10 Gbit/s Data Transmission Using Top Surface-Emitting Vertical-Cavity Laser Diodes

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Intensity modulated proton-implanted top surface-emitting vertical-cavity lasers (VCSELs) with a small signal modulation bandwidth of 12 GHz butt-coupled to multi-mode fibers are investigated as light source for optical interconnection. At 10 Gbit/s pseudo random data rates, the bit error rate (BER) remains under 10^{-11} *after transmission over 500 m of graded-index multi-mode fiber. Optimum transmission behavior is achieved for linearly polarized nearly single-mode laser operation with a side-mode suppression of better than 25 dB under modulation. Spectral characterization indicates that linearly polarized single-mode light output is essential for good BER performance.*

1. Introduction

Performance of short wavelength (λ=850/980 nm) proton implanted vertical-cavity surface-emitting lasers (VCSELs) has improved significantly in the past years such that these devices are now considered as transmitters for optical communication applications alternatively to in plane lasers [1]. The electrical problem of excessive voltage drop in the VCSEL Bragg reflectors and low conversion efficiency has been solved by using modulation and δ-doping at the heterointerfaces [2] and threshold voltages close to the bandgap voltage has been demonstrated by several groups [3,4]. At the present status, VCSELs are investigated as transmitters for short distant data links, board-to-board communication and optical interconnection. Properties such as formation of two-dimensional arrays [5], easy on-wafer testing and low-divergent light output perpendicular to the wafer allowing efficient fiber coupling [6] promise low-cost production. Additionally, bias-free modulation can be expected from oxidized VCSELs where high wall-plug efficiencies [7] and threshold currents below 10 μA have been demonstrated [8]. To achieve low-cost solutions, VCSEL transmitters will be installed with large-core plastic-clad fibers [9] or graded-index multi-mode fiber where transmission of 3 Gbit/s has been reported over 500 m length [10,11].

In this report we study the emission characteristics of VCSELs with 12 GHz optical modulation bandwidth. Transmission of 10 Gbit/s pseudo-random bit sequence (PRBS) data rates with a bit error rate of less than 10^{-11} is achieved for both back to back testing and transmission over 500 m of graded index multi-mode fiber.

2. Device Structure and Modulation Response

The VCSEL used for the transmission experiment is described in [2]. It is grown in $< 100 >$ direction and contains three 8 nm thick strained InGaAs quantum wells embedded in GaAs barriers surrounded by $Al_{0.35}Ga_{0.65}As$ layers for efficient carrier confinement. The active region is sandwiched between two Bragg reflectors where the bottom and the top reflector consists of 35.5 periods and 28 periods of $GaAs/Al_{0.7}Ga_{0.3}As$ layers, respectively. A TiPtAu top ring p-contact is used to achieve both, good ohmic contacts as well as light emission through the top Bragg reflector at 980 nm.

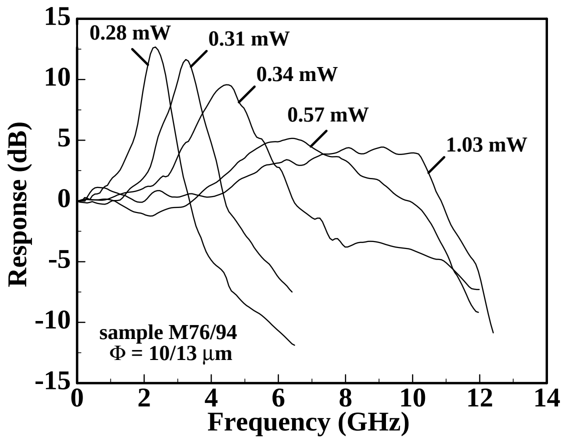

Fig. 1: Small signal frequency response of a 13 μm active diameter VCSEL with 10 μm emission window.

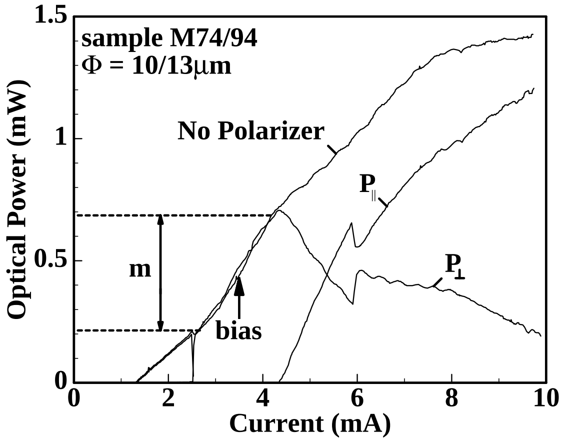

Fig. 2: Polarization resolved output characteristics of top emitting VCSELs with 10 μm diameter emission window and 13 μm active diameter. $P_\perp$ and $P_{||}$ denote orthogonal polarizations.

