

Optically Preamplified Receiver at 10, 20, and 40 Gb/s Using a 1550-nm Vertical-Cavity SOA

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Abstract—In this study, we demonstrate optical preamplification at 1550 nm using a vertical-cavity semiconductor optical amplifier (VC SOA). At 10 Gb/s, a receiver sensitivity of -28.5 dBm was achieved for 13 dB of fiber-to-fiber gain. This corresponds to an improvement in the receiver sensitivity of 9.7 dB. We also evaluated the performance at 20 and 40 Gb/s. A 4.7-dB power penalty was measured at 20 Gb/s with 6-dB fiber-to-fiber gain. Theoretical simulations show that the pattern dependence can be mitigated using a VC SOA with lower mirror reflectivity.

Index Terms—Fabry–Pérot resonators, laser amplifiers, optical filters, optical receivers, semiconductor optical amplifiers (SOAs), surface-emitting lasers, vertical-cavity semiconductor optical amplifiers (VC SOAs).

I. INTRODUCTION

OPTICAL preamplification is an attractive way to increase the receiver sensitivity in fiber optical communication systems especially at high bit rates where avalanche photodiode (APD) are limited by their gain bandwidth product. Optical preamplification has been demonstrated using both erbium-doped fiber amplifiers (EDFAs) [1] and semiconductor optical amplifiers (SOAs) [2]. For this application, vertical-cavity SOAs (VC SOAs) are of interest as a compact solution that can be integrated with a photodetector. VC SOAs are potential low-cost alternatives to in-plane SOAs and EDFAs, and show high fiber coupling efficiency and low noise figure. It is important to note that due to the inherent spectral filtering, optical filters are not needed to remove amplification noise outside the signal bandwidth, as is required for EDFAs and in-plane SOAs. We have previously demonstrated optical preamplification at 10 Gb/s using 1.3- μm VC SOAs [3]. A receiver sensitivity of -26.2 dBm was achieved, which corresponds to a 7-dB improvement over a nonamplified receiver. In the present study, we demonstrate successful preamplification for 1.55 μm at 10 Gb/s and also evaluate the performance at 20 and 40 Gb/s.

II. DEVICE DESIGN

The VC SOA used in these experiments was operated in reflection mode and pumped optically using a 980-nm pump laser module. The structure consisted of an metal–organic

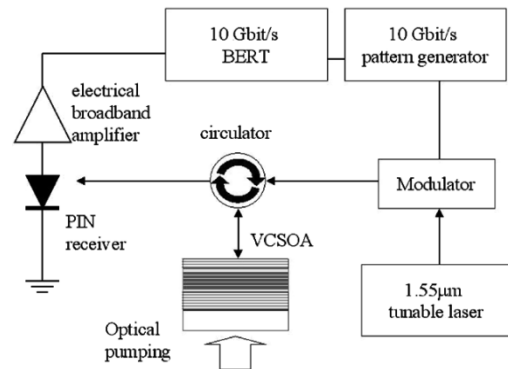


Fig. 1. Experimental setup for 10-Gb/s preamplification.

chemical vapor deposition-grown AlInGaAs–InP active region wafer-bonded to two molecular beam epitaxy-grown AlGaAs–GaAs distributed Bragg reflectors (DBRs). The active region had 25 compressively strained AlInGaAs quantum wells (QWs) and strain compensating barriers. The QWs were grouped together in five sets of five wells each, positioned on the standing wave peaks in the $5/2\text{-}\lambda$ cavity. The bonded interfaces were positioned at standing-wave nulls. The bottom and top DBR had 30 and 11.5 periods resulting in a calculated peak reflectivity of 0.999 and 0.93, respectively. The fiber-to-fiber noise figure of this device was about 10 dB. The frequency response measured by small signal modulation was determined to be very flat at least up to 20 GHz, which is the limit of the equipment. The difference in response between 0.13 MHz and 20 GHz was only 1 dB.

III. 10-Gb/s EXPERIMENT

The experimental setup for 10 Gb/s is shown in Fig. 1. A 1.55- μm tunable laser was used as the signal source. The signal was modulated and coupled into the VC SOA through the top DBR. The pump was injected through the bottom DBR. Fiber focusers were used for both signal and pump. The input and output signal were separated using an optical circulator. The output signal was fed to a Nortel PP-10G PIN receiver, which was followed by an electrical broad-band amplifier. No optical filter was used between the VC SOA and the PIN receiver.

