O-band Reflective Electroabsorption Modulator for 50 Gb/s NRZ and PAM-4 Colorless Transmission

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Abstract: we present a 50 Gb/s O-band reflective electroabsorption modulator operating in both non-return-to-zero (NRZ) and PAM-4 modulation formats without equalization. We obtained >9 dB NRZ dynamic extinction ratio for a peak-to-peak voltage of 2.4 V.

1. Introduction

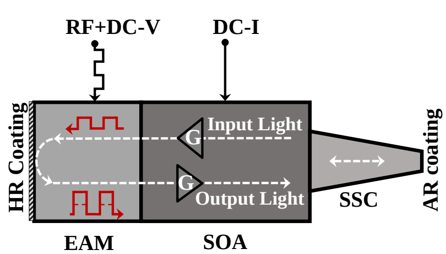
Wavelength division multiplexing (WDM) is introduced to the access network via the next generation passive optical network 2 (NG-PON2) standard by the international telecommunication union (ITU), in order to increase the aggregate capacity of the access network to 40 Gb/s in the downstream and 10 Gb/s in the upstream directions [1]. The standard recommends wavelength-tunable optical components to be used in both the optical network unit (ONU) and the optical line terminal (OLT). However, by the tunable devices' nature, their wavelength is less tightly controlled than fixed-wavelength devices. Therefore, they require a sufficient guard band between adjacent channels to avoid crosstalk.

Generally, the emission wavelength of a laser drifts as the surrounding temperature varies, which becomes a challenge in a multi-channel transmitter where multiple components are integrated on a small area of a chip [2]. One possible solution in such an environment is to use reflective electroabsorption modulators (EAMs) together with a multi-wavelength fixed source, such as a comb-laser. To maximize the modulated output power, a semiconductor optical amplifier (SOA) can be integrated with the EAM. A reflective EAM-SOA (REAM-SOA) can be used as a standalone component (e.g., at the ONU) or as an array in a multi-channel transmitter (e.g., at the OLT).

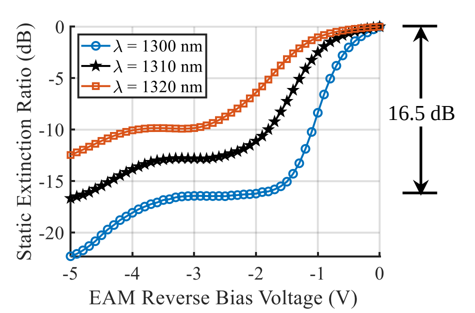
To be compatible with the NG-PON2 standard, most research activities dealing with reflective devices were focused on realizing C-band devices transmitting up to 20 km over a standard single mode fiber (SSMF) at 10 Gb/s [3]. However, due to a higher fiber dispersion in the C-band, there is a tradeoff between transmission distance and data rate. For example, Lawniczuk *et al.* demonstrated a 40 Gb/s non-return-to-zero (NRZ) transmission in the C-band by using an REAM-SOA but only up to 2 km [4]. On the other hand, fiber dispersion is significantly lower in the O-band, and it is interesting to realize very high-speed devices for several applications. State-of-the-art transmitters based on electroabsorption modulated lasers (EMLs) can operate at ≥50 Gb/s NRZ [7]. In this paper, we present a colorless O-band REAM-SOA operating either at 50 Gb/s NRZ or 25 Gbaud/s PAM-4 without equalization.

2. Device Design

Figure 1(a) shows a schematic diagram of an REAM-SOA. The principle of operation is as follows: a continuous wave (CW) light from an external source is injected into the device, and it is first amplified by the SOA and then modulated by the EAM in its forward path. The light is reflected when it hits the back facet of the device. On its return path, the optical carrier is further modulated by the EAM, reamplified by the SOA, and finally coupled to a fiber.



(a)



(b)

Fig. 1. (a) Schematic diagram of a reflective EAM-SOA, and (b) static extinction ratio of a 100 µm EAM in an REAM-SOA configuration.

Our photonic integrated circuit (PIC) comprises a 100 μm EAM, a 300 μm SOA and a 150 μm spot-size converter (SSC). The SSC is a taper with a 7° tilt. The taper broadens the optical mode, and the 7° tilt is intended to minimize optical feedback to the SOA. Our devices are based on an InGaAsP multiple quantum well (MQW) structure on an InP substrate. A semi-insulating buried heterostructure (SI-BH) is used to define the waveguide structures [5]. The EAM and the SOA sections are independently optimized, grown with separate epitaxies, and combined by using a butt-joint integration technology. To realize a reflective device configuration, the front facet (on the taper side) is antireflection coated whereas the back facet (on the EAM side) is high-reflection coated.

