Beam Combination of Multiple Vertical External Cavity Surface Emitting Lasers via Volume Bragg Gratings

Chunte A. Lu*[a], William P. Roach[a], Genesh Balakrishnan[b], Alexander R. Albrecht[b],
Jerome V. Moloney[c], and Leonid B. Glebov[d]
[a]Air Force Research Laboratory, Directed Energy Directorate,
3550 Aberdeen Ave SE, Kirtland AFB, NM 87117, USA
[b]Center for High Technology Materials, University of New Mexico, Albuquerque, NM 87106 USA;
[c]College of Optical Sciences, The University of Arizona, Tucson, AZ 85721 USA;
[d]CREOL/College of Optics and Photonics, University of Central Florida, Orlando, FL 32816, USA

ABSTRACT

We present an experimental study on beam combining techniques with multiple vertical external cavity surface emitting lasers (VECSELs) using volume Bragg gratings (VBGs). The specially designed holographic gratings introduce frequency specific feedback for the near infrared wavelength VECSELs to achieve both spectral linewidth narrowing and beam combination effects. For coherent addition, we obtained >3W output power with 8% slope efficiency in a coherent power scaling cavity scheme. In the multiplexed VBGs (MVBGs) wavelength beam combining compound cavity scheme, we measured >6W combined output with nearly 100% combining efficiency. Both beam combining/power scaling schemes produced spectrally narrowed and near diffraction limited outputs.

Keywords: Power scaling, beam combining, holographic gratings, semiconductor laser, VECSELs

1. INTRODUCTION

In the past few years, semiconductor vertical external cavity surface emitting lasers (VECSELs) have shown significant improvement in both output power and narrow linewidth wavelength tuning range. Especially in the near infrared wavelength region, the output power from a single gain chip has reached more than 100W of optical power[1]. For narrow linewidth operation, greater than 50nm wavelength tuning range has been demonstrated using a birefringent filter[2]. However, the output power is greatly reduced when applying the linewidth narrowing mechanism. In order to reach higher power with narrow spectral linewidth output, it is necessary to conduct beam combination/power scaling using multiple devices.

Several beam combining/power scaling techniques have been investigated in the past to achieve high power narrow linewidth output. In the case of coherent power addition, it has been demonstrated using two VECSELs in a W-shaped cavity[3]. In a different scenario, spectral beam combination using the volume Bragg gratings (VBGs) as an external combining element has also shown efficient beam combining result[4]. Besides spectral beam combination, another method to incoherently overlap two VECSELs outputs has been demonstrated using a polarizer inside a T-shaped cavity[5]. All above beam combining/power scaling scheme used a birefringent filter placed inside the laser cavity to achieve tunable narrow linewidth output. To the best of our knowledge, there has not been any reported study for beam combining/power scaling multiple VECSELs using VBGs as intracavity element.

Therefore, here we propose to conduct beam combination study using the holographic VBGs arranged inside the VECSELs cavity to achieve both spectral narrowing and beam combining effects. The VBGs are holographic gratings inscribed in a photo-thermal-refractive (PTR) glass using an ultraviolet laser source. Depending on the gratings design, it can be a partial reflector or a high reflector for spectral filtering. It has been shown the VBGs are capable of combining multiple lasers both coherently and incoherently[6]. More recently, we have also conducted experimental study to actively coherent combined five high power fiber laser amplifiers using transmissive multiplexed VBGs[7] (MVBGs). In this paper, we present two beam combination techniques using the VBGs. First, we will show the coherent addition scheme using the VBGs in a Z-shaped cavity. Then we will describe the experimental setup and results of a novel wavelength beam combining approach using the reflective MVBGs as the combiner in a compound cavity scheme.