The receiver sensitivity was measured with and without the VC SOA preamplifier. The VC SOA was pumped with 80 mW of 980-nm light and the temperature of the VC SOA was controlled by a thermoelectric cooler at 20 °C. The fiber-to-fiber gain at this condition was measured to be 13 dB and the optical bandwidth was 32 GHz. A 10-Gb/s $2^{23} - 1$ nonreturn-to-zero

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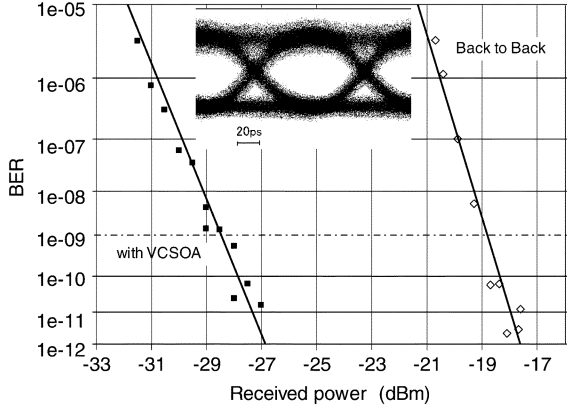


Fig. 2. BER measurement with and without VC SOA at 10 Gb/s. The eye pattern with the VC SOA at BER of 10^{-9} is also shown.

(NRZ) pseudorandom bit sequence (PRBS) was transmitted to the receiver and the bit-error rate (BER) was measured. The results are shown in Fig. 2. The receiver sensitivity (corresponding to 10^{-9} BER) without the VC SOA was -18.8 dBm. With the VC SOA, the receiver sensitivity was improved by 9.7 dB to -28.5 dBm. The 3.3-dB power penalty (difference between VC SOA gain and sensitivity improvement) is caused by the optical noise added by the VC SOA. The eye pattern with VC SOA at BER 10^{-9} is also shown in Fig. 2. This receiver sensitivity for 10 Gb/s closely matches the latest result for APDs of -29.5 dBm [4]. The receiver sensitivity for longer bit sequences was slightly higher, but no error floors were observed at this bit rate. Increasing the input signal power until the VC SOA saturates would result in an error floor since the signal power reaching the detector would no longer increase linearly with input signal power into the VC SOA. This was not observed for the range of signal power used here, and the dynamic range of the VC SOA receiver was not investigated.

IV. 20- AND 40-Gb/s EXPERIMENTS

Optical preamplification could not be measured at these higher bit rates because of equipment limitations. However, by using optical demultiplexing with an electroabsorption modulator (EAM) [5], the power penalty imposed by the VC SOA could be determined for 20 Gb/s. A 10-Gb/s NRZ $2^7 - 1$ PRBS electrical signal from the pattern generator was divided into two tributaries with certain delay and then multiplexed electrically to obtain a 20-Gb/s NRZ signal. The resulting pattern of this is not true PRBS. The setup around the VC SOA was the same as in the 10-Gb/s experiment. After the VC SOA, the 20-Gb/s signal was demultiplexed to 10 Gb/s using an EAM. The output signal was then fed to the PIN receiver and the BER was measured. The input power into the VC SOA was -25 dBm. In order to accommodate the high-bit rate signal, the bandwidth of the VC SOA had to be increased compared to the case of 10 Gb/s. This was obtained by decreasing the VC SOA gain to 6 dB (69 mW of pump power), which resulted in an optical bandwidth of 120 GHz. The power penalty imposed by the VC SOA, extracted from the BER measurements, was found to be 4.7 dB. No error floor was observed at this bit rate. Eye patterns measured after the VC SOA at both 20 and 40 Gb/s are

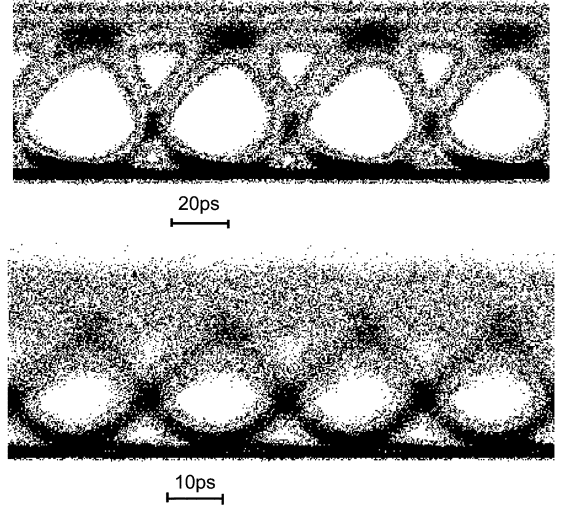


Fig. 3. Eye pattern after VC SOA at 20 (top) and 40 Gb/s (bottom). The gain of the VC SOA was 6 dB and input power to the VC SOA was -25 dBm.

shown in Fig. 3, and a degradation can be seen, especially at 40 Gb/s. Error-free operation was not obtained at 40 Gb/s.

