# Improvement of modulation bandwidth in multisection RSOA for colorless WDM-PON

**Hyun-Soo Kim*, Byung-Seok Choi, Ki-Soo Kim, Dong Churl Kim, O-Kyun Kwon and Dae-Kon Oh**

*Optical/RF device department, ETRI, 161 Gajeong-dong, Yuseong, Daejeon 305-700, Korea*
**kimhyunsoo@etri.re.kr*

**Abstract:** We demonstrated two-section reflective semiconductor optical amplifier (RSOA) with dramatic improvement of small-signal modulation bandwidth above 10 GHz as colorless source for wavelength division multiplexed-passive optical network (WDM-PON). The device provides the fiber-to-fiber gain of 22.8 dB, 3-dB amplified spontaneous emission (ASE) bandwidth of 30 nm, and ripple of 1.5 dB. Good performance at 2.5 Gbps was obtained with an extinction ratio of 8 dB and a power penalty of 2 dB at a $10^{-9}$ bit error rate (BER) up to 20 km transmission.



**OCIS codes:** (250.5980) Semiconductor optical amplifiers; (060.4510) Optical communications.

## References and links

1. S. Park, Y. Choi, J. Oh, S. Koo, and D. Lee, "An Evolution scenario of a broadband access network using R-SOA-based WDM-PON technologies," J. Lightwave Technol. **25**(11), 3479–3487 (2007).
2. J. S. Lee, Y. C. Chung, and D. J. DiGiovanni, "Spectrum-sliced fiber amplifier light source for multichannel WDM application," IEEE Photon. Technol. Lett. **5**(12), 1458–1461 (2006).
3. X. Cheng, Y. J. Wen, Y. Dong, Z. Xu, X. Shao, Y. Wang, and C. Lu, "Optimization of spectrum-sliced ASE source for injection-locking a Fabry-Perot laser diode," IEEE Photon. Technol. Lett. **18**(18), 1961–1963 (2006).
4. W. Lee, M. Y. Park, S. H. Cho, J. Lee, C. Kim, G. Jeong, and B. W. Kim, "Bidirectional WDM-PON based on gain-saturated reflective semiconductor optical amplifiers," IEEE Photon. Technol. Lett. **17**(11), 2460–2462 (2005).
5. S. Park, G. Kim, and T. Park, "WDM-PON system based on the laser light injected reflective semiconductor optical amplifier," Opt. Fiber Technol. **12**(2), 162–169 (2006).
6. S. C. Lin, S. L. Lee, and C. K. Liu, "Simple approach for bidirectional performance enhancement on WDM-PONs with directmodulation lasers and RSOAs," Opt. Express **16**(6), 3636–3643 (2008).
7. C. H. Yeh, C. W. Chow, C. H. Wang, F. Y. Shih, H. C. Chien, and S. Chi, "A self-protected colorless WDM-PONs with 2.5 Gb/s upstream signal based on RSOA," Opt. Express **16**(16), 12296–12301 (2008).
8. M. Omella, I. Papagiannakis, B. Schrenk, D. Klonidis, J. A. Lázaro, A. N. Birbas, J. Kikidis, J. Prat, and I. Tomkos, "10 Gb/s full-duplex bidirectional transmission with RSOA-based ONU using detuned optical filtering and decision feedback equalization," Opt. Express **17**(7), 5008–5013 (2009).
9. N. Storkfelt, B. Mikkelsen, D. S. Olesen, M. Yamaguchi, and K. E. Stubkjaer, "Measurement of carrier lifetime and linewidth enhancement factor for 1.5-μm ridge-waveguide laser amplifier," IEEE Photon. Technol. Lett. **3**(7), 632–634 (1991).
10. K. Sato, and H. Toba, "Reduction of mode partition noise by using semiconductor optical amplifiers," IEEE J. Sel. Top. Quantum Electron. **7**(2), 328–333 (2001).
11. F. Koyama, T. Yamatoya, and K. Iga, "Highly Gain-saturated GaInAsP/InP SOA modulator for incoherent spectrum-sliced light source," in *Indium Phosphide and Related Materials (IPRM)*, (2000), 439–442.
12. J. Kang, Y. Won, S. Lee, and S. Han, "Modulation characteristics of RSOA in hybrid WDM/SCM-PON optical link," in *Optical Fiber Communications Conference (OFC)*, (2006), Paper JThB6.