3. Static Characteristics of EAM

Figure 1(b) shows the static extinction curve of a 100 μm EAM in an REAM-SOA configuration for different input wavelengths at 25°C. Typically, the absorption strength of an EAM is higher with a lower detuning. As a result, a higher extinction ratio (ER) is obtained at the shorter wavelengths. For example, between 0 V and –3 V, the EAM's static ER is 16.5 dB, 13 dB and 10 dB at 1300 nm, 1310 nm and 1320 nm, respectively. In general, a high static ER can be achieved with a reflective device configuration because of the double absorption of light that occurs before and after reflection inside the PIC. Moreover, integrating the SOA on chip allows to fully compensate insertion losses. By using a lensed fiber having a mode diameter of 3 μm at $1/e^2$ point, and by applying 40 mA current to the SOA, our PIC provides a net device gain of >2 dB in static mode, with the EAM being in an ON state ($G_{net} = P_{out} - P_{in}$).

4. Dynamic Characteristics of EAM

4.1. Small Signal Frequency Response

Figure 2(a) shows the small signal frequency response (S_{21} parameter) of the 100 μm EAM in an REAM-SOA configuration for different input wavelengths. The 3-dB cutoff bandwidth of the EAM is 36 GHz at 1310 nm. The high electro-optic (E/O) bandwidth of the EAM suggests that the device could effectively be modulated at a very high bit rate (e.g., >50 Gb/s NRZ) for high-speed applications. On the other hand, the frequency response of the EAM is slightly varying with the input wavelength. However, the 3-dB bandwidth remains above 32.5 GHz over a 20 nm range (between 1300 nm and 1320 nm), which is a desirable feature for colorless operation of our devices.

4.2. 25 Gb/s NRZ Transmission Performance of REAM-SOA

As a preliminary test, we characterized the transmission performance of our REAM-SOA at 25 Gb/s NRZ. The eye diagrams at 1310 nm in both back-to-back (BtB) and 10 km configurations are shown in Fig. 2(b). We obtained open eye diagrams with a high dynamic extinction ratio (DER) of 10.2 dB in BtB, at –1.3 V EAM reverse bias voltage (V_B) and 2.6 V peak-to-peak voltage (V_{PP}). Similarly, the bit error rate (BER) performance of the device at 25 Gb/s NRZ is shown in Fig. 2(b), for an input wavelength of 1310 nm. Since fiber dispersion is very low in the O-band, we did not observe any transmission penalty up to 10 km. On the other hand, wavelength-dependent penalty of the REAM-SOA over a 20 nm operating range (from 1300 nm to 1320 nm) is <0.5 dB as shown in Fig. 2(c). That means, our devices can operate over a wide range of spectrum without performance degradation (colorless operation).

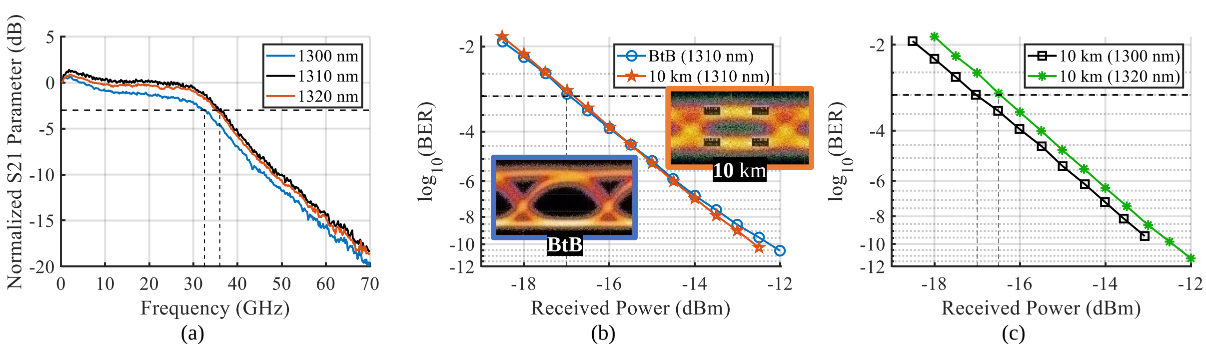


Fig. 2. (a) Small signal frequency response (S_{21} parameter) of a 100 μm EAM in REAM-SOA configuration, (b) 25 Gb/s eye diagrams, and transmission BER in BtB and 10 km configurations at 1310 nm (–1.3 V_B/2.6 V_{PP}), and (c) 25 Gb/s BER performances at 1300 nm and 1320 nm.