Vertical External Cavity Surface Emitting Lasers (VECSELs) IV, edited
by Jerome V. Moloney, Proc. of SPIE Vol. 8966, 89660Y · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2039666

2. VECSELS AND VBGS CHARACTERIZATION

Before implementing the beam combining/power scaling schemes, first we need to characterize the VECSELs and the VBGs. Using the standard ABCD ray tracing matrices and the Gaussian beam optics, we simulated on-chip mode sizes and stability regions for several cavity geometries with a range of cavity lengths. It is well known that in order to obtain the best optical to optical efficiency and good output beam quality, it is important to adjust the on-chip mode size to match the pump spot size or vice versa. Therefore, based on the stability and spot size criteria, we designed cavities suitable for the two proposed schemes and characterized each VECSEL with the similar cavity parameters.

To begin the VECSEL and VBGs characterization, we started with the single chip V-shaped cavity as a comparison to the two chips coherent addition Z-shaped cavity. The experimental setup and results for the V-shaped cavity are shown in Figure 1 with the VECSEL gain chips provided by the University of New Mexico and the University of Arizona. The VECSELs consist of a multi-quantum well active region with 12 InGaAs wells and a 25 pair AlAs/GaAs DBRs for operating at near 1020nm wavelength[8]. The VBGs and MVBGs used in the experiments are provided by OptiGrate Inc. Due to the similar output characteristics between the VECSELs, only one set of data is plotted. The VECSEL was water cooled at 10°C using a unique water jet cooling design. After reimagining, the pump spot size from the 808nm DILAS fiber coupled pump laser was calculated to be 280μm at the focus. The cavity mode size was matched to the pump spot size with a 20cm focal length intracavity lens positioned at nearly center of the cavity. The cavity lengths between the VECSEL and the lens, the VECSEL and the broadband high reflector (HR) or VBGs, the lens and the output coupler were 35.7cm, 4.2cm, and 39.4cm, respectively. With the 95% reflectivity output coupler (OC), we obtained 3.23W broadband wavelength output with the HR and 2.32W spectrally narrowed output with the VBGs at 21W of pump power. We will compare the output characteristics of the single chip V-shaped cavity with the two chips coherent addition Z-shaped cavity configured in the similar cavity parameters in the next section.

