High Brightness 1064-nm grating-outcoupled surface-emitting semiconductor lasers

Scott McWilliams[a], Nuditha V. Amarasinghe[a], Taha Masood[a], Hanxing Shi[a], Nikolai Stelmakh[b], Gary A. Evans[a,c]
[a]Photodigm Inc., 1155 East Collins Blvd, Suite 200, Richardson TX 75081;
[b]University of Texas, Arlington, TX 76019
[c]Southern Methodist University, Dallas, TX 75275

ABSTRACT

Photodigm is developing high brightness grating outcoupled surface emitting (GSE) semiconductor lasers with continuous-wave (CW) output power exceeding 1 W at 1064-nm wavelength. The GSE lasers have full-width at half-maximum (FWHM) spectral bandwidth of less than 0.2 nm and a beam divergence of 1^{o} x 3.4^{o} (FWHM).

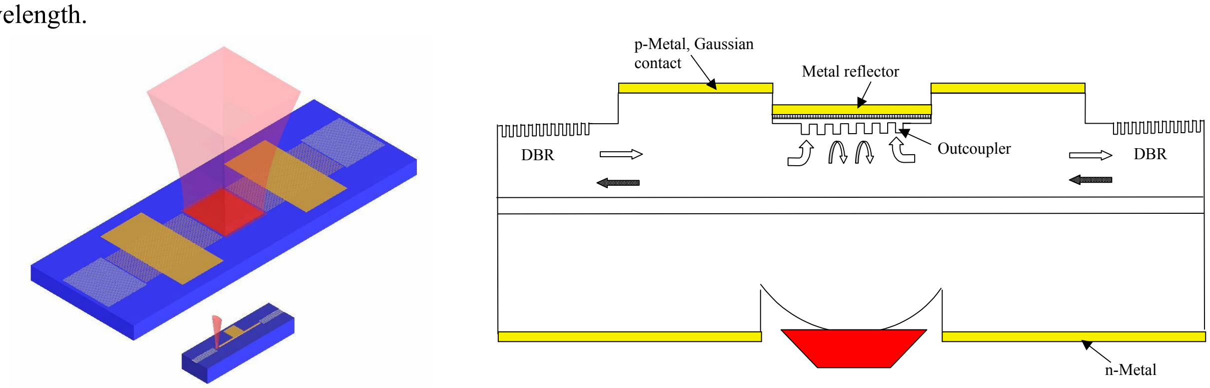
Keywords: Surface emission, grating, long wavelength, high power, distributed Bragg reflector

1. INTRODUCTION

Desirable traits of grating-outcoupled surface-emitting (GSE) lasers include narrow beam divergence, single wavelength emission, high output power [1], low voltage and stable polarization. The combination of in-plane light propagation and surface-normal emission make GSE lasers ideal for electronic and photonic integrated circuits. Surface emission allows complete wafer level processing and testing, which allowed great reductions in cost and enormous increases in performance and reliability for electronic integrated circuits [2].

Semiconductor lasers which emit high power in a single spatial and longitudinal mode are widely sought for applications in displays, laser printers, optical recordings, and free space communication. Applications for the 1064-nm lasers include: optical trapping, wafer inspection, material processing, particle counting, metrology, printing, medical, illumination, pointing and photoluminescence.

This paper reports on modeling and experimental results of high-brightness GSE lasers (Fig. 1) emitting at 1064-nm wavelength.



(a) (b)

Figure 1. Schematic of top emitting (a) and bottom emitting (b) GSE lasers.