## 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 optical network units (ONU) source is a key issue in WDM-PON technologies to reduce the system cost dramatically. Various solutions have been proposed for

#112909 - $15.00 USD  Received 16 Jun 2009; revised 22 Aug 2009; accepted 26 Aug 2009; published 31 Aug 2009

colorless ONU source such as spectrum-sliced light-emitting diodes (SSLEDs) [2], injection locked Fabry-Perot laser diodes (FP-LDs) [3], reflective semiconductor optical amplifiers (RSOAs) [4–8]. Among various solutions, RSOAs is a good candidate due to flexibility to assign a wavelength to the upstream signal, modulation with amplification at the same time. Several groups reported 1.25 Gbps RSOA [4–6]. However, there are only a few reports of 2.5 Gbps RSOA because direct modulation bandwidth of RSOA is limited due to long carrier lifetime of a several hundred pico-second [9,10].

In this paper, we fabricated two-section RSOA (2S-RSOA) as colorless source for WDM-PON. The small-signal modulation bandwidth of 2S-RSOA is about 7.8 GHz at total injection current of 80 mA. This value is dramatic improvement compared to that of single section RSOA (1S-RSOA) with 2.3 GHz at similar injected carrier density. Good performance at 2.5 Gbps was obtained with an extinction ratio of 8 dB and a power penalty of 2 dB up to 20 km transmission.

## 2. Device fabrication

Photograph of a fabricated 2S-RSOA chip is shown in Fig. 1. The lengths of the SOA1 and SOA2 are 100 um and 500 um, respectively. The total length of device was 1.4 mm. The device was fabricated by four-step low-pressure metal-organic chemical vapor epitaxy (MOCVD). The active layer consisted of a tensile-strained (0.12%) 0.2 μm thick InGaAsP ($\lambda_g$ = 1.57 μm) layer for polarization insensitive operation, sandwiched between 0.1 um thick InGaAsP ($\lambda_g$ = 1.15 μm) separated confinement heterostructure (SCH) layers. On the bottom of the lower SCH layer, a 0.6 μm thick n-doped InP spacer layer and 0.1 um thick InGaAsP ($\lambda_g$ = 1.15 μm) spot size converter (SSC) layer were grown. After removing the active layer in a passive region, a 0.4 μm thick InGaAsP ($\lambda_g$ = 1.24 μm) layer was butt-jointed to the active layer of SOA.

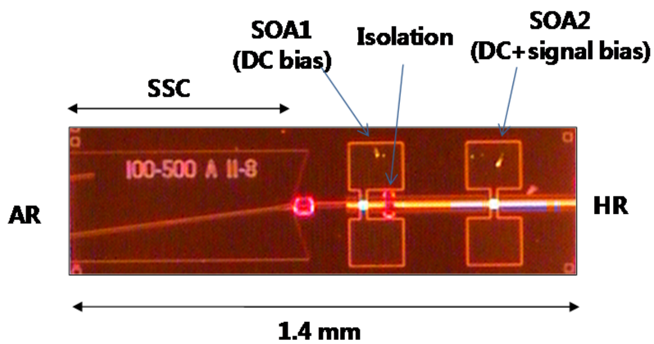


Fig. 1. Photograph of a fabricated 2S-RSOA chip.

Both the active and passive waveguide mesas of 1.0 μm width were formed by conventional photolithography and reactive ion etching (RIE). The lateral structure of SOA consisted of a p/n/p current blocking structure. For efficient coupling to a lensed fiber, the spot size converter at input port was integrated using evanescently coupled double core structure and 7°-tilted for low facet reflectivity. The trench between SOA1 and SOA2 was formed for electrical isolation using wet etching. The rear facet was coated with ~85% high reflection (HR) coating, whereas the residual facet reflectivity of front facet with anti-reflection (AR) coating is estimated to be ~$10^{-4}$. Compared to properties of single section RSOA (1S-RSOA), the 1S-RSOA and 2S-RSOA were fabricated simultaneously on same wafer. The thickness, composition, and width of active and passive waveguide in 1S-RSOA are same to those in 2S-RSOA. Also, the spot-size converter of 1S-RSOA is same structure to that of 2S-RSOA.

