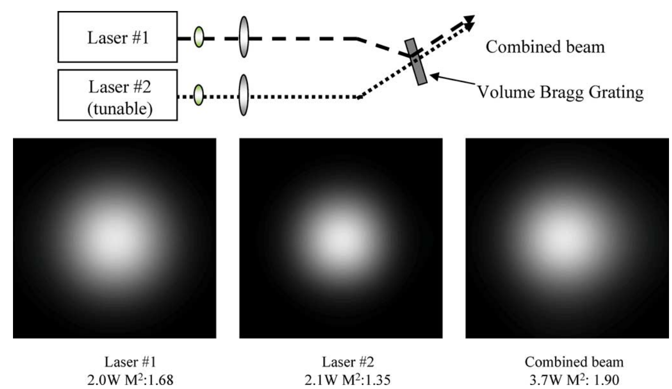

Fig. 3. Experimental schematic and far-field beam profile of the beams.

beam of the VECSEL was collimated and expanded to ~5-mm diameter. This VECSEL had a narrow spectrum, relatively low divergence, and was suitable for diffraction efficiency characterization. The angle of the VBG was fixed and the wavelength was scanned, measuring the diffracted, transmitted, and reflected power at each wavelength. The reflected power varied from below 4% to 8%, indicating that some of the reflection from the output surface was diffracted back and not measured in the direction of the reflection from the input surface.

Diffraction efficiency of VBG as a function of the wavelength is shown in Fig. 1. The diffracted spectrum shows a pattern resembling $\operatorname{sinc}^2 x$ pattern, a reasonable agreement with the theory. The peak diffraction efficiency is 91% and comes to a minimum at around 969 nm, close to its designed value. No overmodulation of refractive index was observed from the spectra.

The transmission almost compliments the diffraction, exhibiting >90% transmission at diffraction minima. Considering the 3.5%–4% of reflection per surface, the sum of diffraction and material loss does not exceed 1%–2%. Therefore, a device with proper AR coating will perform with transmission and diffraction efficiencies 98%–99% at the optimum wavelengths.

We then evaluated the homogeneity of the VBG. The wavelength was fixed at 975 nm, and the angle was adjusted to yield the maximum diffraction efficiency. The VBG was translated in the plane of the device over a 10.16-mm square area, while diffracted power was measured. The result is shown in Fig. 2. Greater than 90% diffraction efficiency was observed over a translation of 1 × 3 mm. Considering the beam size of 5 mm, the device has fair and sufficient homogeneity for beam combining.

Beam combination was performed using two similar VECSELs, one of which (Laser 1) was operating at a fixed wavelength of 982 nm and an output power of 2 W. The other laser (Laser 2) was operated at 2.1 W and was tuned to 975 nm. The output beams from two lasers were individually collimated to approximately 5-mm diameter, and directed to the VBG. The angle of incidence onto the VBG was adjusted so that the 982-nm beam was diffracted, and we adjusted the wavelength of the other laser for maximum transmission. With the total 4.1 W of incident power onto the VBG device, 3.7 W was combined in a single beam, representing 90% combination efficiency. The loss was mainly due to the reflection loss of the VBG that was not AR coated. The M^2 value of the 982-nm laser was 1.68, and that of 975-nm laser was 1.35. We measured the M^2 of the combined beam to be 1.9. The slight increase in the M^2 value for VECSELs could be attributed to the small mismatch of collimation of the two input beams. The beam patterns of the individual lasers and the combined beam are shown in Fig. 3.

As can be seen in Fig. 1, the VBG devices have zero-diffraction wavelengths that are almost equally spaced. By setting Nth VBG to be highly transmissive at wavelengths $\lambda_1, \lambda_2, \ldots, \lambda_{N-1}$, and highly diffractive at λ_N, all beams can be combined into one beam, without significantly impacting the brightness.

If we assume the transmission of the VBG to be η_T, its diffraction efficiency to be η_D, and power from each laser to be P, combined power $P_{\mathrm{total}}(N)$ can be written as

$$P_{\mathrm{total}}(N) = P\left(\eta_T^{N-1} + \eta_D \frac{1-\eta_T^{N-1}}{1-\eta_T}\right). \tag{1}$$

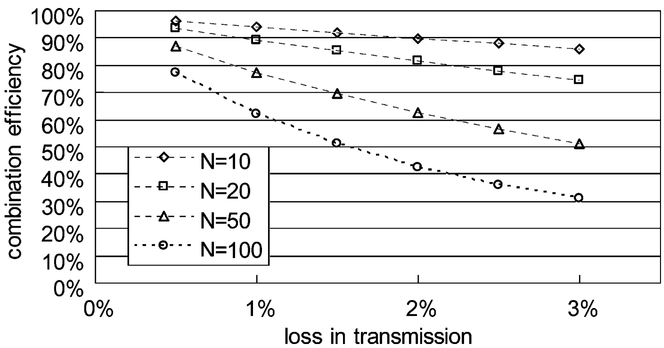

Fig. 4. Total combination efficiency as a function of loss in transmission $(1 - \eta_T)$.

