10.7 Gb/s reflective electroabsorption modulator monolithically integrated with semiconductor optical amplifier for colorless WDM-PON

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Abstract: We demonstrated 10.7 Gb/s reflective electroabsorption modulator monolithically integrated with semiconductor optical amplifier (REAM-SOA) using simplified fabrication process. Good performance at 10.7 Gb/s was obtained with an extinction ratio of > 10 dB and a power penalty of < 1 dB at a 10^{-9} bit error rate (BER) up to 20 km transmission. The device operated over a 50 nm spectral range within 1 dB received power variation at a 10^{-9} BER.

OCIS codes: (250.5300) Photonic integrated circuits; (060.4510) Optical communications.

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1. Introduction

The demand for high bit-rate access networks rapidly grows due to new high bandwidth services. The wavelength division multiplexed passive optical networks (WDM-PONs) is one of promising candidates for the future access networks thanks to its very large capacity, strong security, and high flexibility [1]. However, WDM can be relatively expensive to implement owing to the cost of the specified wavelength sources. In respect to cost effectiveness, the development of colorless source is a key issue in WDM-PON technologies to reduce the system cost dramatically. Various solutions have been proposed for low-speed ($\leq$2.5 Gb/s) colorless source such as spectrum-sliced light-emitting diodes (SSLEDs) [2], injection locked Fabry-Perot laser diodes (FP-LDs) [3], reflective semiconductor optical amplifiers (RSOAs) [4–6]. However, future access networks will need higher speed colorless source (10 Gb/s) as bandwidth demand grows. Recently, 10 Gb/s operation using electronic equalization techniques and forward-error correction code (FEC) has been reported in bandwidth-limited RSOAs [7,8]. And semi-insulating buried heterostructure (SI-BH) reflective electroabsorption modulator monolithically integrated with semiconductor optical amplifier (REAM-SOA) devices have been successfully achieved at 10 Gb/s [9–12]. Generally, the SI-BH type REAM-SOA is fabricated using four-step metal-organic chemical vapor deposition (MOCVD) growth [9]. In order to decrease the transmitter cost, fabrication process of device should be simplified.

In this work, we demonstrated an integration scheme of a buried ridge stripe (BRS) SOA and a deep ridge modulator using three-step MOCVD. To reduce the coupling loss caused by the lateral misalignment and mode mismatch between BRS and deep ridge waveguide, we have introduced a taper-jointed region at the interface between BRS SOA and deep ridge modulator. In fabricated device, good performance at 10.7 Gbps was obtained with an extinction ratio of > 10 dB and a power penalty of < 1 dB at a 10^{-9} bit error rate (BER) over 20 km transmission. The device operated over a 50 nm spectral range within 1 dB received power variation at a 10^{-9} BER.

2. Device fabrication

Photograph of a fabricated REAM-SOA chip is shown in Fig. 1(a). The length of the REAM is 75 μm. The 1030 μm-long SOA includes an integrated bended waveguide and spot-size converter (SSC) to minimize facet reflection and obtain efficient coupling to a lensed fiber. The SSC was evanescently coupled using double core structure [5]. The device was fabricated by three-step low-pressure metal-organic chemical vapor epitaxy (MOCVD). The REAM active layer was composed of eight tensile strained InGaAsP (λ = 1.52 μm, ε = –0.38%) wells and lattice-matched InGaAsP barriers (λ = 1.15 μm), sandwiched between 0.1 um thick InGaAsP (λ_g = 1.15 μm) separated confinement heterostructure (SCH) layers [13]. On the bottom of the lower SCH, a 0.6 μm thick n-doped InP spacer layer and 0.1 um thick InGaAsP (λ_g = 1.15 μm) spot size converter (SSC) layer were grown. The multi-quantum well (MQW) has a room temperature photoluminescence (PL) peak at 1470 nm. The butt-coupled SOA active layer consisted of a tensile-strained 0.15 μm thick InGaAsP (λ_g = 1.55 μm, ε = –0.2%) layer, sandwiched between 0.1 um thick InGaAsP (λ_g = 1.15 μm) separated confinement heterostructure (SCH) layers [14]. After a 1 μm-wide mesa of SOA region was formed by using reactive ion etching (RIE) and slightly wet etching, the wafer was buried by p-InP clad and p^+-InGaAs ohmic layer. And then, a 2 μm-wide mesa of deep ridge REAM region was formed by using RIE etching. As shown in Fig. 1(b), a 150 μm-long taper-jointed region at the interface between BRS SOA and deep ridge modulator was introduced to reduce the coupling loss caused by the lateral misalignment and mode mismatch between BRS SOA and deep ridge modulator, where the width of deep ridge waveguide was varied from 2 μm to 5 μm. A 3 μm-thick polyimide was spin-coated to minimize the capacitance of the bonding pad. The current blocking of BRS SOA and isolation between SOA and REAM were achieved by single-step O^+ ion implantation. The isolation resistance between the SOA and REAM region was measured to be 36.8 kΩ. The rear facet was coated with high reflection (HR) coating,