Optical Technologies for Arming, Safing, Fuzing, and Firing II, edited by William J. Thomes, Jr., Fred M. Dickey, Proc. of SPIE Vol. 6287, 62870F, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.683520

2. DESIGN

2.1 GSE laser structure

The GSE lasers consist of two 750 µm long gain sections that excite each end of a second-order outcoupler gratings. 400 µm first-order shallow DBR gratings terminate the laser cavity (Fig. 1).
The 1064-nm epitaxial material had compressively strained quantum wells. The structures were grown by metal-organic chemical vapor deposition in the InGaAs/AlGaAs/GaAs material system. The 1064-nm laser structure consists of: 0.1 µm GaAs cap layer/ AlGaAs p-cladding layer/ InGaP etch stop layer/ AlGaAs grating region/AlGaAs-GaAs p-GRIN layer/ InGaAs quantum well/GaAs –AlGaAs n-GRIN layer/ AlGaAs n-cladding layer/ GaAs n-substrate.
The ridge waveguide has a lateral index step Δn of ~0.003 determined by the InGaP etch stop layer.

2.2 DBR design

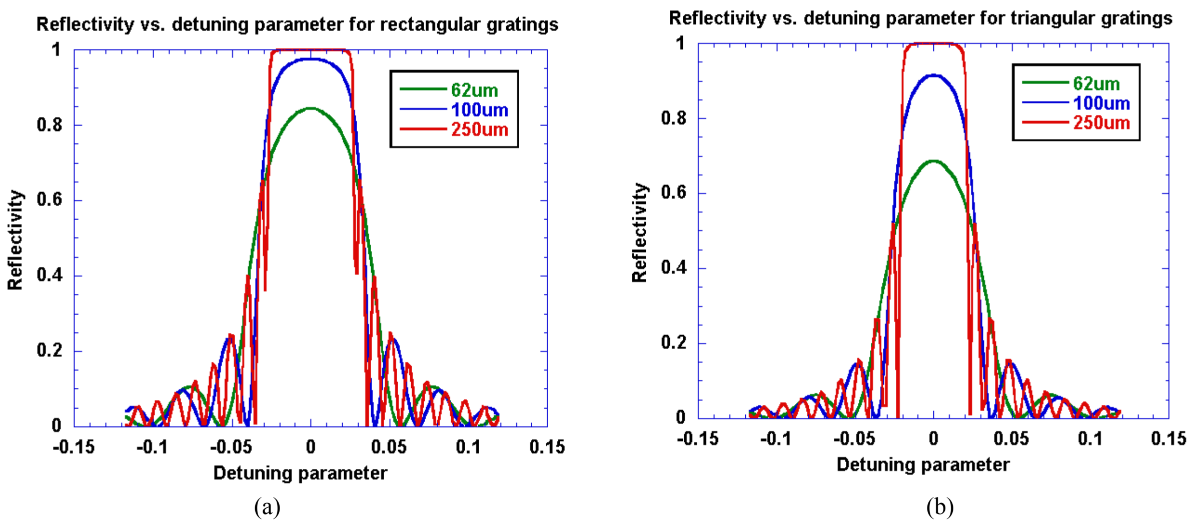
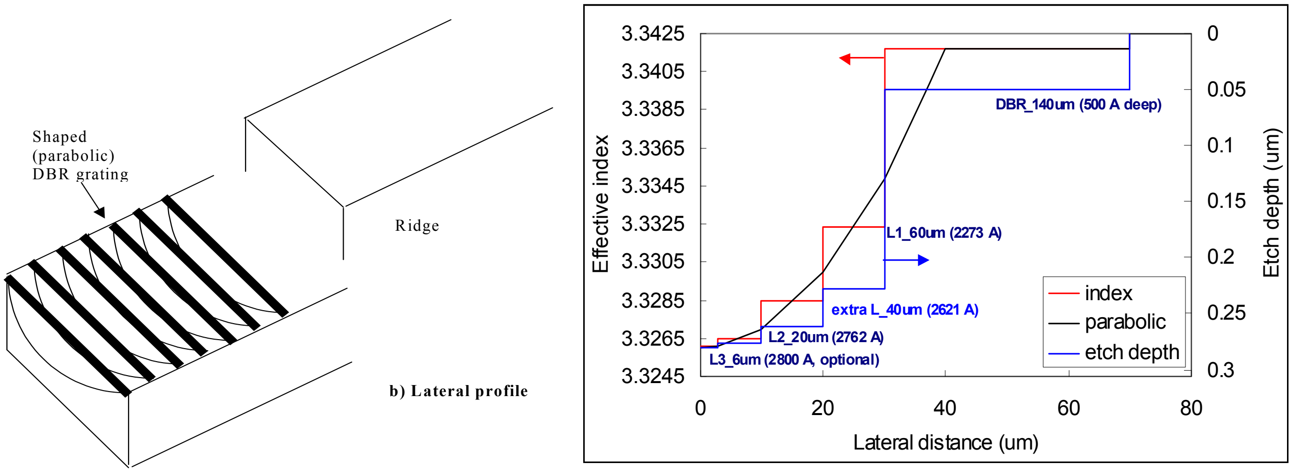


