Bias-Free Data Transmission Using Single-Mode GaAs VCSELs at $\lambda = 835$ nm

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Bias-free 1 Gb/s pseudo-random data transmission using laterally oxidized single-mode GaAs vertical-cavity surface-emitting laser diodes is demonstrated and compared to biased modulation. Bit error rates of 10^{-11} *obtained for* -28 *dBm received optical power make these devices very attractive for optical interconnection.*

1. Introduction

Over the past few years, short wavelength ($\lambda = 850, 980$ nm) vertical-cavity surface emitting lasers (VCSELs) have improved considerably in performance. For selectively oxidized VCSELs, high wall-plug efficiencies of 57 % [P-54] combined with extremely low threshold currents of smaller than 100 μA [1] have been demonstrated. Transmission at data rates as high as 10 Gb/s with proton-implanted InGaAs VCSELs [P-13] as well as 16.3 GHz modulation bandwidth of oxidized InGaAs VCSELs [2] have been reported. Presently, VCSELs are being investigated as transmitters for optical interconnections such as in high-speed board-to-board communication and parallel short range multi-gigabit data links. Bias-free data transmission is highly desirable for reducing power consumption and to simplify laser driving circuits. In this report, we investigate bias-free 1 Gb/s non-return-to zero (NRZ) pseudo-random bit sequence (PRBS) transmission with $2^{31} - 1$ word length using a laterally oxidized single-mode GaAs VCSEL source. The results of non-biased data transmission are compared to those obtained for biased operation.

2. Device Structure

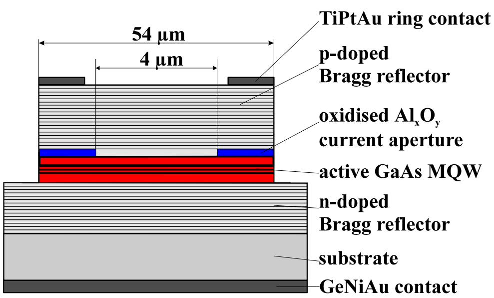

Fig. 1. Cross-sectional view of selectively oxidized GaAs VCSEL.

The layer structure of the molecular beam epitaxially grown GaAs VCSEL used for the experiments is schematically illustrated in Fig. 1. The one-wavelength thick cavity contains a $\lambda/2$

central region with three 8 nm thick active GaAs quantum wells embedded in $Al_{0.2}Ga_{0.8}As$ barriers and surrounded by $\lambda/4$ $Al_{0.5}Ga_{0.5}As$ layers for efficient carrier confinement. The bottom Bragg reflector consists of 28.5 n-type Si-doped $AlAs/Al_{0.2}Ga_{0.8}As$ quarter wavelength layer pairs. To reduce the electrical resistance, the 24 pairs $Al_{0.9}Ga_{0.1}As/Al_{0.2}Ga_{0.8}As$ p-type C-doped step-graded top reflector has an optimized modulation and δ-doping profile. As the lowest layer of the p-doped top Bragg reflector, a single 30 nm thick AlAs layer was grown for selective oxidation. The VCSEL studied has an active diameter of about 4 μm and emits at 836 nm wavelength.

3. Experiment

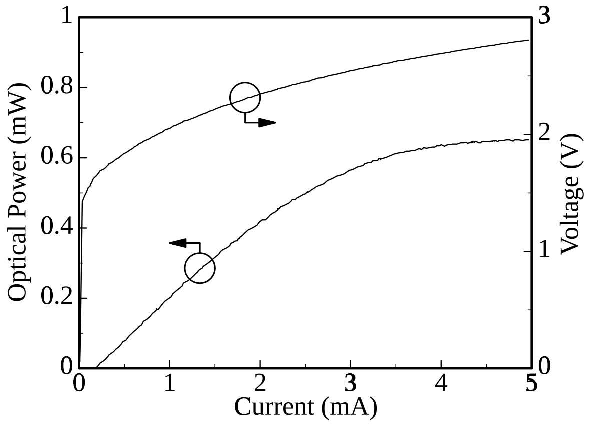

Fig. 2. Output charactristics of a 4 μm diameter selectively oxidized GaAs VCSEL.