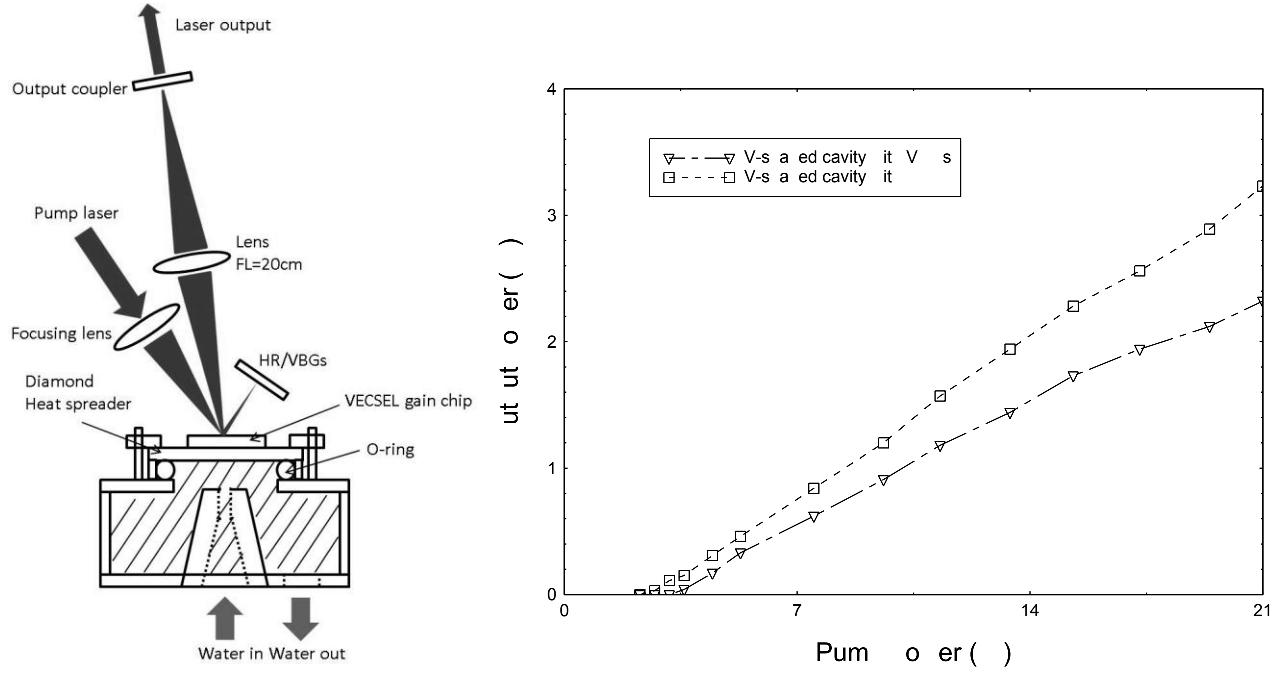


Figure 1. (Left) VECSELs water jet cooling block diagram and V-shaped laser cavity setup. (Right) Output comparison between VBGs and HR placed inside the cavity using a 95% reflectivity OC.

3. VECSELS COHERENT ADDITION USING VBGS IN A Z-SHAPED CAVITY

As previously mentioned, in order to achieve good coherent addition with the two chips Z-shaped cavity, it is critical to adjust the cavity lengths so the mode sizes on both VECSELs are similar to the pump spot sizes. The experimental setup for the two VECSELs coherent addition Z-shaped cavity is shown in Figure 2. From the cavity simulation, with the focal length of 20cm for the intracavity lens, both the stability criteria and the mode matching condition are met only when the total cavity length on the left side of the lens (L1 + L3) and the total cavity length on the right side of the lens (L2 + L4) slightly less than 40cm. Furthermore, L3 and L4 will need to be less than 4.5cm to ensure the on-chip cavity mode matches the pump spot size. The measured cavity parameters were L1=35.7cm, L2=35.1cm, L3=4.2cm, and L4=4.3cm. This cavity is analogous to the coherent addition cavity demonstrated by L. Fan et al.[3], where the lens is replaced by a spherical folding mirror.

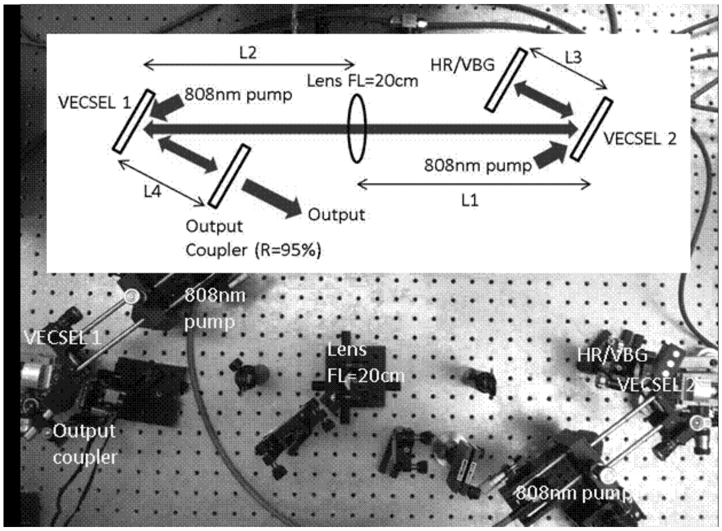


Figure 2. Two VECSELs Z-shaped cavity coherent addition experimental setup.