Figure 2. DBR reflectivity vs. detuning parameter for 62 µm, 100 µm, 200 µm long DBR section with rectangular (a) and triangular (b) grating teeth profile.

DBRs provide feedback as well as wavelength selectivity. Reflectivity for 62, 100 and 200 µm long rectangular and triangular DBR gratings with a depth of 0.13 µm are plotted as a function of the detuning parameter in Figs. 2a and 2b. These plots show that 100 µm long DBR gratings have a peak reflectivity of greater than 90 %, ignoring scattering losses due to grating sidewall roughness and coupling losses between the DBR and the ridge.

2.2.1 Reflectivity engineering

Spatial mode filtering is achieved by shaping the reflectivity of the Distributed Bragg Reflector (DBR). The reflectivity is locally laterally enhanced at the center of the DBR to favor the fundamental mode over higher order modes. The DBR grating teeth are laterally etched deeper in the center and progressively shallower on either side approximating a quadratic anti-guiding index profile (Fig. 3). This type of profile allows the modes to lose energy by radiation, with the loss an increasing function of mode index. The anti-guiding DBR gratings provide gain difference between the fundamental mode and higher order modes for single-mode operation. The refractive index profile in the longitudinal (propagation) direction is assumed uniform.



(a) (b)

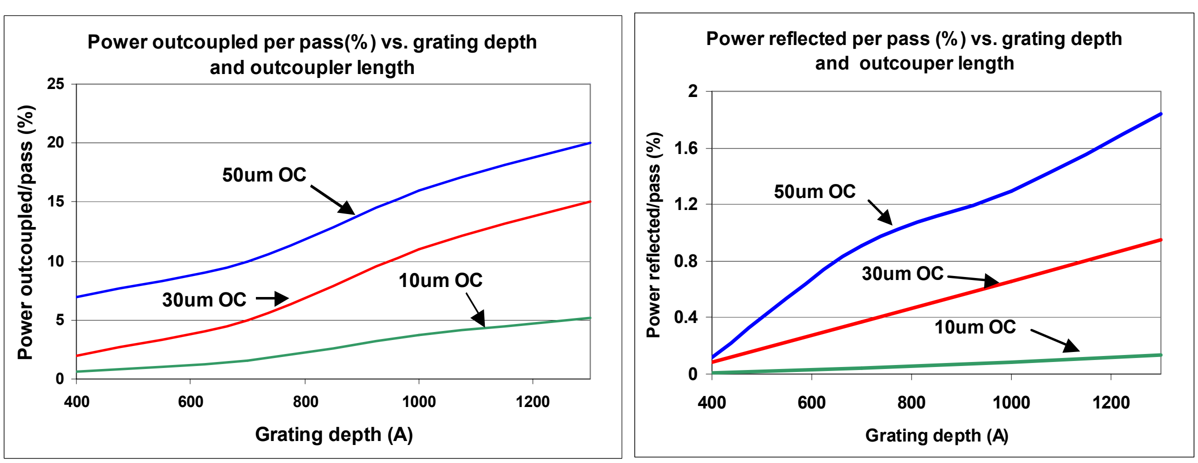
Figure 3. a) Laterally shaped gratings. b) Step approximation of the shaped (parabolic in index profile) gratings

2.3 Outcoupler design

The second-order outcoupler gratings have approximately twice the period of the DBR gratings. The second order gratings provide surface emission normal to the plane of the lasing cavity as shown in Fig. 1. The outcoupler radiates power into the air as well as the substrate.

