Title	Spectral narrowing and locking of a vertical external-cavity surface-emitting laser using an intracavity volume Bragg grating(Published)
Author(s)	Giet, S.; Sun, Handong; Calvez, Stephane; Dawson, M. D.; Suomalainen, S.; Härkönen, A.; Guina, M.; Okhotnikov, O.; Pessa, M.
Citation	Giet, S., Sun, H. D., Calvez, S., Dawson, M. D., Suomalainen, S., Härkönen, A., et al. (2006). Spectral narrowing and locking of a vertical external-cavity surface -emitting laser using an intracavity volume Bragg grating. IEEE Photonics Technology Letters, 18(16), 1786-1788.
Date	2006
URL	http://hdl.handle.net/10220/6014
Rights	

Spectral Narrowing and Locking of a Vertical-External-Cavity Surface-Emitting Laser Using an Intracavity Volume Bragg Grating

S. Giet, H. D. Sun, S. Calvez, *Member, IEEE*, M. D. Dawson, *Senior Member, IEEE*, S. Suomalainen, A. Härkönen, M. Guina, O. Okhotnikov, and M. Pessa

Abstract—We report the use of a volume Bragg grating as an output coupler mirror to improve and stabilize the spectral characteristics of 1058-nm vertical-external-cavity surface-emitting laser which is thermally managed using an intracavity diamond heatspreader. Spectrally narrow and locked emission with up to 645 mW of $TEM_{0,0}$ output power is demonstrated.

Index Terms—Diode-pumped laser, high-power laser, semiconductor disk laser, semiconductor laser, vertical-cavity laser, wavelength stabilization.

I. INTRODUCTION

OPTICALLY pumped vertical-external-cavity surface-emitting lasers (VECSELs) are very attractive devices that have emerged at the boundary between conventional diode-pumped solid-state lasers and electrically pumped semiconductor lasers [1]. They capitalize on the wavelength versatility offered by a semiconductor gain structure [1]–[13] while simultaneously exploiting intracavity control and mode-matching techniques to produce high-power $TEM_{0,0}$ tunable single-frequency [3]–[6], frequency-doubled [7], [8] or mode-locked operation [9], [10]. These VECSEL characteristics have generated much attention recently for applications including laser projection displays, reprographics and printing, telecommunications and as sources for scientific and instrumentation applications.

Critical to VECSEL high-power operation has been the introduction of two thermal management strategies to improve the heat extraction from the gain region. The first technique consists in removing the semiconductor substrate and soldering the very thin ($\sim$6 μm thick) gain structure directly to a heatsink [6]–[8]. The second approach is based on the bonding of a high-thermal-conductivity window onto the intracavity surface of the semiconductor chip [11]–[13]. While the latter method requires less intensive postprocessing, it introduces an intracavity etalon which generally leads to a multilongitudinal mode, spectrally
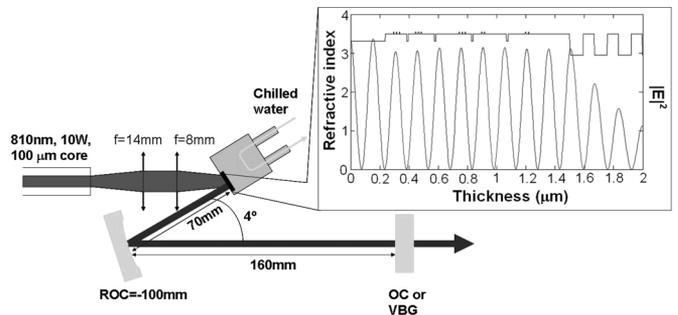
Fig. 1. Laser setup with representation of the active region structure and E-field pattern. OC: output coupler.

broad ($\sim$5–10 nm) emission. The careful selection of a thin intracavity heatspreader has been proven to produce narrow spectral output, but at the expense of reduced heat removal efficiency [13].