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whereas the residual facet reflectivity of front facet with anti-reflection (AR) coating is estimated to be ~10^{-5}. The device was sub-packaged with a 50 Ω matching circuit in a temperature controlled mode for static and dynamic properties. All static measurements were carried out at 25°C.

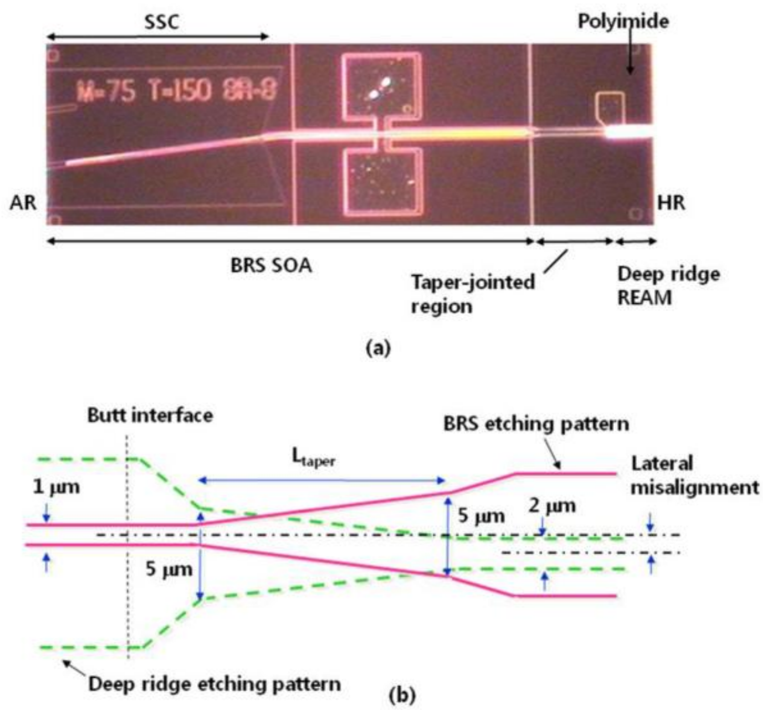

Fig. 1. Photograph of a fabricated REAM-SOA chip (a) and schematic view of taper-jointed region at the interface between BRS SOA and deep ridge modulator (b).

3. Results and discussion

The deep ridge etching step after formation of SOA waveguide leads to a lateral misalignment. In order to know the lateral misalignment tolerance of taper-jointed region, deep ridge REAM was integrated with BRS SOA without bending waveguide and SSC. An intentional misalignment between two waveguides was varied by 0.2 μm step. Output power of REAM-SOAs without bending waveguide and SSC were measured at 100 mA of SOA. Figure 2 shows calculated loss and relative output power versus intentional lateral misalignment with different lengths of taper-jointed region (L_{taper}). The calculated loss was simulated using 3-dimensional BPM (beam propagation method, supplied by RSoft Co.). As shown in Fig. 2(a), calculated lateral misalignment tolerance below 0.5 dB excess loss is about ± 1.9 μm in 100 μm-long and 150 μm-long taper-jointed region. However, calculated lateral misalignment tolerance below 0.5 dB excess loss is about ± 0.2 μm in no taper-jointed region. As shown in Fig. 2(b), in in 150 μm-long taper-jointed region, measured lateral misalignment tolerance within 0.5 dB output power variation is larger than ± 1 μm.