Figure 4a shows the fraction of incident power that is radiated (both up and down) and reflected per pass on-resonance as a function of grating depth for 10, 30, 50 μm long outcoupler. For a second order grating depth of 1300 A, the on-resonance outcoupled power per pass is 5 %, 15 %, and 20 % for a 10, 30, 50 m long outcoupler respectively.

Figure 4b shows that on-resonance the reflectivity per pass from a 50 μm long and 1300 A deep second-order grating outcoupler is about 2 %.



(a) (b)

Figure 4. Radiated (a) and reflected (b) power per pass vs. grating depth for 10, 30, 50 μm long outcouplers.

On-resonance the second order outcoupler grating provides in-plane feedback. To avoid mode hops the outcoupler grating may be detuned from the DBR selected lasing wavelength.

2.4 Gaussian contact design

Distributed contacts are incorporated to provide additional fundamental mode beam stabilization while maintaining a low contact resistance. Degradation of the output beam quality (such as filamentation, self focusing, and beam instability) at higher current drives is generally associated with refractive index variations due to gain saturation effects. Gaussian contacts are designed to reduce self-focusing, beam instability effects and to help maintain a fundamental, Gaussian near- and far-field in 1064-nm lasers.

Broad-stripe diode lasers with a lateral injected-current profile reduce the filamentation by using a digitized electrical contact pad that smoothes the edges of the lateral distribution of injected carriers, suppressing the formation of filaments and high-order modes. The proposed approach compensates for lateral spatial-hole burning by applying a patterned electrode realized by locally etching the highly p-doped semiconductor layer in order to make a two-dimensional array (Fig. 5). The electrical resistance in this device depends on lateral position. The resistivity is higher where the p-doped semiconductor layer is etched. The central region of the electrode has higher conductivity than the outside region, so that the injected current density is higher in the center and decreases toward the edges. The cross section of the distributed contact consists of regularly spaced contact elements whose widths $l(x)$ vary following Gaussian law:

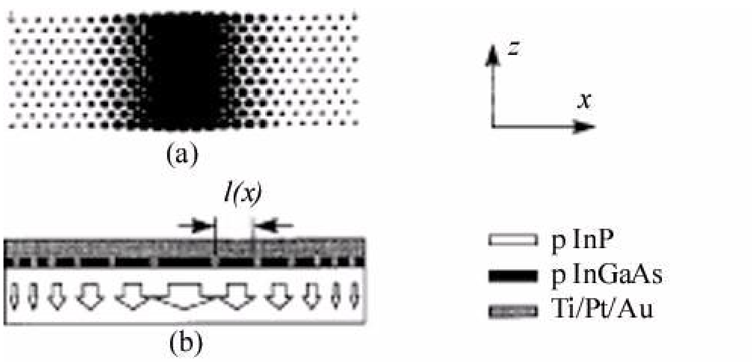


Figure 5. Principle of the distributed electrode: (a) Top view showing the contact array. (b) Cross section with indication of current flow distribution within the structure.

The mask for the Gaussian patterned contact is shown in Fig. 5 and consists of a quasi-random array of rectangular pixels. The pixels form a lateral distribution that is Gaussian on average. A quasi-random pattern was chosen to avoid spurious spatial periodicities from a more regular array of contact pixels. The rectangular pixels forming the pattern were 3 μm squares.