The experimental results for the single chip V-shaped cavity and the two chips coherent addition z-shaped cavity are shown in Figure 3. For the single chip, we obtained 3.23W output with 15% slope efficiency with the broadband HR and 2.32W output with 11% slope efficiency with the 1021.7nm resonated VBG. In the case of the two chips cavity, we obtained 5.03W output with 11% slope efficiency with the HR and 3.48W output with 8% slope efficiency with the VBGs. The decreased slope efficiency from the V-shaped cavity to the Z-shaped cavity is due to the additional cavity loss introduced by the second VECSEL. The slope efficiency decreases further more when replacing the HR with the spectral narrowing VBGs. However, the degradation in slope efficiency is expected as the addition output has much higher stabilized spectral density.

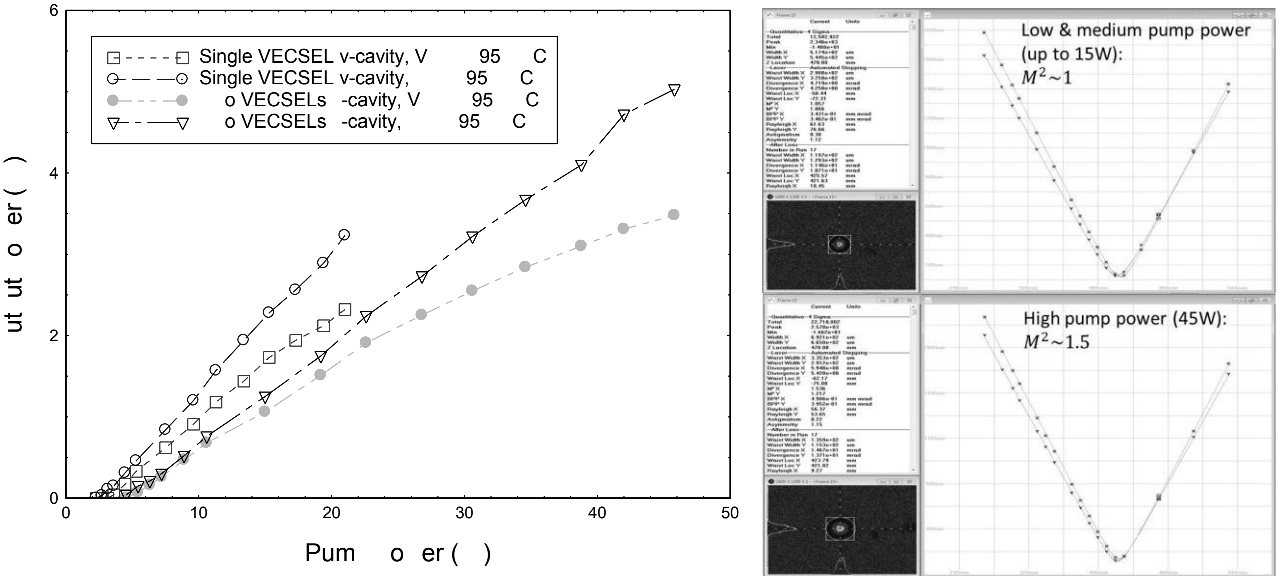


Figure 3. Coherent addition experimental results and measured beam quality at low & high pump power in the two VECSELs Z-shaped cavity with the VBGs. All four cavities produce similar output beam qualities.

The measured combined output beam quality is also shown in Figure 3. At low and medium pump power, we obtained excellent beam quality of $M^2 \sim 1$; however, the beam quality is slightly degraded ($M^2 \sim 1.5$) due to heating induced higher order mode excitation in the VECSELs at high pump power. The output beam qualities are similar for all the cavity geometries used in the experiment. For the effect of coherent addition, we obtained greater than 70% coherent scaling efficiency for both HR and VBG cavities. The coherent scaling efficiency is calculated using $\eta = \frac{P_{out}(z-cavity)}{2 * P_{out}(v-cavity)}$, as both VECSELs have the same output characteristics. The output spectra for the cavities with the broadband HR (left graph) and the VBGs (right graph) at different pump powers are shown in Figure 4. With the broadband HR, the spectrum is red shifted and broaden at higher pump power. It is also well known that the spectral broadening is due to the conduction band overfilling so multiple frequencies lase simultaneously and the red shifting is caused by the heating on the semiconductor gain materials. The effect of spectral broadening and shifting is mitigated in the case with the 1021.7nm resonated VBG as shown in the plot below.