To measure the modulation characteristics free of parasitics laser diodes are processed in 250 μm pitch ground-signal configuration and contacted with microwave probes. The modulated light is detected with a 15 GHz bandwidth InGaAs pin photodiode and recorded with a RF spectrum analyzer. Fig. 1 depicts the measured small-signal amplitude modulation behavior of a laser diode with 13 μm active diameter and 10 μm emission window aperture. The modulation bandwidth increases with increasing driving current. The maximum electrical and optical bandwidth obtained at 1.03 mW optical output is 11.2 GHz and 12 GHz, respectively.

3. Emission Characteristics

Fig. 2 shows the polarization resolved output characteristics of the VCSEL with 13 μm active diameter and 10 μm emission window. Above the threshold current of 1.5 mA the laser oscillates in the linear polarization state $P_{||}$. At 2.6 mA polarization switching to the orthogonal eigenstate is observed which might be due to a change in crystallographic strain induced by the current. Since the frequency splitting of the nearly degenerate orthogonal eigenstates is less than the 0.1 nm resolution bandwidth of the grating spectrometer [12], the polarization modes are not resolved in the emission spectra depicted in Fig. 3. Above 4.3 mA the LP_{11} mode appears 0.3 nm blue shifted and orthogonally polarized to the fundamental LP_{01} mode. The power in the LP_{01} and the LP_{11} equal at approximately 6 mA where again a polarization mode transition occurs. A third transverse mode oscillates for currents higher than 8.4 mA.

4. Bit Error Rate Measurement

For high bit rate data transmission the VCSELs with short feeding lines and bondpads are connected to SMA sockets. The electrical 3 dB frequency of the packaged device is 9 GHz. Bias current and 10 Gbit/s PRBS are combined in a bias-tee. After transmission over 500 m of multi-mode fiber the signal is attenuated, and focused on a 15 GHz bandwidth InGaAs

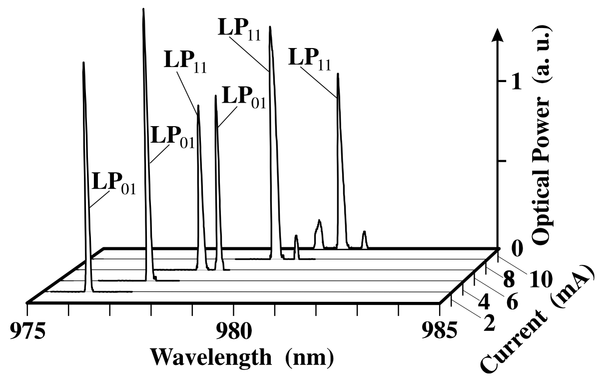

Fig. 3: Emission spectra of 10/13 μm VCSEL for various bias currents.

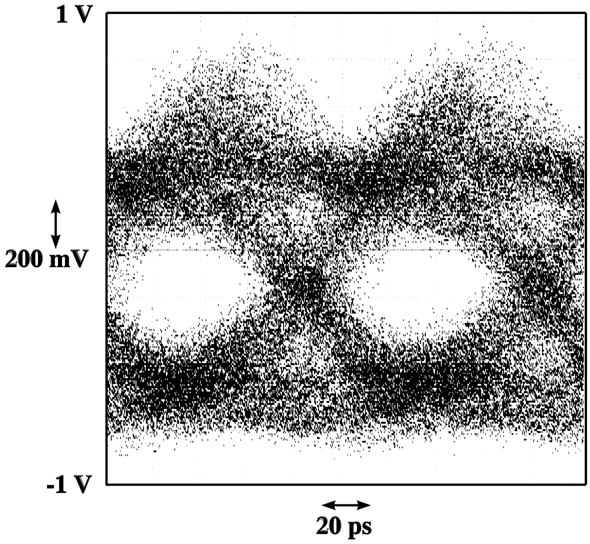

Fig. 4: Eye diagram at 10 Gbit/s PRBS modulation at a BER of 10^{-9}.

photodiode. Focal spot size is smaller than the active diameter of 50 μm of the photodiode such that modal noise is negligible. The electrical signal is amplified in two stages and fed to an electrical sampling oscilloscope and the bit error detector. Fig. 4 depicts the eye diagram at a BER of 10^{-9}. The eye opening is symmetric though laser relaxation oscillation is observed when switching from low to high level. The results of the transmission experiments are summarized in Fig. 5 where full circles denote back to back testing. A 2^7–1 non-return-ow zero PRBS has been choosen since long sequences of "1" lead to additional errors caused by the low end cut-off frequency of the second stage amplifier.