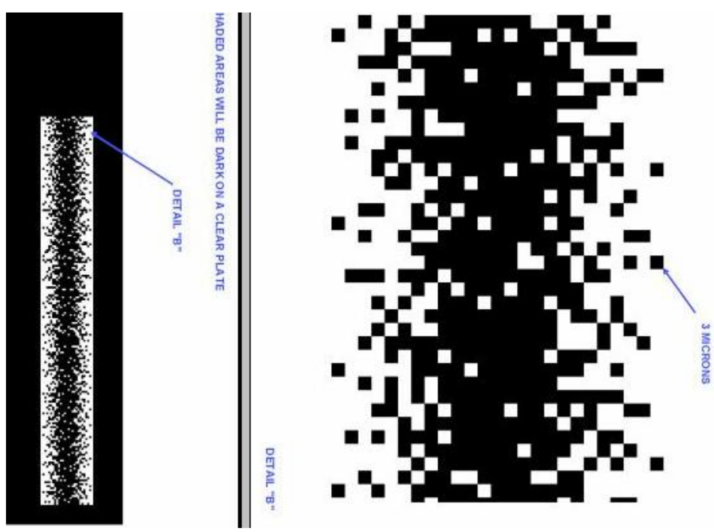


Figure 6. Gaussian contact for improved stability of the GSE laser.

The Gaussian patterned contact approximately matches the current distribution to the optical mode profile. Figure 6 shows a semi-random gaussian contact. The black area depicts the region where a good contact with the semiconductor laser is made whereas the white region is where the contact resistance is high. Gaussian contact increases filamentation threshold for broad-area lasers and improves laser brightness. Gaussian contact with the shaped gratings provide substantial discrimination against higher order lateral modes for a range of laser drive currents.

3. FABRICATION

The ridge-guide, DBR and the outcoupler regions are defined by etching away the p-cap and p-cladding layers down to the etch stop layer as shown in Fig. 7. A standard holographic lithography process is used to define a photoresist grating pattern with a 0.1606-µm period for target output wavelengths of 1064-nm. The outcoupler grating period is 0.3237-µm.

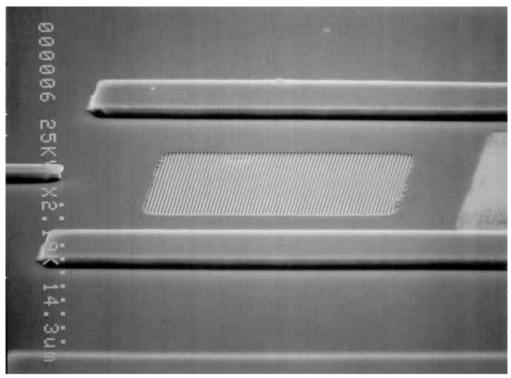


Figure 7. SEM image of the outcoupler and DBR gratings

4. EXPERIMENTAL RESULTS AND DISCUSSION

The light-current (LI) curve for a 3.7 µm wide and 750-µm long ridge single-mode GSE laser is shown in Fig.8. The outcoupler length is 30-µm. More than 100 mW of surface emitting power is measured at 400 mA of pump current. The kinks in the LI-curve are a result of mode hops that can be minimized by process and design improvements.