In this letter, we report an alternative and potentially very versatile method to controllably narrow the spectrum of a VECSEL. It is based on the replacement of the output coupler mirror by a volume Bragg grating (VBG), a component used so far to wavelength-stabilize edge-emitting diode lasers [14]. This technique is applicable to VECSELs incorporating thick intracavity heatspreaders and has the further advantage of locking the emission wavelength.

II. SEMICONDUCTOR STRUCTURE AND GROWTH DESCRIPTION

The semiconductor epi-structure includes a 30.5-pair AlAs–GaAs distributed Bragg reflector and an 8.5-λ-thick GaAs-based active region which contains 13 nonstrain-compensated, nominally 7-nm-thick $In_{0.26}Ga_{0.74}As$–GaAs quantum wells (QWs). An $Al_{0.3}Ga_{0.7}As$ confinement region capped with a 10-nm GaAs layer to avoid oxidation degradation completes this resonant semiconductor structure. Four 20-nm-thick $Al_{0.2}Ga_{0.8}As$ layers divide the GaAs active region into five sections containing respectively 3, 3, 3, 2, and 2 QWs positioned for resonant periodic gain, as shown in the inset of Fig. 1. The QW separation is set to be 15 nm. This structure is used to obtain a uniform carrier distribution [15] by establishing approximately constant average pump-absorption per well. The structure was grown by molecular beam epitaxy on a (100) n-doped GaAs substrate. The growth temperature was 600 °C throughout, apart from that for the QWs which were grown at 490 °C.
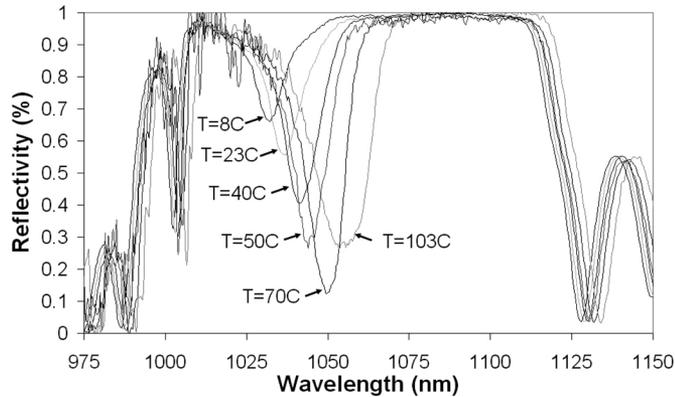
Fig. 2. Temperature-dependent reflectivity of the VECSEL epistructure.

Temperature-dependent reflectivity of the structure used for this work, prior to its liquid-capillarity bonding to a 250-μm -thick type-IIa natural diamond heatspreader, is shown in Fig. 2. It can be observed that the QW emission and the subcavity resonance match for a temperature of $\sim$70 °C, indicating that the structure has a negative QW/resonance offset of $\sim$ -10 nm at 20 °C. The semiconductor/heatspreader composite was then mounted in a water-cooled brass-mount.

III. RESULTS

Initial characterization was performed with the three-mirror cavity represented in Fig. 1. The curved mirror of radius of curvature $R = -100$ mm was positioned $\sim$70 mm away from the semiconductor/heatspreader composite and 160 mm away from a plane output coupler. The cavity mode at the semiconductor wafer matched the $\sim$80-μm-diameter pump spot size obtained by relaying up to 8.9 W of the output of a 100-μmcore fiber-coupled 808-nm diode array using a 14 mm/8 mm collimator/focuser.

Fig. 3(a) shows the power transfer of the VECSEL with the optimum 7% output coupler and the water-cooling temperature set to 5 °C. The spectrum under maximum pump power excitation is given in Fig. 3(b). It clearly is multilongitudinal mode with a 0.85-nm spacing defined by the semiconductor/ heatspreader composite etalon. It can also be noted that the maximum gain is at $\sim$1054 nm. Additionally, Fig. 3(a) also provides the evolution of the output power with output coupler reflectivity under maximum pump injection.