Optimum results with no noise floor and $\eta\langle P\rangle$=–13.1 dBm required for a BER of 10^{-11} are obtained at 3.4 mA bias current and m = 50 % optical modulation depth determined with an optical sampling oscilloscope. The driving conditions avoid dynamic transverse mode transitions as well as dynamic polarization switching and yield extremly stable single-mode linearly polarized light output as indicated in Fig. 2 and Fig. 3. The receiver sensitivity limit is given by thermal noise of the 50 Ω resistor in the front end and the noise figure F=2.5 (F_{dB}=4 dB) of the first stage amplifier. Using

$$\eta < P >= \frac{h\nu}{q}\frac{Q}{m}\sqrt{\frac{FkT\Delta f}{R}} \tag{1}$$

where η is the quantum efficiency of the photodetector, h Planck's constant, ν the optical frequency, q the electron charge, k Boltzmann's constant, T the temperature and Δf the bandwidth a mean optical power of $\eta\langle P\rangle$ = –16.7 dBm for a quality factor Q = 6 as required for a BER of 10^{-9} is calculated. The difference of 2.7 dB is attributed to laser relaxation oscillation and intersymbol interference caused by the low end cut-off frequency of the electrical amplifier. The power penalty after 500 m graded index fiber transmission of 1.7 dB at a BER of 10^{-11} is due to fiber dispersion. The fiber dispersion power penalty is lower than expected for graded index

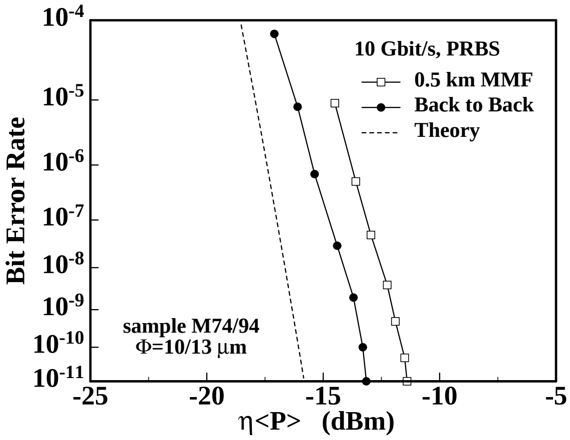

Fig. 5: BER measurement at 10 Gbit/s with 2^7–1 PRBS using small size VCSEL for transmission over 500 m of graded index multi-mode fiber. The dashed line indicates the receiver limit for 50 % optical modulation depth.

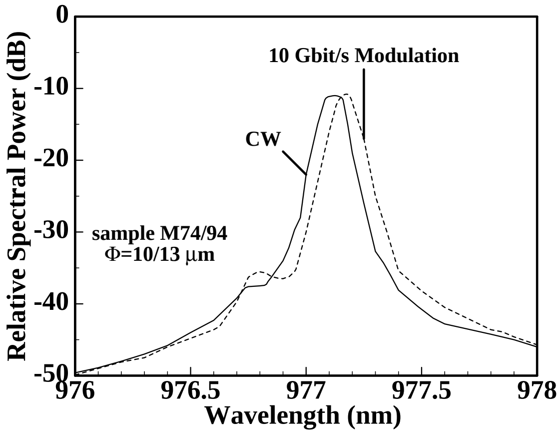

Fig. 6: Spectra of 10/13 μm VCSEL at I_L=3.4 mA measured with 0.1 nm resolution. The full line depicts cw-operation only and the dashed line 10 Gbit/s PRBS modulation.

multi-mode fibers since the power is mainly guided in the center of the fiber core. Sharp bending at the transmitter end leading to higher order mode excitation is avoided. Fig. 6 shows both the cw-spectrum as well as the spectrum of the modulated laser on a logarithmic plot at a bias current of 3.4 mA. With 10 Gbit/s PRBS the lasing mode is 0.1 nm red shifted due to additional power dissipation. Since no spectral broadening is observed the chirp is certainly less than the resolution bandwidth of 0.1 nm. The suppression of the side mode at 976.8 nm decreases from 27 dB for cw operation to 25.2 dB in the modulated case.