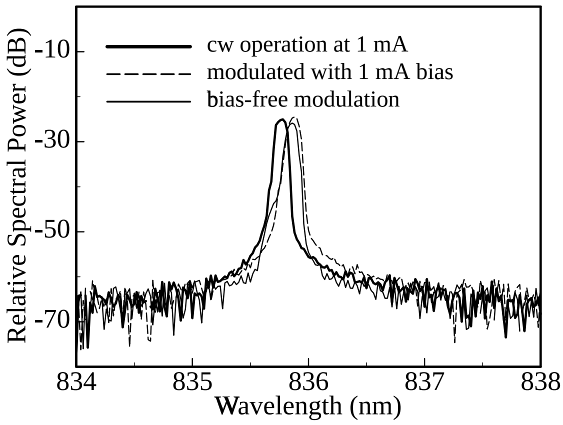

Fig. 3. Optical spetrca for biased and bias-free modulation.

The VCSEL is wire bonded to an SMA socket and either driven with a cw current or modulated with a PRBS signal at 1 Gb/s NRZ data rate. Fig. 2 shows the output characteristics of the laser diode. The threshold current is 250 μA at a threshold voltage as low as 1.7 V, while an output power of 0.55 mW is obtained at 3 mA.

Fig. 3 depicts the spectra recorded for bias-free 1 Gb/s modulation with $V_{pp} = 2$ V and 1 Gb/s modulation at 1 mA bias current and $V_{pp} = 0.5$ V. All spectra indicate single-mode emission at 836 nm with a side mode suppression exceeding 30 dB. Fig. 4 illustrates the experimental setup. For data transmission experiments, the laser is either directly driven by a pattern generator at 1 Gb/s with $V_{pp} = 2$ V without any additional bias, or a bias current of 1 mA and 1 Gb/s modulation with $V_{pp} = 0.5$ V are combined in a bias-tee and fed to the VCSEL. The emitted light is butt-coupled to a 50 μm core diameter graded index multimode fiber. After 100 m transmission, the signal is passed through a variable attenuator and detected with a Germanium avalanche photodiode and preamplified in two stages.

Fig. 5 shows the eye diagrams for biased and bias-free 1 Gb/s PRBS modulation. In the diagram of the biased VCSEL the eye is wide open and symmetric. For non-biased modulation we observe a turn-on delay of $\tau_d \approx 150$ ps and an asymmetric eye shape due to a significant relaxation oscillation peak. For an average driving current of 1 mA inferred from the spectra in Fig. 3 one can estimate a logic on-state current of about $I_p = 1.55$ mA from the nonlinear

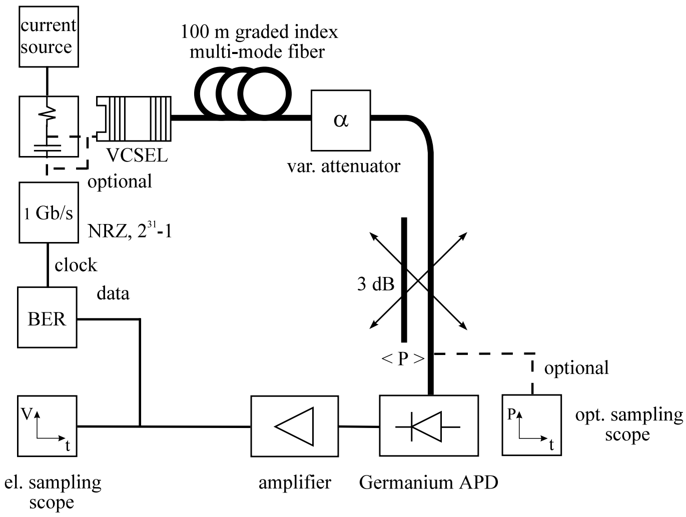

Fig. 4. Experimental setup.

I-V characteristics displayed in Fig. 2, taking an on-off ratio of 50 % into account. The turn-on delay is then calculated as

$$\tau_d = \tau_e \ln \frac{I_p}{I_p - I_{th}} = 150 \text{ ps}$$

using a threshold current of 250 μA and assuming a carrier lifetime of $\tau_e = 1$ ns. This result is in reasonable accordance with the experimental observation in Fig. 5. The results of the transmission experiments are summarized in the bit error rate (BER) characteristics in Fig. 6, where circles denote biased 1 Gb/s PRBS modulation while squares denote bias-free transmission over 100 m of multimode fiber. The bit error rate for 1 Gb/s remains better than 10^{-11} for biased as well as for bias-free operation. The received optical power necessary for a bit-error