One reason for the degradation of the eye at 20 and 40 Gb/s is the pattern dependence. The pattern dependence was observed experimentally, but not quantified due to the pattern dependence of the electrical multiplexer. The pattern dependence of the VC SOA is caused by the cavity even though it is very short. Since a VC SOA is a Fabry-Pérot SOA that has high mirror reflectivity, the output light is the sum of all fields leaving the cavity after multiple reflections. The output at a certain point in time has memory corresponding to the photon lifetime. When the pulsewidth is much longer than the photon lifetime, this is not significant. However, for short pulsewidths, this results in pattern dependence. An easy way to reduce the photon lifetime is to decrease the mirror reflectivity. The photon lifetime in the VC SOA can be calculated using $\tau_p = 1/v_g(\alpha_i + \alpha_m)$, where v_g is the group velocity and α_i and α_m are the internal loss and mirror loss, respectively. At 6 dB of gain, the photon lifetime was calculated to be 1.19 and 0.6 ps for $R_f = 0.93$ and 0.85, respectively. Fig. 4 shows the calculated output power after each round-trip versus time for $R_f = 0.93$ and 0.85, and amplifier gain of 6, 10, and 15 dB. The total output power is given by the integral of each curve.

Fig. 5(a) shows the signal pattern after VC SOA at 40 Gb/s. In this measurement, we used a multiplexed 10-Gb/s NRZ $2^7 - 1$ PRBS. There is strong pattern dependence at 40 Gb/s. Fig. 5(b) and (c) show the result of numerical analysis of integrating the rate equations [6] at 40 Gb/s for top mirror power reflectivities $R_f = 0.93$ [Fig. 5(b)] and $R_f = 0.85$ [Fig. 5(c)]

$$\begin{aligned} \frac{dN}{dt} &= G_{\text{gen}} - \Gamma_{\text{enh}} v_g g S - (AN + BN^2 + CN^3) \quad (1) \\ \frac{dS}{dt} &= \frac{\eta_s P_s(t)}{h\nu_s V_s} + \beta \Gamma BN^2 + \Gamma_{\text{enh}} \Gamma v_g g S - (\alpha_i + \alpha_m) v_g S \quad (2) \end{aligned}$$

where the mirror loss α_m is

$$\alpha_m = \left(\frac{G_R + G_T}{G_R + G_T - 1} \right) \cdot \ln g_S \quad (3)$$

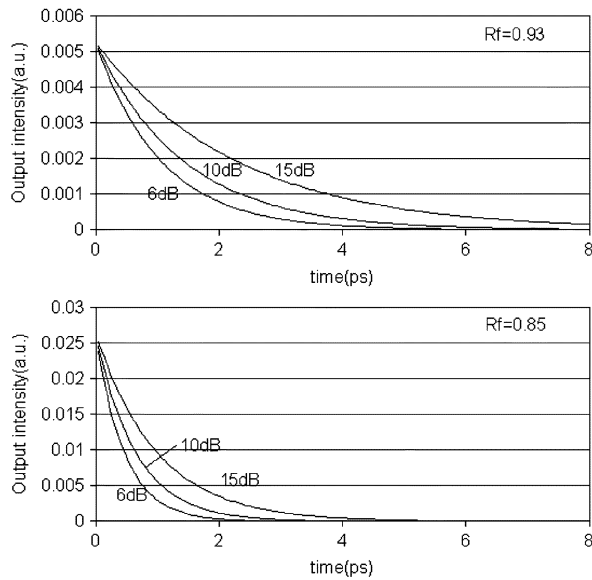


Fig. 4. Output power after each round-trip versus time for $R_f = 0.93$ and 0.85 . The total output power corresponds to integral of each curve. The number inside the figure is total signal gain of VCISOA.