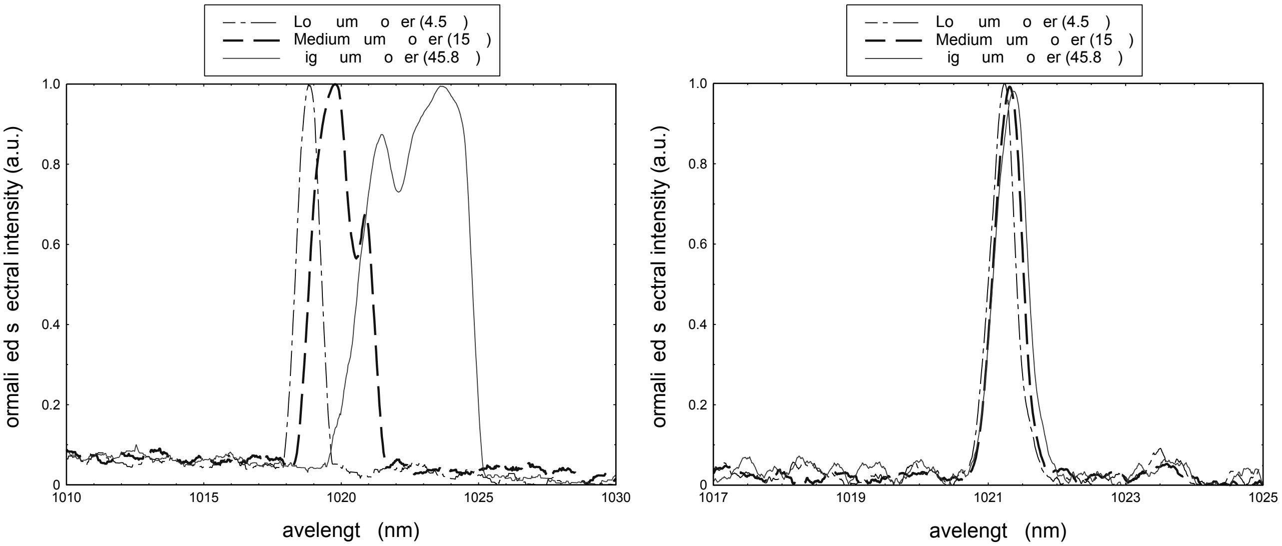


Figure 4. Z-shaped cavity combined output spectra at various pump power. Left plot shows output spectra for the cavity with the broadband HR and right plot shows spectral narrowed and stabilized output using the VBGs.

Although the output power in the two chips VBGs cavity starts to show signs of rollover at near 30W of pump power, the output spectrum is still stabilized and frequency locked to the VBGs. To further increase the output in the VBGs cavity, one can either design the VECSELs to match the resonate frequency of the VBGs at the desired pump power or vice versa and design the VBGs to work more efficiently with the frequency shifted VECSELs. The coherent addition cavity with the HR has not shown power rollover at 45W of pump power and is capable of producing higher output power without the spectral constraint. However, the lens inside the cavity has shown significant heating (>80°C) at 5W output power. The lens heating can be resolved by either reducing the reflectivity of the OC or replacing the intracavity lens with one capable of handling higher optical power. Since this is not within our scope of study, we will not continue power scaling with the HR cavity. Instead, we will move on to the other proposed multiple chips beam combining approach using the MVBGs.

