Radiation Resistance of Single-Frequency 1310-nm AlGaInAs–InP Grating-Outcoupled Surface-Emitting Lasers

Jingbo Ye, Tiankuan Liu, Ryszard Stroynowski, Benjamin E. Wakeland, Annie C. Xiang, Nuditha Amarasinghe, Scott McWilliams, Taha Masood, and Gary Evans, *Fellow, IEEE*

***Abstract*—The results of two irradiation tests on 14 single-frequency 1310-nm grating-outcoupled surface-emitting semiconductor lasers that have been exposed to ionizing radiation using 200-MeV/c proton beams are reported. Twelve powered lasers survived a total radiation dose of up to 22.3 Mrad. One of the two not-powered lasers survived a total dose of 1.5 Mrad. The other failed after an integrated dose of 22.3 Mrad, suggesting that annealing may play an important role in laser performance during irradiation. The static and dynamic characteristics of the lasers after irradiation indicate the suitability of these lasers for medical, space, and accelerator-based nuclear and particle physics applications.**

***Index Terms*—Gratings, high-energy physics, radiation hard, semiconductor lasers, space applications, surface-emitting lasers.**

I. INTRODUCTION

GRATING-outcoupled surface-emitting (GSE) lasers [1], [2] consisting of a 500-μm-long active ridge, a 15-μm-long intracavity grating outcoupler, and 200-μm-long first-order distributed Bragg reflector (DBR) gratings at both ends were exposed to proton beams with doses up to 22.3 Mrad. A conceptual design of the GSE lasers is shown in Fig. 1. Surface emission allows for complete wafer-level processing and testing leading to a reduction in cost and to increases in performance and reliability. The geometrical arrangement of the lasers around a common grating allows for multiple wavelengths with independent modulation into a single fiber [3]. These lasers are well suited for optical interconnects, for the data links used in particle and nuclear physics experiments, and for space and medical applications. Typical radiation doses in medical applications range from a few rad to about 10 krad. Radiation doses in space applications [4], [5] are typically a few hundred kilorad, where incident particles are mostly gamma rays, electrons, and protons, in one, to a few hundred megaelectronvolts energy range. Applications in particle and nuclear physics experiments require a much higher radiation resistance of the electronic components, ranging from a few hundred kilorad to about 10 Mrad, depending on the location inside the detector and the nature of the colliding particles.

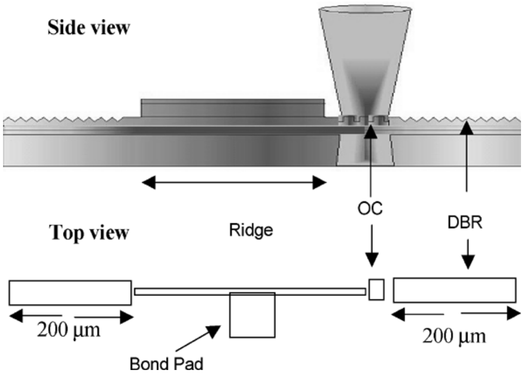


Fig. 1. Side and top views of GSE laser geometry.

Incidence of heavy particles (protons, neutrons, or ions) cause lattice damage in semiconductors, resulting in degraded optical and electrical properties. Ionizing radiation from gamma sources and charged particles produce trapped charges in dielectric layers. For III–V semiconductor lasers, most radiation damage is believed to come from lattice displacement [6], [7]. In the case of edge-emitting lasers (EEL), the threshold current increases proportionately with the total received fluence, but the slope of the light–current (L–I) curve remains unchanged. In vertical-cavity surface-emitting lasers (VCSELs), the threshold increase is much smaller compared to EEL, but the L–I slope and the thermal rollover point both decrease with increasing radiation fluence [6], [7].

II. EXPERIMENTAL RESULTS AND DISCUSSION

A 200-MeV/c proton beam at the Indiana University Cyclotron Facility was used for tests of the GSE lasers. The facility delivers a beam of protons with a tunable momentum in the range of 30–200 MeV/c. The highest momentum of 200 MeV/c was chosen to irradiate the lasers. The average beam flux was 3.1×10^9 protons/cm^2/s, i.e., about a factor of 1000 higher than that in most particle physics experiments.