#112909 - $15.00 USD Received 16 Jun 2009; revised 22 Aug 2009; accepted 26 Aug 2009; published 31 Aug 2009

### 3. Results and discussion

Figure 2 shows the amplified spontaneous emission (ASE) spectrum of 2S-RSOA. The 3-dB bandwidth of ASE spectrum is ~30 nm and ripple is less than 1.5 dB at 30 mA of SOA1 and 50 mA of SOA2.

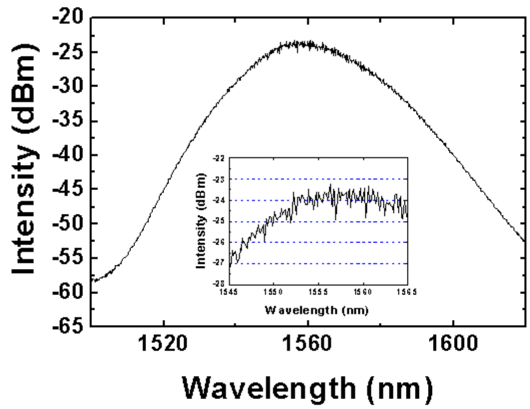


Fig. 2. Amplified spontaneous emission (ASE) spectrum of 2S-RSOA. The inset shows magnified view of ASE at central wavelength. The injection currents were applied at 30 mA of SOA1 and 50 mA of SOA2.

Figure 3 shows the far-field pattern of 2R-SOA. The FWHM (full width at half maximum) of Gaussian-shaped far-field patterns is 19° × 21° (horizontal × vertical).

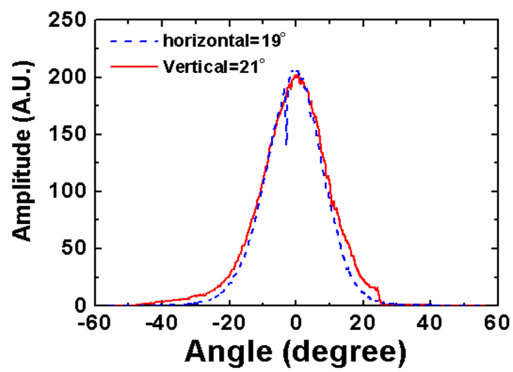


Fig. 3. Far-field pattern of two-section RSOA

The fiber-to-fiber gain curves of 2S-RSOA as a function of SOA injection current are shown in Fig. 4. The wavelength and power of input beam are 1550 nm and −20 dBm, respectively. The saturation input power is around −20 dBm at 30 mA of SOA1 and 50 mA of SOA2. The fiber-to-the fiber gain was ~22.8 dB at 30 mA of SOA1 and 50 mA of SOA2. This value is similar to fiber-to-fiber gain of 20 dB in case of 400 um long 1S-RSOA at injection current of 50 mA. The polarization dependent gain (PDG) of 2S-RSOA increases slightly from 1.5 dB to 2.5 dB as SOA1 current increases. It seems to be due to blue-shift of ASE center wavelength of SOA1. The blue-shift of ASE center wavelength is due to band-filling effect. As the injection current of SOA1 is varied from 10 mA to 30 mA (SOA2 current was fixed at 0 mA), the ASE center wavelength of SOA1 is changed from 1510 nm to 1455 nm. Since polarization insensitive operation is designed near 1.55 um, the PDG of 2S-RSOA increases due to large blue-shift of SOA1.