4. VECSEL WAVELENGTH BEAM COMBINATION USING MVBGS

The MVBGs are multiple holographic gratings inscribed in a PTR glass. With proper design and fabrication, the MVBGs can be used to split a single laser beam or combine multiple laser sources at the resonant wavelength. Initially, we intended to coherently combine multiple VECSELs using the reflective MVBGs. However, due to the small gain volume, the VECSELs cavity would not reach lasing threshold with the MVBGs placed inside the cavity. Thus we evolved the coherent beam combining scheme into a more effective wavelength beam combining scheme as shown in Figure 5. By utilizing the short cavities with the concave OC (OC1), we constructed a compound cavity for combining two VECSELs with the reflective MVBGs. The OC1 for the short cavities have radius of curvature of 25cm and 95% broadband reflectivity. In order to satisfy the stability criteria, the cavity parameters L1 and L2 were adjusted to within

4cm. And the collimating lens were placed outside the short VECSEL cavities with the cavity parameters L3=L4~20cm. The characteristics of the reflective MVBGs are also shown in Figure 5. The diffraction wavelength for the MVBGs is centered at 1020.9nm and the angles of diffraction are ±6.7° with -0.03° near normal incident angle. Each laser was aligned through the MVBGs and OC2 using a pair of HR turning mirrors.

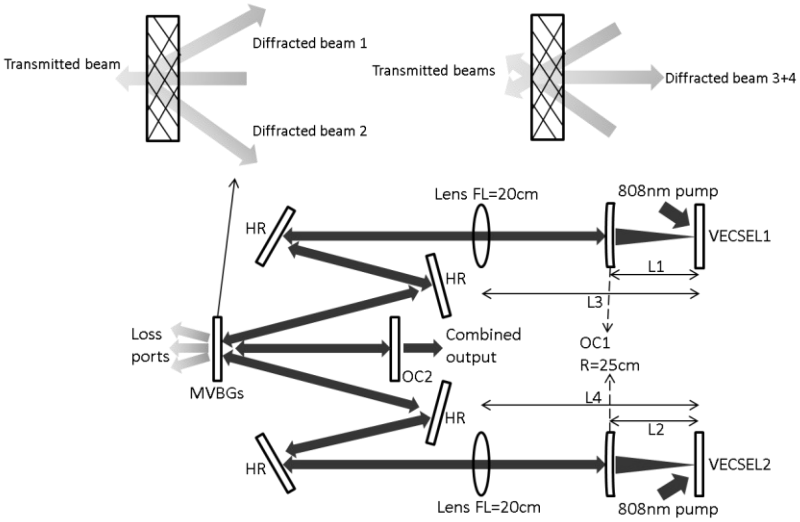


Figure 5. VECSELs wavelength beam combining experimental setup using the MVBGs with the reflective MVBGs diffraction characteristics shown on the top.

The experimental results for the case of 30% and 10% reflectivity OC2 are shown in Figure 6 and Figure 7, respectively. We have achieved 5.02W combined output with the 30% reflectivity OC2 and 6.25W combined output with the 10% reflectivity OC2. In both cases, close to 100% combining efficiencies (calculated as $\eta = \frac{P_{out}}{P_{laser1}+P_{laser2}}$) were obtained with excellent beam quality and spectrally narrowed outputs and as shown in the figures below. The output power is limited due to the VECSELs emission wavelengths shift outside of the diffraction wavelength of the reflective MVBGs. As mentioned in the previous section, a better resonant wavelength matched pair of the MVBGs and the VECSELs can be designed to further increase the combined output power.