Two irradiation tests were performed. For the initial test, two passive (not powered) GSE lasers were exposed to an integrated fluence of 2.69×10^{13} and 4.0×10^{14} protons/cm^2, respectively. These fluencies correspond to total doses of 1.5 and 22.3 Mrad,

---

Manuscript received February 25, 2005; revised September 16, 2005. This work was supported in part by the Department of Energy under Grant DE-FG02-04ER41299 and by the Texas Higher Education Coordinating Board's Technology Development and Transfer Program under Grant 003613-0019-2001.

J. Ye, T. Liu, R. Stroynowski, and B. E. Wakeland are with the Department of Physics, Southern Methodist University, Dallas, TX 75275 USA.

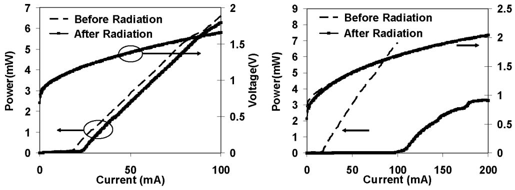
A. C. Xiang and G. Evans are with Photodigm, Inc., Richardson, TX 75083-0938 USA, and also with Southern Methodist University, Dallas, TX 75275 USA.

N. Amarasinghe, S. McWilliams, and T. Masood are with Photodigm, Inc., Richardson, TX 75083-0938 USA.

Digital Object Identifier 10.1109/LPT.2005.860055

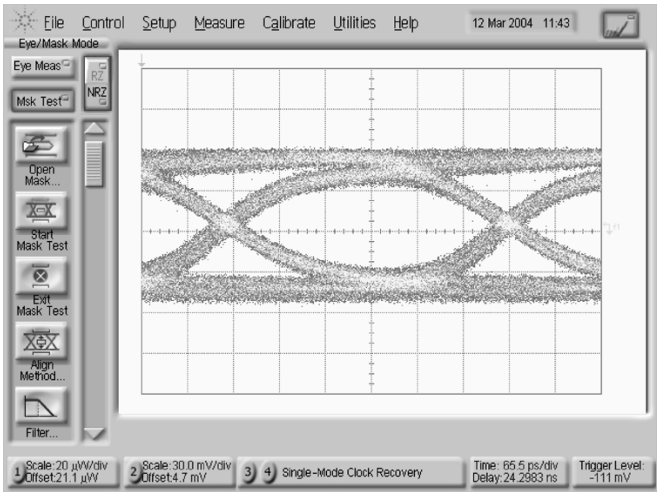
TABLE I
PROTON FLUENCE FOR GROUPS OF GSE LASERS IN SECOND TEST

Group	Fluence (proton/cm^2)	Ionization dose (Mrad)
A	3.15×10^{13}	1.8
B	1.05×10^{14}	5.9
C	2.05×10^{14}	11.4
D	4.00×10^{14}	22.3



(a) (b)

Fig. 2. GSE L–I–V curves for GSE lasers that were not powered during irradiation (a) after 1.5-Mrad radiation dose and (b) after 22.3-Mrad radiation dose.



1 Scale:20 µW/div Offset:21.1 µW
2 Scale:30.0 mV/div Offset:4.7 mV
3 4 Single-Mode Clock Recovery
Time: 65.5 ps/div Delay:24.2983 ns
Trigger Level: -111 mV

Fig. 3. 2.5-Gb/s eye diagram for GSE laser irradiated (but not-powered during irradiation) with 1.5-Mrad dose.

TABLE II
THRESHOLD INCREASE, RISE TIME, FALL TIME, AND BER OF LASERS AFTER IRRADIATION IN SECOND TEST

Group	Laser No.	I$_{th}$ increase	Rise/fall time	BER
A	5-85	1.6 mA	48.5 ps/83.4 ps	$< 10^{-12}$
1.8	6-73	2.0 mA		
Mrad	6-74	4.4 mA		
B	5-84	5.2 mA	68.9 ps/86.5 ps	$< 10^{-12}$
5.9	16-79	8.0 mA		
Mrad	13-72	3.6 mA		
C	4-79	17.2 mA	66.7 ps/90.7 ps	$< 10^{-12}$
11.4	5-81	8.43 mA		
Mrad	13-73	5.6 mA		
D	5-66	24.1 mA	67 ps/115 ps	1.9×10^{-11}
22.3	13-80	18.1 mA		
Mrad	16-80	Damaged		

respectively. Following the exposure, the lasers were stored at the radiation facility for 90 days before they were shipped back to the laboratory and tested. In the second test, 12 GSE lasers were biased at 42 mA during irradiation. The lasers were put in four groups with three lasers in each group and inserted into the chamber. As each group reached its designated total dose, it was moved out of the beam. All 12 lasers were checked with a hand-held optical power meter after irradiation and were still lasing. The particle fluences and the corresponding ionization doses received by each group are listed in Table I.