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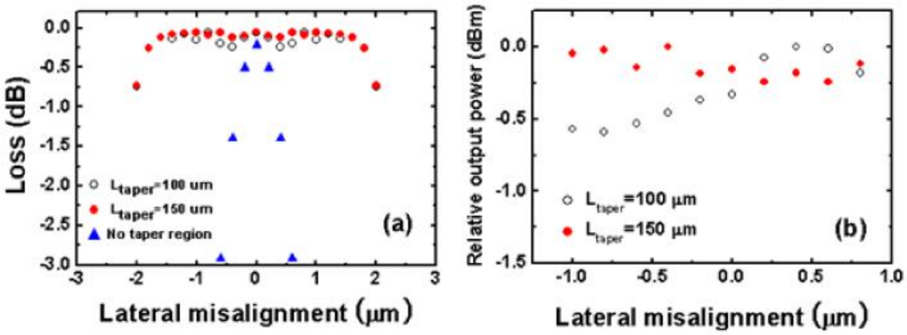

Fig. 2. Calculated loss (a) and relative output power (b) versus intentional lateral misalignment with different lengths of taper-jointed region (L_{taper}).

Figure 3 shows the amplified spontaneous emission (ASE) spectrum of SOA-REAM. The 3-dB bandwidth of ASE spectrum is ~30 nm and ripple is ~1 dB, which indicates the low reflectivity of SOA facet, butt-coupled interface and BRS-deep ridge transition region. The fiber-to-fiber gain curves of REAM-SOA are shown in Fig. 4. The wavelength of input beam was 1550 nm. The saturation input power is about −15 dBm. The fiber-to-fiber gain of REAM-SOA is ~11.7 dB at 150 mA of SOA. Compared to fiber-to-fiber gain of reflective SOA, the loss of REAM with 150 μm-long taper-jointed region is estimated to be ~7 dB. As SOA injection current increases, the polarization dependent gain (PDG) in unsaturated gain region increases from 0.4 dB to 2 dB.

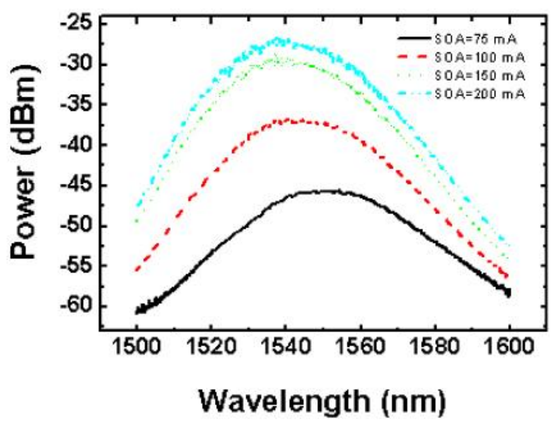

Fig. 3. Amplified spontaneous emission (ASE) spectrum of SOA-REAM as a function of SOA current. Applied voltage of REAM is 0 V.

Figure 5 shows the output power of the REAM-SOA as a function of reverse biases of REAM. The injection current of SOA was 100 mA. The wavelength and power of input beam was 1550 nm and 0 dBm, respectively. Although the operating voltage of REAM is relatively large due to large detuning (~80 nm) between SOA and modulator, a maximum (minimum) static extinction ratio (ER) is 21 dB (15 dB).