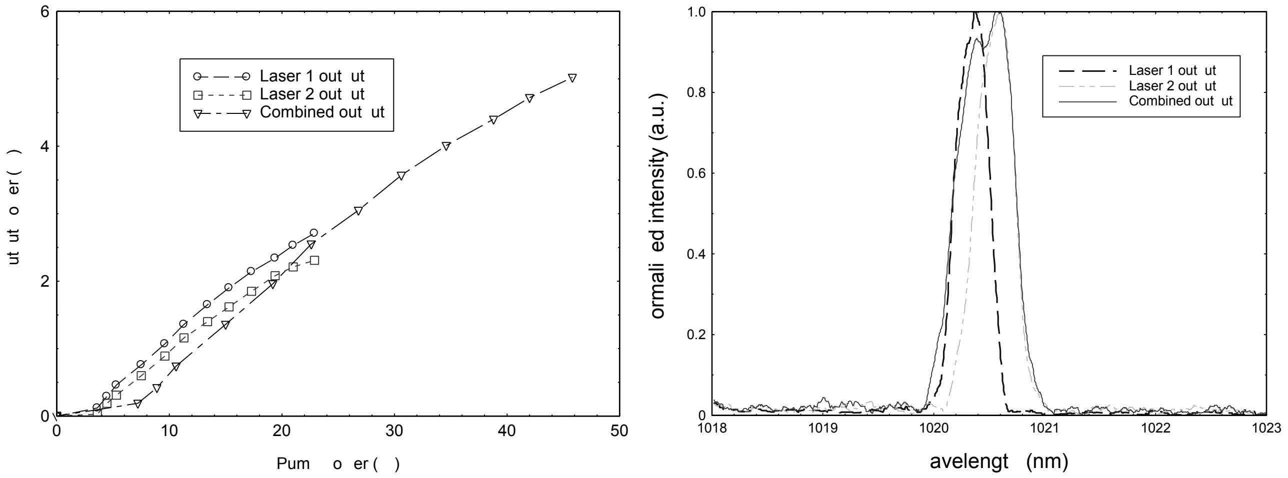
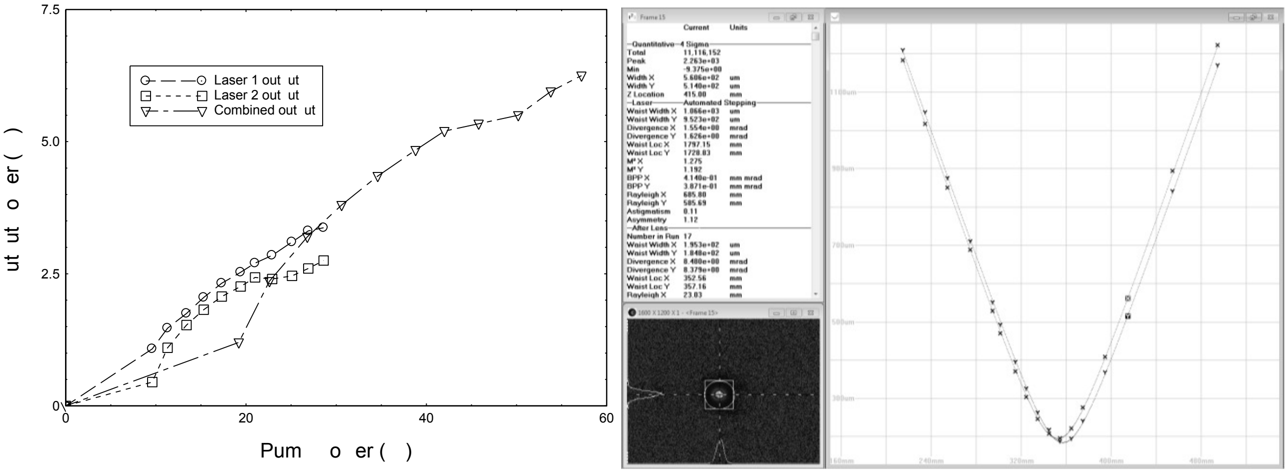


Figure 6. Output characteristics with 30% reflectivity output coupler. Left plot shows output power vs pump power and right plot shows spectra of individual lasers and combined output.