#112909 - $15.00 USD Received 16 Jun 2009; revised 22 Aug 2009; accepted 26 Aug 2009; published 31 Aug 2009

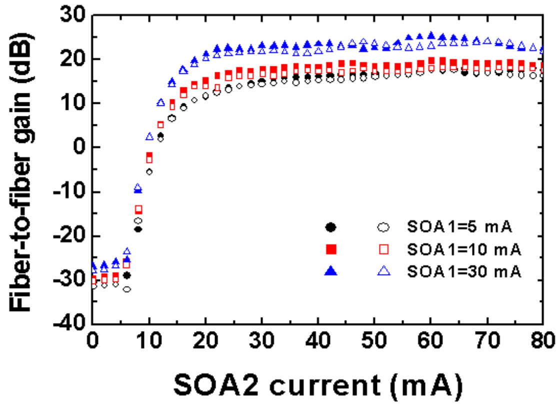


Fig. 4. Fiber-to-fiber gain curves of 2S-RSOA as a function of SOA injection current. The solid and open symbols indicate TE and TM gain, respectively. The wavelength and power of input beam were 1550 nm and −20 dBm, respectively.

Figure 5 shows the small-signal electro/optical (E/O) response of 2S-RSOA and 400 μm long 1S-RSOA. The SOA1 of 2S-RSOA was injected with only DC-bias. And the SOA2 of 2S-RSOA was injected simultaneously with DC-bias and small-signal modulation bias. The 400 μm long 1S-RSOA was injected simultaneously with a fixed current of 50 mA and small-signal modulated bias. Figure 5(a) shows the small-signal E/O response curves as a function of SOA1 current. The SOA2 of 2S-RSOA was injected with a fixed current of 50 mA and small-signal modulation bias. And the only DC-biased SOA1 current of 2S-RSOA was varied from 10 mA to 60 mA by steps of 10 mA. The input wavelength and power are 1550 nm and −10 dBm, respectively. We define that modulation bandwidth is frequency where E/O response at 40 MHz is reduced by 3 dB. The modulation bandwidth of 2S-RSOA is about 7.8 GHz at total injection current of 80 mA. The modulation bandwidth of 2S-RSOA is improved dramatically compared to that of 400 μm long 1S-RSOA with 2.3 GHz at similar injected carrier density. The 2S-RSOA exhibits the increase of E/O response with frequency up to 1.5 GHz. This is similar shape to well-known relaxation oscillation resonance found in semiconductor laser. Enhanced modulation bandwidth of 2S-RSOA can be explained as follows. Only DC-biased SOA1 acts as a high-pass filter [10–12], which is well known as the performance of noise reduction and gain squeezing of gain-saturated SOA in low frequency region [10,11]. In other words, O/O (optical/optical) frequency response of only DC-biased gain-saturated SOA is reduced at low frequency region [10–12]. And then, the E/O response of 1S-RSOA decreases with the increase of frequency as shown in Fig. 5(a).We think that resonance-like behavior of 2S-RSOA appears as a result of combination with O/O frequency response of DC-biased gain-saturated SOA and E/O frequency response of RSOA injected with small-signal modulation. Figure 5(b) shows E/O response curves as a function of SOA2 current. The only DC-biased SOA1 current of 2S-RSOA was fixed at 30 mA. The SOA2 of 2S-RSOA was injected with DC-bias and small-signal modulated bias. The DC-bias of SOA2 was varied from 15 mA to 50 mA. The input wavelength and power are 1550 nm and −20 dBm, respectively.

#112909 - $15.00 USD  Received 16 Jun 2009; revised 22 Aug 2009; accepted 26 Aug 2009; published 31 Aug 2009