All dynamic measurements were performed as a following. The seed light of continuous beam (CW) light from tunable laser passed through REAM-SOA via variable optical attenuator (VOA), polarization controller (PC), and circulator. The modulation speed was 10.709 Gb/s with pseudorandom data of a 2^7-1 nonreturn-to-zero bit sequence. Dynamic properties of REAM-SOA was little dependent on pattern length. Modulated output beam passed through an erbium-doped fiber amplifier (EDFA) and band-pass filter before a receiver and sampling oscilloscope.

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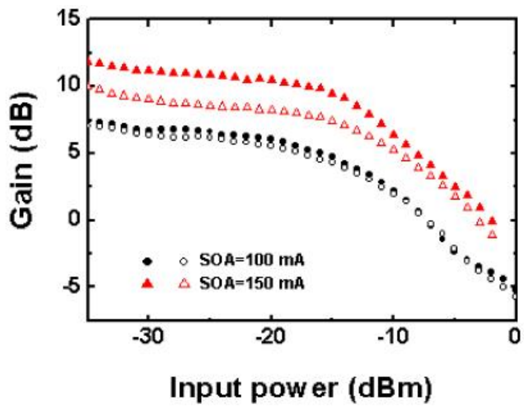

Fig. 4. Fiber-to-fiber gain curves of REAM-SOA. The solid and open symbols indicate TM and TE gain, respectively. Applied voltage of REAM is 0 V.

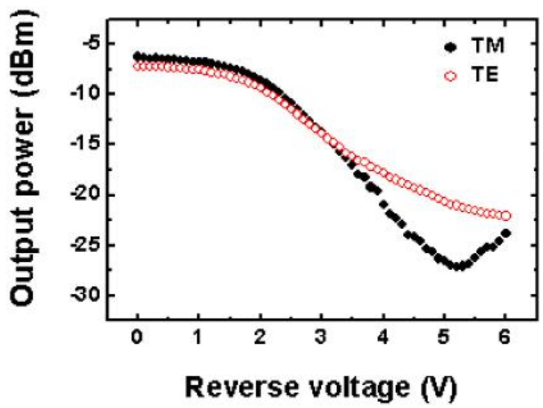

Fig. 5. Output power of the REAM-SOA as a function of reverse biases of REAM. The SOA current was 100 mA.

Figure 6 shows 10.7 Gb/s back-to-back BER curves of REAM-SOA as a function of the input power. The temperature was fixed at 25 °C. The DC bias and AC modulation amplitude of REAM was fixed at –3 V and 4.3 V_{pp}, respectively. The SOA current and input wavelength was fixed at 100 mA and 1550 nm, respectively. With input power between –10 dBm and + 7 dBm, the REAM-SOA operated below 1 dB received power variation at a 10^{-9} BER and with an extinction ratio of > 10 dB. The BER degradation at low input power is caused by a low signal-to-noise ratio (SNR) due to device ASE, whereas the BER degradation at high input power is slightly caused by patterning effects due to gain saturation. Figure 7 shows received power at 10^{-9} BER for various temperatures. The temperature was varied from 25°C to 70°C. The input power was fixed at 0 dBm. The SOA current and EAM bias voltage were adjusted in the range 85~230 mA and –2.5~-3 V, respectively. In case of 40°C, the REAM-SOA operated over a 50 nm spectral range within 1 dB received power variation. Although the working spectral range was red-shifted due to change of material gap, minimum received power was little changed up to 70°C. And it was possible to cover a common spectral range of 30 nm up to 60°C within 1 dB received power variation.

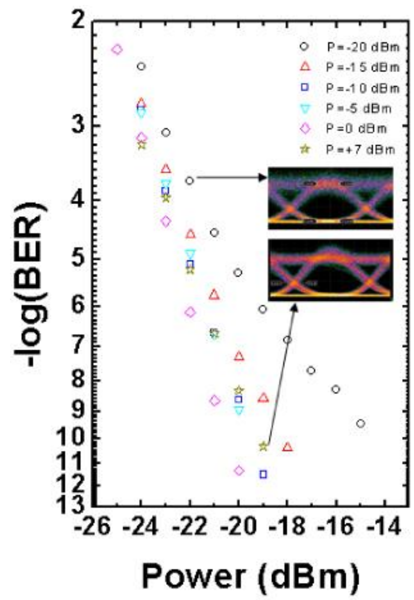

Fig. 6. 10.7 Gb/s back-to-back BER curves of REAM-SOA as a function of the input power. The inset shows eye pattern at input power of −20 dBm (upper) and + 7 dBm (lower).