	Current	Units
Quantitative	4 Sigma	
Total	11,116,152	
Peak	2.263e+03	
Min	-9.375e+00	
Width X	5.606e+02	um
Width Y	5.140e+02	um
Z Location	415.00	mm
Laser	Automated Stepping	
Waist Width X	1.066e+03	um
Waist Width Y	9.523e+02	um
Divergence X	1.554e+00	mrad
Divergence Y	1.626e+00	mrad
Waist Loc X	1797.15	mm
Waist Loc Y	1728.83	mm
M² X	1.275	
M² Y	1.192	
BPP X	4.140e-01	mm mrad
BPP Y	3.871e-01	mm mrad
Rayleigh X	685.80	mm
Rayleigh Y	585.69	mm
Astigmatism	0.11	
Asymmetry	1.12	
After Lens		
Number in Run	17	
Waist Width X	1.953e+02	um
Waist Width Y	1.848e+02	um
Divergence X	8.480e+00	mrad
Divergence Y	8.379e+00	mrad
Waist Loc X	352.56	mm
Waist Loc Y	357.16	mm
Rayleigh X	23.03	mm

Figure 7. (Left) Output power vs pump power with 10% reflectivity output coupler. (Right) Measured quality beam at 5W combined output ($M^2 \sim 1.2$).

5. CONCLUSION

In summary, we have successfully demonstrated narrow linewidth coherent addition of two VECSELs using VBGs Z-shaped cavity with >3W output and 8% slope efficiency. In addition, we have also shown a novel approach to spectrally narrow and combine two VECSELs with 6.25W high spectral density output and ~100% combining efficiency using the reflective MVBGs wavelength beam combining compound cavity. In both schemes, the output powers were limited by the redshifted effect in the VECSELs at high pump power. To further increase the combined output power, one can design a matching pair of the MVBGs and the VECSELs to work at the desired wavelength and pump power. However, the transmission window of the PTR glass decreases significant for the wavelength longer than 2.3µm. It has been demonstrated to efficiently combine several quantum cascade lasers using a surface gratings[8], so we believe it is also possible to combine multiple longer wavelength VECSELs with a surface gratings using similar approaches presented in this paper.

6. ACKOWLEDGEMENT

This work was funded by the Air Force Office of Scientific Research (AFOSR).

7. REFERENCES

[1] Heinen, B., et al., “106 W continuous-wave output power from vertical-external-cavity surface-emitting laser,” Electronics Letters, Volume 48, Issue 9 (2012)

[2] T. Leinonen, et al.," High power (23W) vertical external cavity surface emitting laser emitting at 1180 nm ", Proc. SPIE 8606, Vertical External Cavity Surface Emitting Lasers (VECSELs) III, 860604 (February 18, 2013)

[3] Li Fan, et al., "Extended Tunability in a Two-Chip VECSEL," Photonics Technology Letters, IEEE, vol.19, no.8, pp.544,546, April15, 2007

[4] Chris Hessenius, et al., “High-power tunable two-wavelength generation in a two chip co-linear T-cavity vertical external-cavity surface-emitting laser,” Applied Physics Letters 101, 121110 (2012)

[5] Yushi Kaneda, et al., “High Brightness Spectral Beam Combination of High-Power Vertical-External-Cavity Surface-Emitting Lasers,” IEEE Photonics Technology Letters, Vol. 18, No. 17 (2006)

[6] Oleksiy Andrusyak et al., “Spectral Combining and Coherent Coupling of Lasers by Volume Bragg Gratings,” IEEE Journal of Selected Topics in Quantum Electronics, Vol. 15, No. 2 (2009)

[7] Chunte A. Lu, et al., “Active coherent superposition of five fiber amplifiers at 670W using multiplexed volume Bragg gratings," Proc. SPIE 8601, Fiber Lasers X: Technology, Systems, and Applications, 86011A (2013)

[8] Alexander R. Albrecht, et al., “Progress towards cryogenic temperatures in intra-cavity optical refrigeration using a VECSEL,” Proc. Of SPIE 8638, Laser Refrigeration of Solids VI, 863805-1 (2013)

[9] Bloom G, et al., “Passive coherent beam combining of quantum-cascade lasers with a Dammann grating,” Optics Letters, Vol. 36, Issue 19, pp. 3810-3812 (2011)