After irradiation, the lasers were packaged and stored for an additional six months, allowing the activated elements to decay.

The light–current–voltage (L–I–V) curves for the first test, in which the lasers were not biased during irradiation, are shown in Fig. 2. The L–I–V curve for the laser that received the 1.5-Mrad dose [Fig. 2(a)] indicates $\sim$10% increase in the threshold current and a similar drop of the output power at a driving current below 80 mA. The forward voltage remains the same or decreases after irradiation, which can be explained by either: 1) additional annealing of the contacts while biased or 2) a measurement error since the L–I–V measurements before irradiation were made by probe testing at the wafer level. The postirradiation measurements were made on packaged devices. The slope efficiency dL/dI, however, remains unchanged, allowing for error-free operation of the laser as illustrated by the eye diagram shown in Fig. 3. In Fig. 3 is shown an open eye diagram for the laser modulated at 2.5 Gb/s after a total radiation dose of 1.5 Mrad. The laser is driven by a nonreturn-to-zero 2^{23}-1 back-to-back pseudorandom signal. It is biased at 35 mA and the modulation depth is 50 mA. The measured rise time is 69 ps and the fall time 118 ps. All performance parameters are consistent with those observed before irradiation. The L–I–V curve, shown in Fig. 2(b), indicates that a not-powered laser subjected to a radiation dose of 22.3 Mrad has a factor of five increase in the threshold current. Together with the change of the L–I slope, this laser is not useful after receiving 22.3-Mrad total dose.

The lasers in the second test were biased at 42 mA during irradiation. After irradiation they all exhibit a small increase in threshold current with no change in the slope of the L–I curve. One laser in group D was mechanically damaged during shipment and was removed from further consideration. The threshold change, the 20%–80% rise and fall times and the bit-error rate (BER) after the irradiation are listed in Table II. The rise and fall times were only measured after irradiation and are typical of nonirradiated devices from the same lot. The L–I–V curves for each group of lasers are shown in Fig. 4. The L–I curves indicate a monotonic increase of the threshold current with increasing dose. However, the BER remain below 10^{-12} for doses up to 11.4 Mrad.

The laser ID (Table II, Figs. 4 and 5) indicates the position (row and column) of the laser on the wafer. All lasers are from the same wafer.

The eye diagrams of a laser from each irradiated group are shown in Fig. 5. Degradation in the opening of the eye with increasing dose is observed. However, lasers in group A, B, and C still pass the 2.5-Gb/s eye mask test. Because of the large increase in threshold for devices in group D, the modulation current was reduced from 50 to 40 mA to avoid excessive current through the device. Therefore, the degradation of the eye in Fig. 5(d) is partly due to the reduced signal-to-noise ratio resulting from the reduced modulation current.

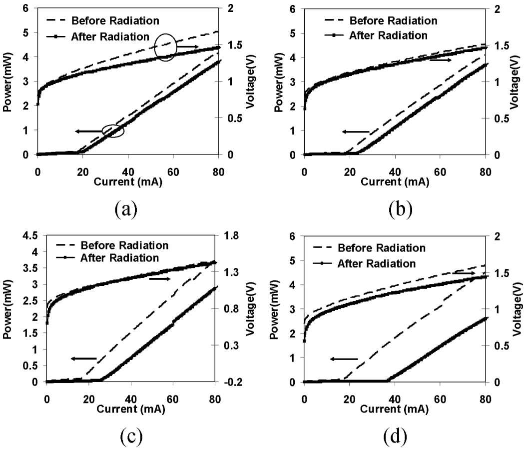


Fig. 4. L–I–V curves for GSE lasers that were powered during irradiation test. Dashed lines describe lasers' behavior before irradiation. Solid lines describe lasers' behavior after irradiation. (a) Laser 6-73 in group A. (b) Laser 5-84 in group B. (c) Laser 5-81 in group C. (d) Laser 13-80 in group D.