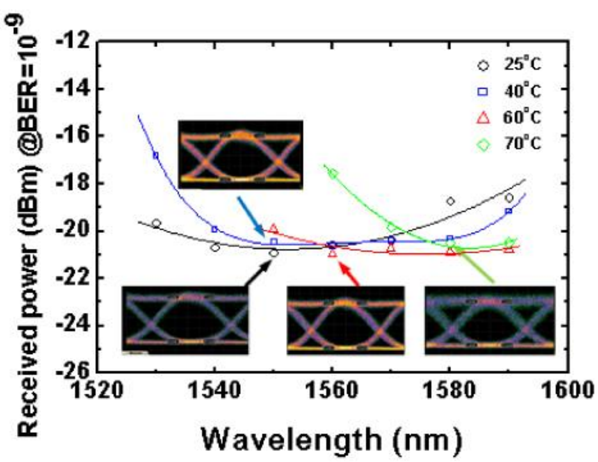

Fig. 7. Received power at 10^{-9} BER for various temperatures. Eye patterns are shown in insets.

Figure 8 shows 10.7 Gb/s BER curves of back-to-back and up to 30 km span of a standard single mode fiber. The temperature was fixed at 25 °C. The DC bias and AC modulation amplitude of REAM was fixed at −3 V and 4.3 V_{pp}, respectively. The SOA current was fixed at 100 mA. The input wavelength and power was 1550 nm and 0 dBm, respectively. The power penalty for 20 km transmission was below 1 dB at a 10^{-9} BER. But, the power penalty for 30 km transmission increased up to 3.4 dB at 10^{-9} BER. Previous papers reported that power penalty of SOA-REAM is increased due to chromatic dispersion and Rayleigh backscattering [9,10].

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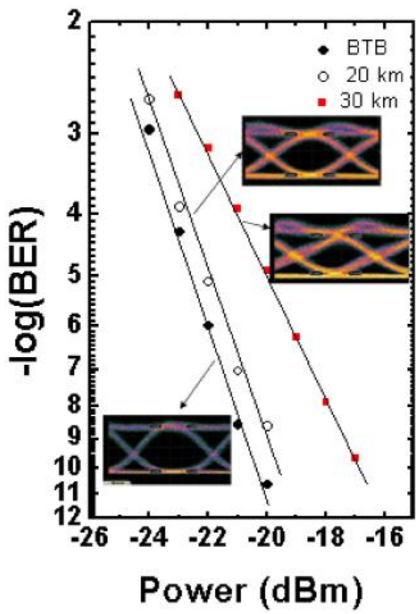

Fig. 8. 10.7 Gb/s BER curve of back-to-back (BTB) and up to 30 km transmission. The inset shows eye pattern.

4. Conclusion

We fabricated monolithic integration of deep ridge REAM and BRS SOA using three-step MOCVD growth and RIE process. In spite of nonself-aligned processing, a relatively wide tolerance for misalignment in the fabrication process was obtained by introducing a taper-jointed region, which should make the fabrication process more reproducible. The device provides the 3-dB amplified spontaneous emission bandwidth of 30 nm, and ripple of 1 dB. A maximum (minimum) static extinction ratio (ER) was 21 dB (15 dB). Good performance at 10.7 Gb/s was obtained with an extinction ratio of > 10 dB and a power penalty of < 1 dB at a 10^{-9} bit error rate (BER) up to 20 km transmission. The device operated over a 50 nm spectral range within 1 dB received power variation at 40°C. And it was possible to cover a common spectral range of 30 nm up to 60°C within 1 dB received power variation.

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