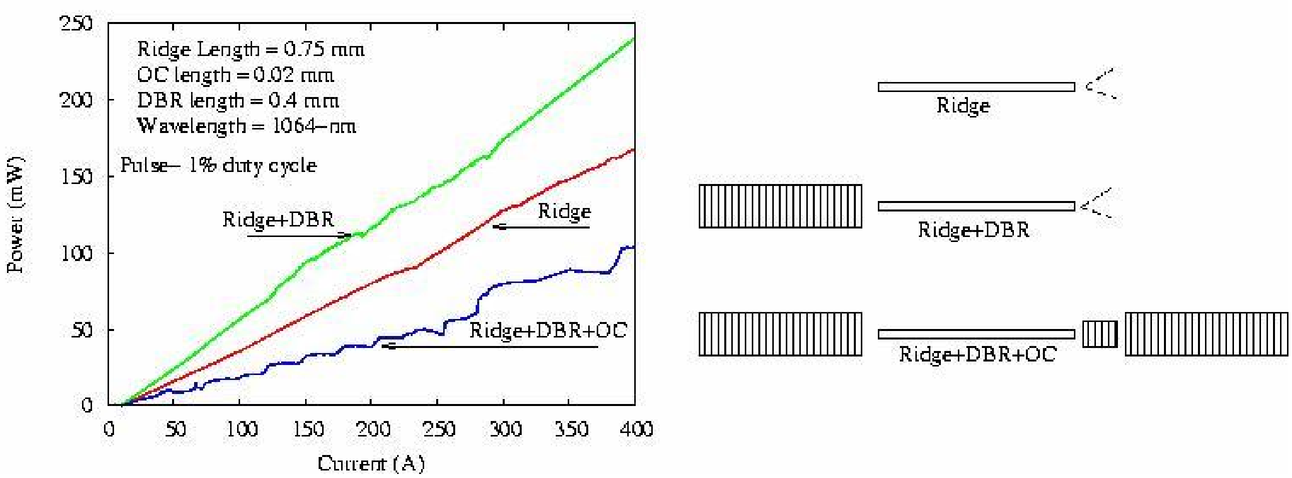


Figure 8. L-I characteristics of a single-mode ridge (edge emission), ridge + DBR (edge emission), and ridge + DBR + OC (surface emission) laser driven by a 10 us (1 % duty cycle) pulse.

Figure 9 shows the spectrum of the single-mode GSE laser.

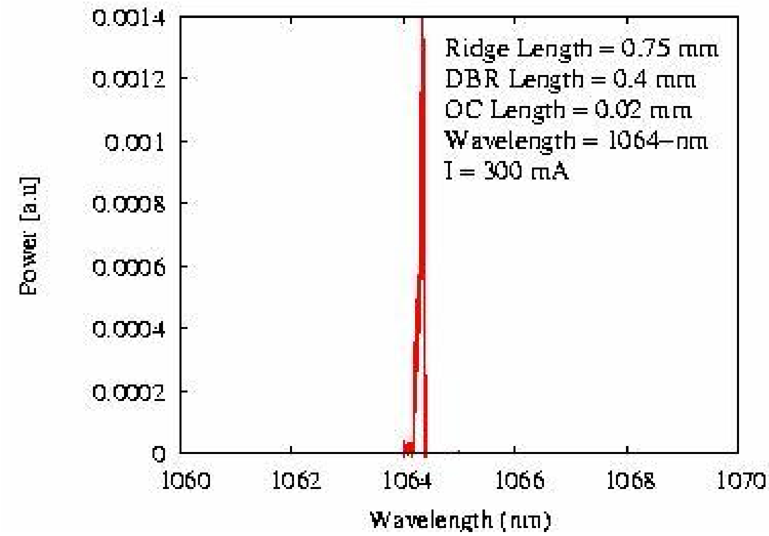
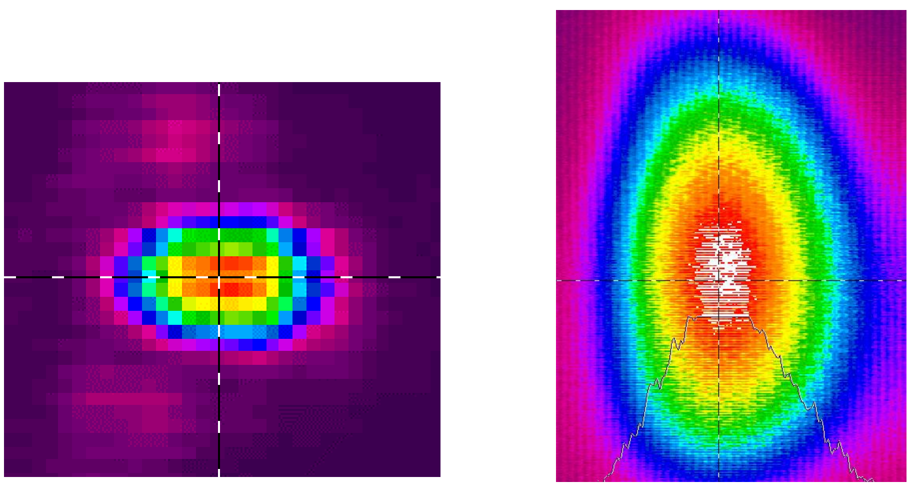


Figure 9. Spectrum af a single-mode GSE laser.