The plane output coupler was then replaced with a 5-mm-thick VBG of nominal reflectivity >99% at 1058 nm commercially sourced from ONDAX, Inc. Power transfer characteristics of the emission at different water-cooling temperatures are provided in Fig. 4. The threshold and maximum output power evolutions with temperature are represented in the inset of Fig. 4. Considering both these figures, it can be seen that up to 40 °C, the output power decreases slowly with temperature, essentially because of reduction in efficiency, while at temperatures above 40 °C, thermal rollover and increased threshold (due to increased nonradiative recombination) become the limiting factors to device performance. The effective reflectivity was found to be 99.0%±0.7% by transmission characterization of the VBG. This reflectivity value partly explains
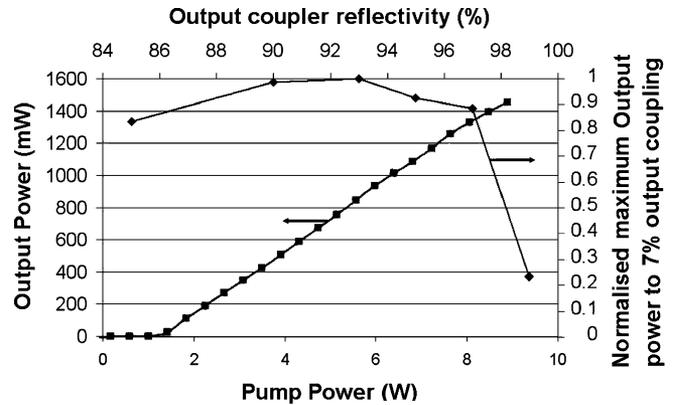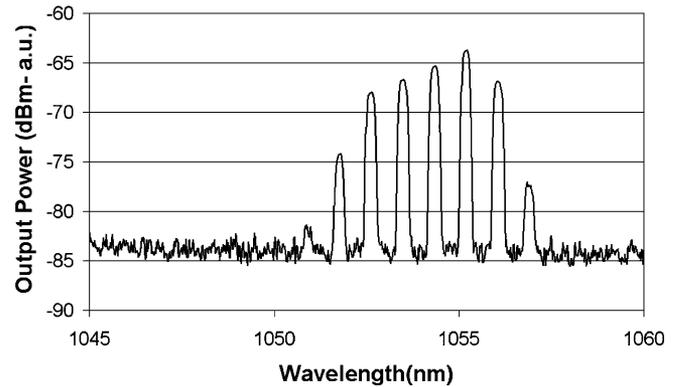
Fig. 3. (a) Power transfer characteristics and (b) spectrum at maximum power of conventional VECSEL with thick intracavity heatspreader.
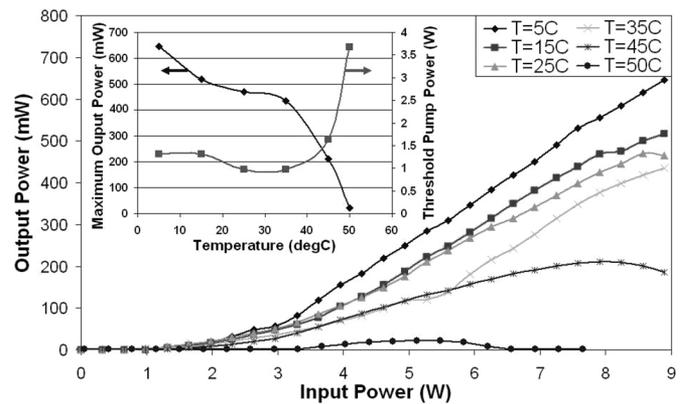

Fig. 4. Temperature-dependent power transfer characteristics of the VBG-stabilized 1058-nm VECSEL. Inset: maximum output power and threshold of the VBG-stabilized 1058-nm VECSEL as a function of water-cooling temperature.

the observed drop in maximum output power as compared to the optimum conventional output coupler situation [of Fig. 3(a)]. It also suggests that this spectral narrowing technique is low-loss in par with the more commonly used birefringent filtering method [4]–[6]. An optimization of the VBG reflectivity should enable better laser performance to be reached.