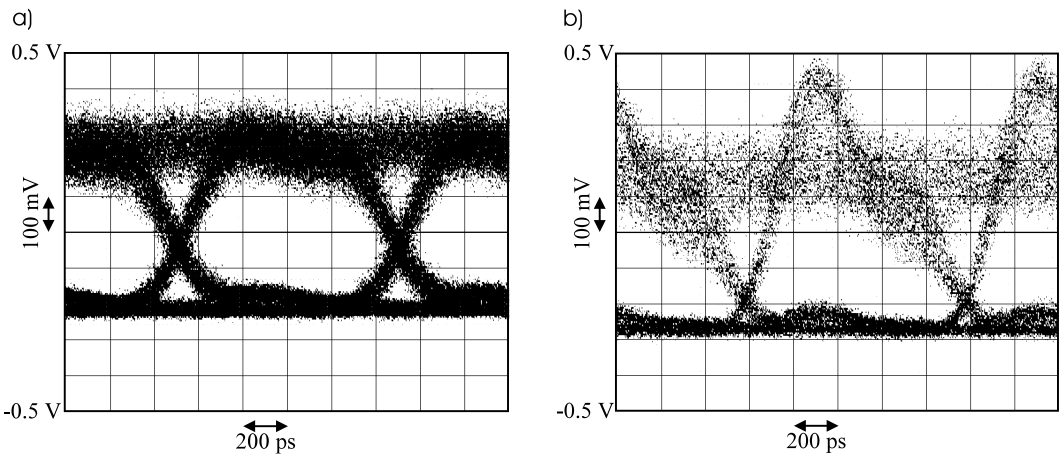

Fig. 5. Eye diagrams for a) biased modulation at 1 Gb/s $2^{31} - 1$ PRBS and b) bias-free modulation at 1 Gb/s $2^{31} - 1$ PRBS.

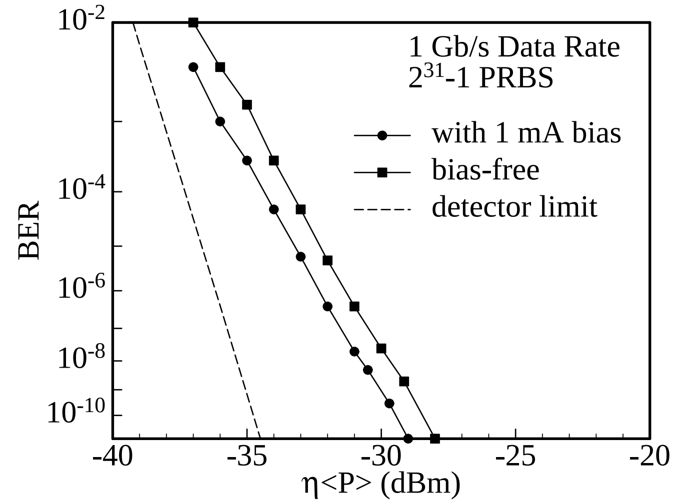

Fig. 6. Bit error rate measurement at 1 Gb/s and $2^{31}-1$ word length.

rate of $< 10^{-11}$ is as low as -29 dBm for biased operation, while bias-free operation shows a penalty of 1 dB nearly independent of the BER. Also indicated in Fig. 6 is the APD detector noise limit.

4. Conclusion

For the first time we have successfully demonstrated bias-free data transmission with $2^{31}-1$ PRBS signals at 1 Gb/s data rate using a high performance GaAs VCSEL source emitting in the 800 to 850 nm wavelength regime [P-56]. A BER of 10^{-11} is obtained at a received power of -29 dBm for biased and -28 dBm for bias-free transmission over 100 m graded index multimode fiber. Bias-free operation greatly facilitates optical interconnection systems.

References

[1] Y. Hayashi, T. Mukaihara, N. Hatori, N. Ohnoki, A. Matsutani, F. Koyama, and K. Iga, "Lasing characteristics of low-threshold oxide confinement InGaAs-GaAlAs vertical-cavity surface-emitting lasers", *IEEE Photon. Technol. Lett.*, vol. 7, pp. 1324–1326, 1995.

[2] K. L. Lear, A. Mar, K. D. Choquette, S. P. Kilcoyne, R. P. Schneider, Jr., and K. M. Geib, "High-frequency modulation of oxide confined vertical cavity surface emitting lasers", *Electron. Lett.*, vol. 32, pp. 457–458, 1996.