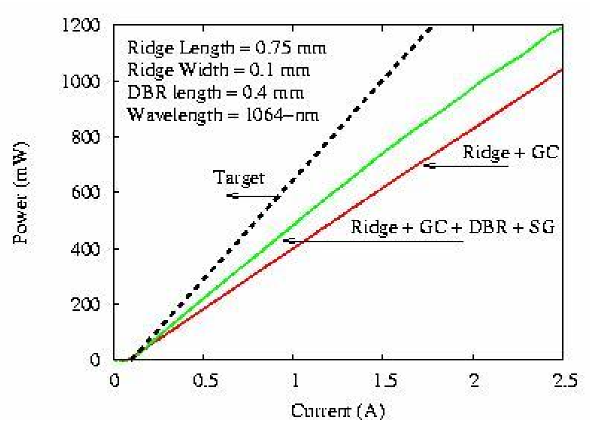
The far field beam divergence was measured at full-width-half-maximum (FWHM) to be 3^{o} x 8^{o} (Fig. 10).

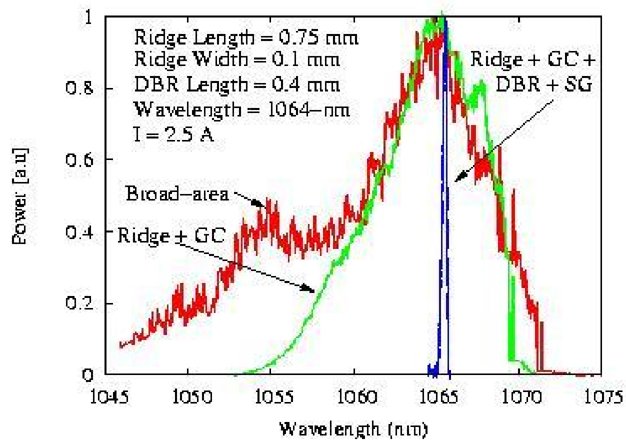


(a) (b)

Figure 10. a) Near and b) far field radiation pattern of the single-mode GSE laser.

Gaussian contact (GC) and shaped gratings (SG) are patterned to improve the coherence of a 100-µm broad ridge laser. Figure 11 shows the LI and spectral characteristics (edge emission). The spectral bandwidth of less than 0.2-nm (FWHM) was measured at 2.5 A.

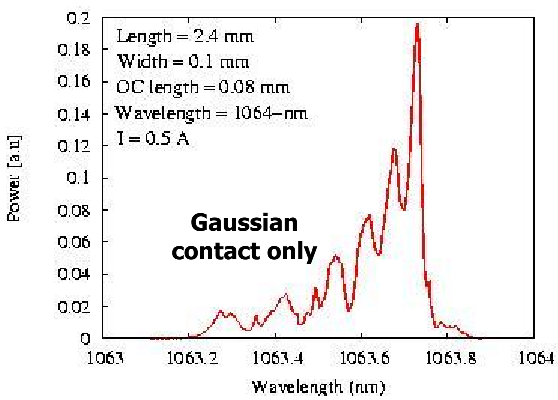


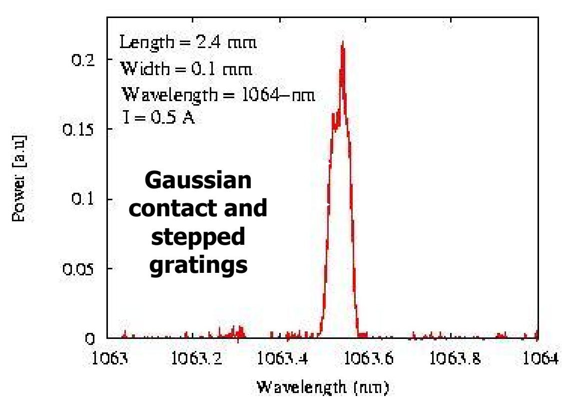


(a) (b)