At maximum output power, the beam was found to be Gaussian with an $M^2 \sim 1.09$, as shown in Fig. 5. We measured the polarization to be elliptical with an ellipticity of 0.903. To our knowledge, it is the fist time that such a polarization state
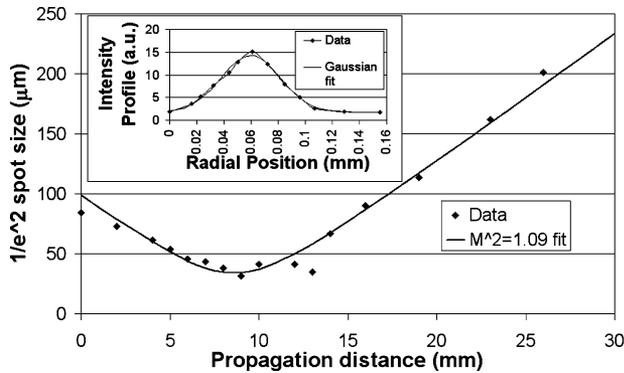
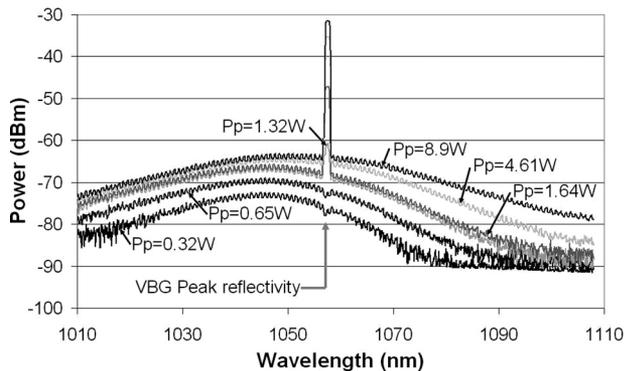Fig. 5. Beam profile characterization of VBG-stabilized VECSEL.

Fig. 6. Spectral characteristics of the VBG-stabilized 1058-nm VECSEL at a water-cooling temperature of 45 °C.

has been reported in a VECSEL and a study of its origin will form the subject of further investigations.

The evolution of the output spectrum for different pump powers and a water-cooling temperature of 45 °C is shown in Fig. 6. The spectra, measured at the output side of the VBG, all have the same characteristics. They are composed of a reflection/laser feature around the VBG reflection-peak and a broadband emission which corresponds to the amplified spontaneous emission of the semiconductor/heatspreader composite, unaffected by the fully transmissive nature of the VBG outside its narrow reflection band. Laser emission occurs at the peak reflectivity of the VBG with a linewidth lower than the optical spectrum analyzer resolution (0.06 nm). It is, therefore, independent of the semiconductor sample temperature and pump power but controlled and locked to the properties of the VBG whose center wavelength can be manufactured with an accuracy of $+/-0.5$ nm and has only a very weak dependence (~0.01 nm/K) on the environmental temperature. It can be noticed that the peak gain shifts towards longer wavelengths at a rate of ~0.84 nm/W but, even at 45 °C, stays on the short wavelength side of the VBG reflection peak even under high-power excitation.

IV. CONCLUSION

We have introduced and experimentally demonstrated a novel method to narrow and lock the emission spectrum of a VECSEL which is thermally managed using a thick heatspreader. Laser output with pump-limited powers up to 645 mW at 1058 nm was achieved with a sidemode suppression ratio greater than 20 dB when the epilayer temperature is kept at 5 °C.

REFERENCES

[1] A. C. Tropper, H. D. Foreman, A. Garnache, K. G. Wilcox, and S. Hoogland, "Vertical-external-cavity semiconductor lasers," *J. Physics D: Appl. Phys.*, vol. 37, pp. R75–R85, 2004, Topical Review.

[2] J. E. Hastie, S. Calvez, M. D. Dawson, T. Leinonen, A. Laasko, J. Lyytikainen, and M. Pessa, "High power, CW red VECSEL with linearly polarized TEM$_{00}$ output beam," *Opt. Express*, vol. 13, no. 1, pp. 77–78, 2005.