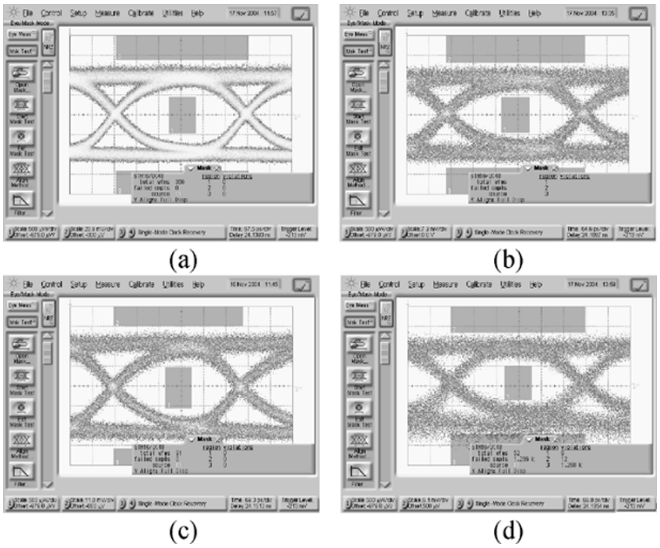


Fig. 5. Eye diagrams of GSE lasers modulated at 2.5 Gb/s after irradiation. (a) Laser 5-85 in group A. (b) Laser 5-84 in group B. (c) Laser 4-79 in group C. (d) Laser 5-66 in group D.

A comparison of the near fields and far fields of irradiated devices in groups A and D with devices in the same production batch that were not irradiated shows no observable changes. The spectrum after irradiation (1337.5 nm) of device 13–80 was compared to the spectrum obtained at the wafer level before irradiation (1336.4) at the same drive current. The side lobe-suppression ratios remained unchanged at over 40 dB. However, the wavelength increase of 0.9 nm is somewhat larger than expected, since the wavelength shift for GSE lasers is typically 0.14 nm/C and corresponds to a temperature rise of 6.4 °C. The thermal resistance of the p-side-up packaged device is higher than that of a die still on the wafer and the wafer level testing is not temperature controlled. As a result, the increase in wavelength may only be due to testing conditions and experimental error.

A scanning electron microscopy analysis of the devices exposed to the lowest and highest amount of radiation revealed no observable damage and suggests that defects occurred internally.

III. CONCLUSION

All lasers that were operated during irradiation degraded gradually. The initial tests on two lasers that were not powered during irradiation suggest the possibility that annealing may have occurred in the devices that were powered during irradiation in the second test.

All irradiated lasers that were biased during the test perform well at a total dose up to 11 Mrad, which exceeds the highest dose expected in space applications and equals the most stringent requirements for nuclear and particle physics experiments. At a total dose of 22.3 Mrad, the lasers still operate at an acceptable but reduced BER.

REFERENCES

[1] G. A. Evans and J. M. Hammer, *Surface Emitting Semiconductor Lasers and Arrays*. San Diego, CA: Academic, 1993.

[2] T. Masood, S. Patterson, N. V. Amarasinghe, S. McWilliams, D. Phan, D. Lee, Z. A. Hilali, X. Zhang, G. A. Evans, and J. K. Butler, "Single-frequency 1310-nm AlGaInAs-InP grating-outcoupled surface-emitting lasers," *IEEE Photon. Technol. Lett.*, vol. 16, no. 3, pp. 726–728, Mar. 2004.

[3] D. Roh, T. Masood, S. Patterson, N. V. Amarasinghe, S. McWilliams, G. A. Evans, and J. Butler, "Dual-wavelength AlInGaAs-InP grating-outcoupled surface-emitting laser with an integrated two dimensional photonic lattice outcoupler," *IEEE Photon. Technol. Lett.*, vol. 17, no. 2, pp. 270–272, Feb. 2005.

[4] J. P. G. Bristow, J. A. Lehman, R. A. Morgan, and J. DeRuiter, "The advancement of photonic interconnects for spaceborn systems," in *Proc. SPIE Critical Rev. Technology—Advancement Photonics Space*, E. W. Taylor, Ed: SPIE, 1977, vol. CR66, to be published.

[5] R. F. Carson, E. W. Taylor, A. H. Paxton, H. Schone, K. D. Choquette, H. Q. Hou, M. E. Warren, and K. L. Lear, "Surface emitting laser technology and its application to the space radiation environment," in *Proc. SPIE Critical Rev. Technology—Advancement Photonics Space*, E. W. Taylor, Ed: SPIE, 1977, vol. CR66, to be published.

[6] C. Claeys and E. Simoen, *Radiation Effects in Advanced Semiconductor Materials and Devices*. Berlin, Germany: Springer-Verlag, 2002.

[7] A. Holmes-Siedle and L. Adams, *Handbook of Radiation Effects*, 2nd ed. New York: Oxford Univ. Press, 2002.