Therefore, the total combination efficiency $\eta_{\rm total}(N)$, the fraction of the power from all N source lasers that is transmitted to the combined beam through $N-1$ VBGs is

$$\eta_{\rm total}(N) = \frac{1}{N}\left(\eta_T^{N-1} + \eta_D \frac{1-\eta_T^{N-1}}{1-\eta_T}\right). \quad (2)$$

We examine the effects of the diffraction loss and transmission loss to the total combination loss. It was found that the total combination efficiency does not suffer much from the loss in diffraction, maintaining fairly constant total combination efficiency with increasing diffraction loss of up to a few percents. On the other hand, as can be seen in Fig. 4, the total combination efficiency is significantly affected by the transmission losses. In this simulation, η_D is assumed to be 0.98. This difference in effects of the losses to the total efficiency is because the transmission loss affects the throughput multiple times, particularly for the output in the upstream in the combination chain.

From these calculations, it seems possible to combine tens of lasers with 60%–80% combination efficiency.

Although the efficiency becomes lower, for the increased N, the combined power can be increased to $P_{\max} = P(\eta_D/1-\eta_T)$, and cannot be increased beyond it. For example, for the case of $\eta_D = 0.98$ and $\eta_T = 0.99$. To reach 50% of $P_{\max}$, combination of 69 lasers would be needed to obtain a combined beam that is 49 times the power of individual lasers. Wavelength-tunable VECSEL similar to described here has been reported with output power of greater than 10 W with similar spectral characteristics, only limited by the available pump power up to at least a few tens of watts of output power [6]. Assuming TEM_{00} – mode, 20-W, spectrally narrow output is available, the combined output would approach the level of 1 kW. VBGs with narrower bandwidths should be used to maintain the total spectral width of the combined beam to a practical range. For instance, a total spectral width of 140 nm and a 2-nm channel-spacing would allow 70 beams to be combined, giving ~1 kW of total combined power with similar combination performances. In this case, the total electrical-to-optical efficiency, excluding the power needed for heat dissipation, would be around 9%, given the 30% power efficiency of the fiber-coupled diode bars, 40% efficiency for the VECSEL [6], and 70% for the spectral combination.

In summary, spectral beam combination of two VECSELs emitting at 982 and 975 nm using PTR VBG was demonstrated. The combination efficiency was 90%, giving 3.7-W output from source lasers having 2 and 2.1 W. The efficiency is limited mainly by the reflection at the uncoated surfaces of the VBG. The quality of the combined beam is similar to that of each laser, and suffers a very small increase in the M^2 value. Slight increase in the M^2 value of the combined beam may be attributed to the mismatch in collimation. Modeling of the combination of multiple lasers has found that the transmission loss has significant impact in total combination efficiency. From this model, we have shown that near-diffraction-limited, kilowatt-level output should be possible by combining tens of lasers each having tens of watts, allowing soft-failure operation.

REFERENCES

[1] S. J. Augst, A. K. Goyal, R. L. Aggarwal, T. Y. Fan, and A. Sanchez, "Wavelength beam combining of ytterbium fiber lasers," *Opt. Lett.*, vol. 28, pp. 331–333, 2003.
[2] V. Daneu, A. Sanchez, T. Y. Fan, H. K. Choi, G. W. Turner, and C. C. Cook, "Spectral beam combining of a broad-stripe diode laser array in an external cavity," *Opt. Lett.*, vol. 25, pp. 405–407, 2000.
[3] L. B. Glebov, V. I. Smirnova, C. M. Stickleyb, and I. V. Ciapurina, "New approach to robust optics for HEL systems," *Proc. SPIE*, vol. 4724, pp. 101–109, 2002.
[4] I. V. Ciapurin, L. B. Glebov, L. N. Glebova, V. I. Smirnov, and E. V. Rotari, "Incoherent combining of 100-W Yb-fiber laser beams by PTR Bragg grating," *Proc. SPIE*, vol. 4974, pp. 209–219, 2003.
[5] L. Fan, M. Fallahi, J. T. Murray, R. Bedford, Y. Kaneda, A. R. Zakharian, J. Hader, J. V. Moloney, W. Stolz, and S. W. Koch, "Tunable high-power high-brightness linearly polarized vertical-external-cavity surface-emitting lasers," *Appl. Phys. Lett.*, vol. 88, no. 021105, 2006.
[6] J. L. A. Chilla, S. D. Butterworth, A. Zeitschel, J. P. Charles, A. L. Caprara, M. K. Reed, and L. Spinelli, "High-power optically pumped semiconductor lasers," *Proc. SPIE*, vol. 5332, pp. 143–150, 2004.