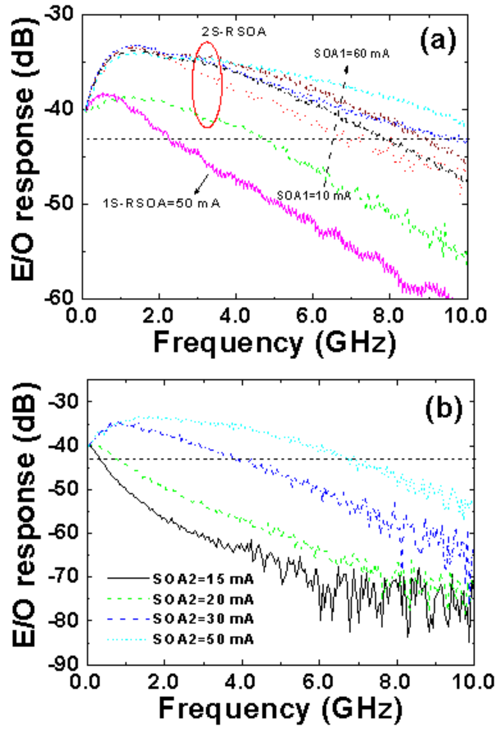


Fig. 5. Small-signal electro/optical (E/O) response of 2S-RSOA and 400 μm long 1S-RSOA. The SOA1 of 2S-RSOA was injected with only DC-bias. And the SOA2 of 2S-RSOA was injected simultaneously with DC-bias and small-signal modulation bias. The 400 μm long 1S-RSOA was injected simultaneously with a fixed current of 50 mA and small-signal modulated bias; (a) small-signal E/O response curves as a function of SOA1 current. The SOA2 was injected simultaneously with a fixed current of 50 mA and small-signal modulation. The input power was fixed at −10 dBm (b) small-signal E/O response curves as a function of SOA2. The only DC-biased SOA1 current of 2S-RSOA was fixed at 30 mA. The input power was fixed at −20 dBm.

As shown in Fig. 5(b), the E/O response of 2S-RSOA is dramatically changed by SOA2 current. As shown in Fig. 4, the fiber-to-fiber gain of 2S-RSOA is more dependent on SOA2 current than SOA1 current. It means that most of gain in 2S-RSOA is obtained by SOA2 region. In other words, gain saturation of SOA1 is very dependent on SOA2 current (gain of SOA2) because amplified input beam via SOA1 and SOA2 is reflected at rear facet and is re-propagated toward SOA1. Although injection current of SOA2 has influence on E/O response of SOA2, modulation bandwidth of single section RSOA is not improved dramatically by injection current. According to Fig. 4 and Fig. 5(b), modulation bandwidth and shape of E/O response in 2S-RSOA are changed dramatically above 20 mA of SOA2 because gain saturation of SOA1 seems to happen above 20 mA of SOA2. Previous papers reported that the reduction of O/O frequency response in gain-saturated SOA is enhanced as saturation level of SOA increases [10,11]. As shown in Fig. 5, the small-signal modulation bandwidth of 2S-RSOA can be improved by increasing injection current of SOA2 as well as only DC-biased SOA1. Figure 6 shows 2.5 Gbps bit error rate (BER) measurement setup of 2S-RSOA. The seed light of continuous beam (CW) light from DFB laser at 1550 nm passed through 2S-RSOA via variable optical attenuator (VOA), circulator and array waveguide grating (AWG). The injection power into 2S-RSOA was −5 dBm for gain-saturated operation. The modulation speed was 2.5 Gbps with pseudorandom data of a $2^7$-1 nonreturn-to-zero bit sequence. The SOA1 was only DC-biased at 5 mA. The DC bias and signal modulation amplitude of SOA2 are 71.7 mA and 102.6 mA, respectively. The APD (avalanche photo detector) was used as

#112909 - $15.00 USD  Received 16 Jun 2009; revised 22 Aug 2009; accepted 26 Aug 2009; published 31 Aug 2009