[3] A. Ouvrard, A. Garnache, L. Cerutti, F. Genty, and D. Romanini, "Single-frequency tunable Sb-based VCSELs emitting at 2.3 μm," *IEEE Photon. Technol. Lett.*, vol. 17, no. 10, pp. 2020–2022, Oct. 2005.

[4] M. A. Holm, D. Burns, A. I. Ferguson, and M. D. Dawson, "Actively stabilised, single-frequency, vertical external cavity AlGaAs laser," *IEEE Photon. Technol. Lett.*, vol. 11, no. 12, pp. 1551–1553, Dec. 1999.

[5] K. S. Gardner, R. H. Abram, and E. Riis, "A birefringent etalon as singlemode selector in a laser cavity," *Opt. Express*, vol. 22, no. 11, pp. 2365–2370, 2004.

[6] L. Fan, M. Fallahi, J. T. Murray, R. Bedford, Y. Kaneda, A. R. Zakharian, J. Hader, J. V. Moloney, W. Stolz, and S. Koch, "Tunable high-power high-brightness linearly polarized vertical-external-cavity surface-emitting lasers," *Appl. Phys. Lett.*, vol. 88, no. 021105, 2006.

[7] J. Chilla, S. Butterworth, A. Zeitschel, J. Charles, A. Caprara, M. Reed, and L. Spinelli, "High power optically pumped semiconductor lasers," in *2004 Photonics West: Solid State Lasers XIII*, San Jose, CA, 2004.

[8] S. Lutgen, M. Kuelnelt, U. Steegmueller, P. Brick, T. Albrecht, W. Reill, J. Luft, B. Kunert, S. Reinhard, K. Yolz, and W. Stolz, "0.7 W CW output power from a green semiconductor disk laser," presented at the Eur. Conf. Lasers and Electro-Optics (ECLEO 2004), Munich, Germany, Paper CB1263.

[9] S. Hoogland, A. Garnache, I. Sagnes, J. Roberts, and A. C. Tropper, "10-GHz train of sub-500 fs optical soliton-like pulses from a surface-emitting semiconductor laser," *IEEE Photon. Technol. Lett.*, vol. 17, no. 2, pp. 267–269, Feb. 2005.

[10] A. Aschwanden, D. Lorensen, H. J. Unold, R. Paschotta, E. Gini, and U. Keller, "10 GHz passively mode-locked external-cavity semiconductor laser with 1.4 W average output power," *Appl. Phys. Lett.*, vol. 86, p. 131102, 2005.

[11] W. J. Alford, T. D. Raymond, and A. A. Allerman, "High power good beam quality at 980 nm from a vertical external-cavity surface-emitting laser," *J. Opt. Soc. Amer. B*, vol. 19, no. 4, pp. 663–666, 2002.

[12] J.-M. Hopkins, S. A. Scott, S. Calvez, and M. D. Dawson, "A 0.6 W CW GaInNAs vertical external cavity surface emitting laser emitting at 1.32 μm," *Electron. Lett.*, vol. 40, no. 1, pp. 30–31, 2004.

[13] H. Lindberg, H. Strassner, and A. Larsson, "Improved spectral properties of an optically pumped semiconductor disk laser using a thin diamond heat spreader as an intracavity filter," *IEEE Photon. Technol. Lett.*, vol. 17, no. 7, pp. 1363–1365, Jul. 2005.

[14] B. L. Volodin, S. V. Dolgy, E. D. Melnik, E. Downs, J. Shaw, and V. S. Ban, "Wavelength stabilization and spectrum narrowing of high-power multimode laser diodes and arrays by use of volume Bragg gratings," *Opt. Lett.*, vol. 29, no. 16, pp. 1891–1893, 2004.

[15] J. Geske, K.-G. Gan, Y. L. Okuno, J. Piprek, and J. E. Bowers, "Vertical-cavity surface-emitting laser active regions for enhanced performance with optical pumping," *IEEE J. Quantum Electron.*, vol. 40, no. 9, pp. 1155–1162, Sep. 2004.