Figure 11. a) LI (edge emission) and b) spectral characteristics of a 100-µm wide ridge GSE laser with Gaussian contact and shaped gratings as compared to broad-area laser

Figure 12 shows the contribution of Gaussian contact in minimizing the spectral bandwidth of the GSE laser.





(a) (b)

Figure 12. a) Spectrum of a GSE laser with Gaussian contact only, b) spectrum of the GSE laser with Gaussian contact and shaped gratings (stepped approximation).

Figure 13 shows the near and the far-field of the lasing modes at twice the threshold for a 100-µm wide ridge GSE laser.

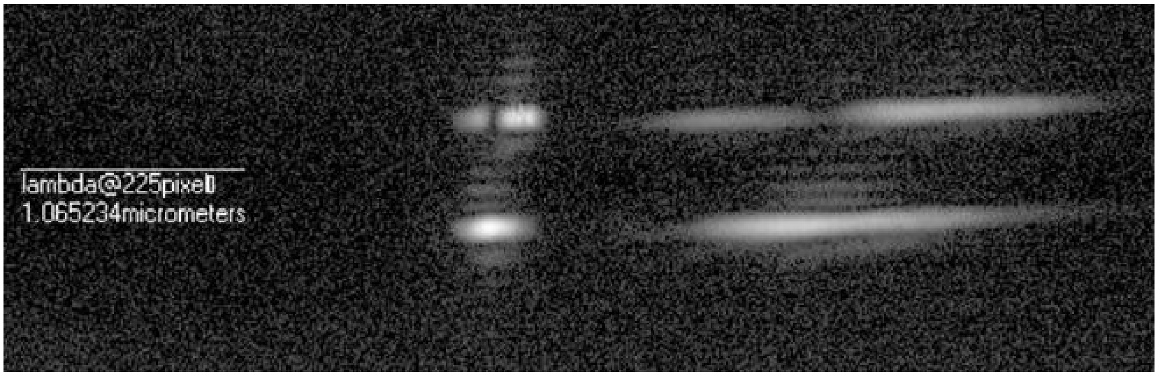


Figure 13. Lasing modes of the 100-µm wide GSE Laser.

5. CONCLUSION

Photodigm is developing high brightness grating outcoupled surface emitting (GSE) semiconductor lasers with continuous-wave (CW) output power exceeding 1 W at 1064-nm wavelength. The GSE lasers have full-width at half-maximum (FWHM) spectral bandwidth of less than 0.2 nm and a beam divergence of 1^o x 3.4^o (FWHM).

6. REFERENCES

[1]. G. A. Evans, D. P. Bour, N. W. Carlson, R. Amantea, J. M. Hammer, H. Lee, M. Lurie, R. C. Lai, P. F. Pelka, R. E. Farkas, J. B. Kirk, S. K. Liew, W. F, Reichert, C. A. Wang, H. K. Choi, J. N. Walpole, J. K. Butler, W. F. Ferguson, Jr., R. K. DeFreez, and M. Felisky, "Characteristics of coherent two-dimensional grating surface emitting diode laser arrays during CW operation," *IEEE Journal of Quantum Electronics*, vol. 27, 1991, pp. 1594-1605.
[2]. G. A. Evans, and J. M. Hammer, "Surface emitting semiconductor lasers and arrays," Academic Press, Inc., San Diego, ISBN 0-12-244070-6, 1993, pp.1-8.