V. Conclusion

We demonstrate 10 Gbit/s PRBS data transmission with nearly single-mode operating VCSELs using intensity modulation and direct detection. A BER of 10^{-11} is achieved for both back to back testing as well as transmission over 500 m of graded index multi-mode fiber. The power penalty of 1.7 dB compared to back to back testing is attributed to fiber dispersion. To our knowledge this is the highest pseudo random bit sequence transmitted with a VCSEL to date. The LP_{11} mode suppression of the modulated VCSEL is better than 25 dB. Analysis of spectral and polarization characteristics show that dynamic polarization mode switching as well as higher order transverse mode oscillation should be avoided to achieve minimum laser noise and a minimum BER as long as modal noise is negligible. The transmission experiments demonstrate that polarization control in top surface-emitting VCSELs is very important to enhance VCSEL performance in high-speed optical interconnects, short distance communication and board-to-board data links.

References

[1] K. Hahn, "Gigabyte/s Data Communication with the VCSEL based POLO Module," *in Proc. 8th Annual Meeting LEOS*, San Francisco, vol. 1, pp. 228-229, 1995.

[2] G. Reiner, E. Zeeb, M. Ries, and K.J. Ebeling, "Optimization of planar Be-doped InGaAs VCSELs with two-sided output," *IEEE Photonics Technol. Lett.*, vol. 7, pp. 730-732, July 1995.

[3] M.G. Peters, D.B. Young, F.H. Peters, J.W. Thibeault, and L.A. Coldren, "17.3 % peak wall-plug efficiency vertical-cavity surface-emitting lasers using lower barrier mirrors," *IEEE Photonics Technol. Lett.*, vol. 6, pp. 31-33, Jan. 1995.

[4] K.L. Lear, R.P. Schneider, K.D. Choquette, S.P. Kilcoyne, J.J. Figiel, and J.C. Zolper, "Vertical cavity surface emitting lasers with 21 % efficiency by metalorganic vapor phase epitaxy," *IEEE Photonics Technol. Lett.*, vol. 6, pp. 1053-1055, Sept. 1994.

[5] B. Möller, E. Zeeb, T. Hackbarth, and K.J. Ebeling, "High speed performance of 2-D vertical-cavity laser diode arrays," *IEEE Photonics Technol. Lett.*, vol. 6, pp. 1056-1058, Sept. 1994.

[6] U. Fiedler and K.J. Ebeling, "Design of VCSELs for feedback insensitive data transmission and external cavity active mode-locking," *IEEE J. of Select. Topics in Quantum Electron.*, vol. 1, pp. 442-450, June 1995.

[7] K.L. Lear, K.D. Choquette, R.P. Schneider, S.P. Kilcocyne and K.M. Geib, "Selectively oxidised vertical cavity surface emitting lasers with 50 % power conversion efficiency," *Electron. Lett.*, vol. 31, pp. 208-209, Feb. 1995.

[8] G.M. Yang, M.H. MacDougal, and P.D. Dapkus, "Ultralow threshold current vertical-cavity surface-emitting lasers obtained with selective oxidation," *Electron. Lett.*, vol. 31, pp.886-888, May 1995.

[9] H. Kosaka, A.K. Dutta, K. Kurihara, Y. Sugimoto, and K. Kasahara, "Giga-bit-rate optical-signal transmission using vertical-cavity surface-emitting lasers with large-core plastic-cladding fibers," *IEEE Photonics Technol. Lett.*, Aug. 1994, vol. 7, Aug. 1995, pp.926-928.

[10] U. Fiedler, B. Möller, G. Reiner, D. Wiedenmann, and K.J. Ebeling, "Proton implanted VCSELs for 3 Gbit/s data links," *IEEE Photonics Technol. Lett.*, vol. 7, Oct. 1995, in press.

[11] J.W. Scott, F.H. Peters, B.J. Thibeault, D.B. Young, L.A. Coldren, and C.J. Mahon, "2.488 Gbit/s optical data transmission with linear arrays of intra-cavity contacted, top emitting vertical cavity lasers," *20th European Conf. on Optical Comm.*, pp. 339-342, Firenze, Sept 1994.

[12] K.D. Choquette, R.P. Schneider, K.L. Lear, R.E. Leibenguth, "Gain-dependent polarization properties of vertical-cavity lasers," *IEEE J. of Select. Topics in Quantum Electron.*, vol. 1, pp. 661-666, June 1995.