receiver. Figure 7 shows the eye pattern of back-to-back and BER curves at 2.5 Gbps up to 20 km transmission. A eye pattern with an extinction ratio (ER) of 8 dB was achieved. And the power penalty for 10 km and 20 km transmission was about 1 dB and 2 dB at a $10^{-9}$ BER, respectively. We think that one reason of 2.5Gbps transmission penalty may be pattern effect (double rise pulse front) of eye diagram. Double rise pulse front happens due to following cause. As shown in Fig. 4, gain of 2S-RSOA increases steeply up to 20 mA of SOA2 and increase gradually above 20 mA of SOA2. The ER of 2S-RSOA is quite dependent on 0 level of DC + signal bias injected to SOA2. To obtain high ER of 2S-RSOA, 0 level of DC + signal bias injected to SOA2 should be reduced near or below 20 mA. Because gain of 2S-RSOA increases little at high injection current, the ER increases little with 1 level of DC + signal bias injected to SOA2. When 0 level of DC + signal bias injected to SOA2 is reduced, it causes significant reduction of modulation bandwidth as shown in Fig. 5(b). The 0 level of DC + signal bias injected to SOA2 has relation of trade-off between extinction ratio and modulation bandwidth. Double rise pulse front of 2.5Gbps eye pattern happens due to low modulation bandwidth of 1 GHz at 0 level of DC + signal bias. That is, it causes long falling time of 2.5 Gbps eye pattern compared to rising time. When DC + signal bias is changed from "…00000" level to "1" level, optical pulse changes fast from "0" level to "1" level because modulation bandwidth increases fast with SOA2 current. When DC + signal bias is changed from "1" level to "0" level recursively, optical pulse don't fall completely from "1" level to "0" level due to low modulation bandwidth and then is changed to "1" level. In future, we should improve gain increment of SOA2 under high injection current to achieve sufficient extinction ratio of 2S-RSOA above 2.5 Gbps.

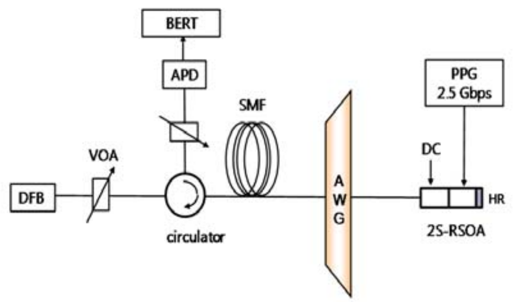


Fig. 6. 2.5 Gbps bit error rate (BER) measurement setup of 2S-RSOA.

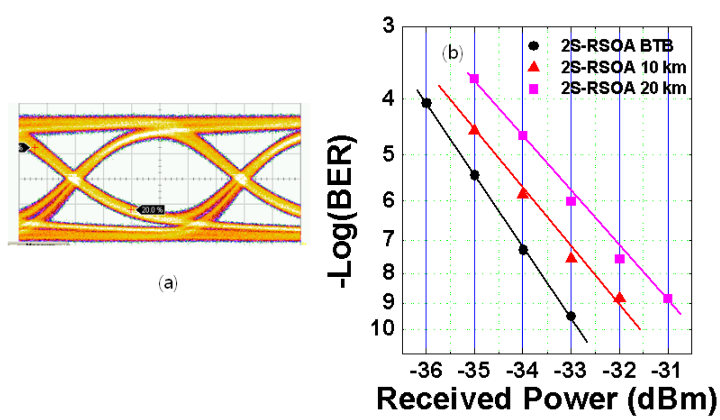


Fig. 7. Eye pattern of back-to-back (a) and BER curves at 2.5 Gbps up to 20 km transmission (b).

#112909 - $15.00 USD Received 16 Jun 2009; revised 22 Aug 2009; accepted 26 Aug 2009; published 31 Aug 2009

## 4. Conclusion

We demonstrated two-section RSOA of improved modulation bandwidth as colorless source for WDM-PON. The device provides the fiber-to-fiber gain of 22.8 dB, 3-dB amplified spontaneous emission bandwidth of 30 nm, and ripple of 1.5 dB. The small-signal modulation bandwidth of two-section RSOA is about 7.8 GHz at total injection current of 80 mA. This value is dramatic improvement compared to that of 400 μm long single section RSOA with 2.3 GHz at similar injected carrier density. We think that modulation bandwidth of 2S-RSOA can be enhanced due to combination with O/O frequency response of DC-biased SOA as high-pass filter and E/O frequency response of slightly modulated RSOA. The Good performance at 2.5 Gbps was obtained with a power penalty of 2 dB up to 20 km transmission.


## Acknowledgment

This work has been derived from a research undertaken as a part of the information technology (IT) development business by Ministry of Knowledge Economy and Institute for Information Technology Advancement, Republic of Korea (Project management No.: 2008-S-008-01, Project title: FTTH enhanced optical component technology development).


#112909 - $15.00 USD Received 16 Jun 2009; revised 22 Aug 2009; accepted 26 Aug 2009; published 31 Aug 2009