4.3. Eye Diagrams at 50 Gb/s NRZ and PAM-4

To generate a 50 Gb/s NRZ signal, two 25-Gb/s NRZ signals that are generated by a signal quality analyzer are combined by using a 2:1 selector module from III-V Lab [6]. The analyzer is set to generate a bit pattern of 2^{31}–1 pseudorandom binary sequence (PRBS). A delay line is connected to one arm so that the input signals are interleaved in time inside the selector resulting in a 50 Gb/s NRZ signal. The signal is then amplified to obtain a peak-to-peak voltage swing (V_{PP} = 2.4 V). Finally, the electrical driving signal is combined with an offsetting DC voltage by using a bias-T and applied to the EAM for modulation. Figure 3(a) shows the 50 Gb/s NRZ electrical signal.

Instead of the selector, a digital to analog converter (DAC) is used to generate a 25 Gbaud/s PAM-4 signal. The 50 Gb/s PAM-4 electrical signal after amplification is shown in Fig. 3(c). The peak-to-peak eye amplitude is 1.9 V, which is sufficient to operate our EAM in a region where its extinction curve is linear. Moreover, the PAM-4 electrical signal is slightly predistorted in order to compensate for the EAM's operation outside its linear region.

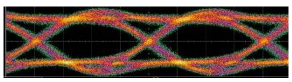
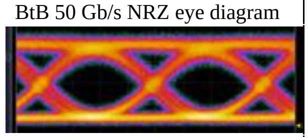
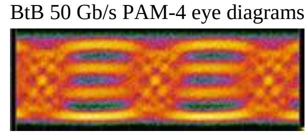
50 Gb/s NRZ electrical signal	BtB 50 Gb/s NRZ eye diagram	50 Gb/s PAM-4 electrical signal	BtB 50 Gb/s PAM-4 eye diagrams
			
	↑5 mV/div, →5 ps/div		↑5 mV/div, →10 ps/div
Peak-to-peak amplitude: 2.4 V	Eye ampl.: 15.8 mV, width: 12.8 ps, height: 9.7 mV. DER = 9 dB	Peak-to-peak amplitude: 1.9 V	V_{00} = 2.68 mV, V_{01} = 7.48 mV, V_{10} = 12.36 mV, V_{11} = 16.68 mV
(a)	(b)	(c)	(d)

Fig. 3. Dynamic performance of a 100 μm EAM in REAM-SOA configuration at 50 Gb/s: (a) NRZ electrical signal shape, (b) BtB NRZ eye diagram at −1.1 V_B/2.4 V_{PP}, (c) PAM-4 electrical signal shape, and (d) BtB PAM-4 eye diagrams at −1.1 V_B/1.9 V_{PP} (λ = 1310 nm, T = 25°C).

Figure 3 (b) shows the eye diagram of the 50 Gb/s NRZ signal from the 100 μm EAM in a BtB configuration. A symmetric eye diagram is obtained, with a DER of ~9 dB at –1.1 V_B/2.4 V_{PP} (λ = 1310 nm). Moreover, we obtained high DER in NRZ over a wide range of operating spectrum. For example, the DERs at 1300 nm and 1320 nm are ~10 dB and ~6.7 dB at 2.4 V_{PP}, respectively. Compared to the device performance at 25 Gb/s NRZ, the DER is not significantly degraded at 50 Gb/s, with only a 1.2-dB reduction at 1310 nm. As a result, we expect no transmission penalty up to 10 km, and no significant degradation of the 50 Gb/s NRZ eye diagrams. On the other hand, almost equally-spaced, open eye diagrams are obtained in BtB at 50 Gb/s PAM-4, with a bias voltage of –1.1 V_B/1.9 V_{PP} as shown in Fig.3(d). The outer extinction ratio (DER between the 0-level and the 3-level) is ~8 dB, which is slightly lower than the one obtained in NRZ because of a lower V_{PP} used in the PAM-4 case.

5. Conclusion

We presented a reflective EAM-SOA operating at 50 Gb/s NRZ and 25 Gbaud/s PAM-4 without equalization. The devices are realized with a robust and industrially compatible SI-BH technology. The 3-dB cutoff bandwidth of the EAM is 36 GHz at 1310 nm, which is comparable to state-of-the-art transmitters based on EAMLs. Moreover, our component provides a high DER of 9 dB in NRZ. We also demonstrated a colorless transmission in the O-band over a spectral range of 20 nm, with <0.5 dB wavelength-dependent penalty. The E/O bandwidth and the DER of our REAM-SOA can be further improved by using a shorter EAM, and by optimizing its vertical structure, to reach very high bit rates per-channel. Finally, our component can find several application areas in the next generation of high-speed networks such as in a 5G fronthaul, high-capacity PONs and data centers.

6. Acknowledgment

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