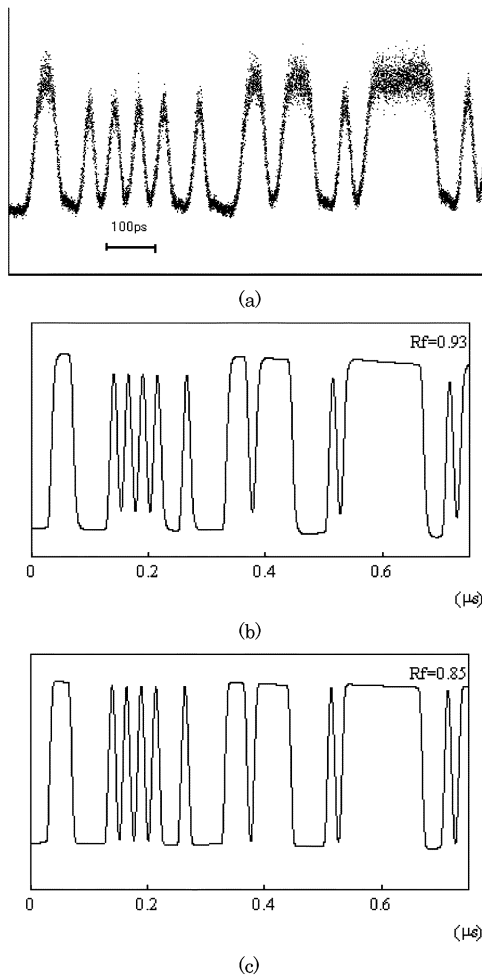


Fig. 5. Measurement and simulation of signal pattern after VCISOA at 40 Gb/s for a $2^7 - 1$ PRBS. The VCISOA gain was 6 dB and the input signal power was -25 dBm. (a) Measured signal. (b) Results of numerical simulation for $R_f = 0.93$ and (c) for $R_f = 0.85$.

where G_T and G_R are the signal gain for transmission and reflection mode of VCISOA, which depend on the mirror reflectivity [5]. The symbols used in these equations are defined in [6]. Using (1), (2), and (3), the carrier and photon densities are calculated using

$$N(t + \Delta t) = N(t) + \left. \frac{dN}{dt'} \right|_{t'=t} \cdot \Delta t \quad (4)$$

$$S(t + \Delta t) = S(t) + \left. \frac{dS}{dt'} \right|_{t'=t} \cdot \Delta t \quad (5)$$

where Δt is a sufficiently short time compared with pulsewidth. $P_s(t)$ was changed to simulate the input signal. The gain of the VCISOA for continuous-wave operation was fixed at 6 dB. The bottom mirror reflectivity was used 0.999 for both cases. This calculated result for $R_f = 0.93$ shows good agreement with the measurement. As shown in Fig. 5(c), the reduced top mirror reflectivity causes the high level of the data to be more even. This would clearly reduce the pattern dependence. Reducing the mirror reflectivity is also effective to get wider gain bandwidth [6].

V. CONCLUSION

In this study, we have demonstrated optical preamplification at $1.55 \mu\text{m}$ using a VCISOA. At 10 Gb/s, a receiver sensitivity of -28.5 dBm was achieved for 13 dB of fiber-to-fiber gain. This corresponds to an improved receiver sensitivity of 9.7 dB. The 10-Gb/s result indicates that a VCISOA can be a good low-cost preamplifier.

We also evaluated the VCISOA performance at 20 and 40 Gb/s. A 4.7-dB power penalty with 6-dB fiber-to-fiber gain was measured at 20 Gb/s. This pattern dependence can be mitigated by lowering the top mirror reflectivity of the VCISOA.

REFERENCES

- [1] R. I. Laming, A. H. Gnauch, C. R. Giles, M. N. Zervas, and D. N. Payne, "High-sensitivity two-stage erbium-doped fiber preamplifier at 10 Gbit/s," *IEEE Photon. Technol. Lett.*, vol. 4, no. 12, pp. 1348–1350, Dec. 1992.
- [2] P. J. S. Heim, M. Dagenais, M. A. Krainak, and R. Leavitt, "High-sensitivity semiconductor optical preamplified 25 GHz receiver," in *LEOS Annual Meeting '96*, 1996, pp. 245–255.
- [3] E. S. Björlin, J. Geske, and J. E. Bowers, "Optically preamplified receiver at 10 Gbit/s using vertical-cavity SOA," *Electron. Lett.*, vol. 37, no. 22, pp. 1474–1475, 2001.
- [4] H. Matsuda, A. Miura, Y. Okamura, H. Irie, K. Ito, T. Toyonaka, H. Takahashi, and T. Harada, "High performance of 10-Gb/s APD/preamplifier optical-receiver module with compact size," *IEEE Photon. Technol. Lett.*, vol. 15, no. 2, pp. 278–280, Feb. 2003.
- [5] H.-F. Chou, Y.-J. Chiu, W. Wang, J. E. Bowers, and D. J. Blumenthal, "Compact 160-Gb/s demultiplexer using a single-stage electrically gated electroabsorption modulator," *IEEE Photon. Technol. Lett.*, vol. 15, no. 10, pp. 1458–1460, Oct. 2003.
- [6] J. Piprek, S. Björlin, and J. E. Bowers, "Design and analysis of vertical-cavity semiconductor optical amplifiers," *IEEE J. Quantum Electron.*, vol. 37, no. 1, pp. 127–134, Jan. 2001.