103-Gb/s Long-Reach WDM PON Implemented by Using Directly Modulated RSOAs

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***Abstract*— We propose and demonstrate a long-reach wavelength-division-multiplexed passive optical network (WDM PON) capable of providing 100-Gb/s service to each subscriber, for the first time to the best of our knowledge. For cost-effectiveness, this network is implemented in loopback configuration by using directly modulated reflective semiconductor optical amplifiers (RSOAs) at 25.78 Gb/s. For the modulation of the RSOA at such a high-speed, we have to minimize the electrical parasitics by using the butterfly package. Also, to overcome the limited bandwidth of the RSOA, we utilize the electronic equalization technique at the receiver. We use four RSOAs at each optical network unit for the 103-Gb/s upstream transmission. The operating wavelengths of these RSOAs are separated by the free-spectral range of the cyclic arrayed waveguide gratings used at the central office and remote node (RN) for (de)multiplexing the WDM channels. We extend the maximum reach of this WDM PON to be >120 km by using Erbium-doped fiber amplifiers at the RN. The results show that the error-free transmission can be achieved for all WDM channels in the wavelength range of >35 nm with sufficient power margins.**

***Index Terms*— Passive optical network, semiconductor optical amplifiers, wavelength division multiplexing.**

I. Introduction

DUE TO the recent standardization activities of 100 Gigabit Ethernet (100 GbE), there have been growing interests in the 100-Gb/s passive optical network (PON) [1]. For example, it has been already demonstrated that 100-Gb/s PON can be realized by using the optical orthogonal-frequency-division- multiple access (OFDMA) technique [2]–[4]. However, it should be noted that these 100-Gb/s OFDMA PONs are not intended to deliver 100-Gb/s service to each subscriber. In other words, the term "100 Gb/s" in these reports merely indicates the maximum per-wavelength transmission speed. Thus, if we assume that this network is consisted of 10 optical network units (ONUs), it can provide only 10-Gb/s service to each subscriber on average.

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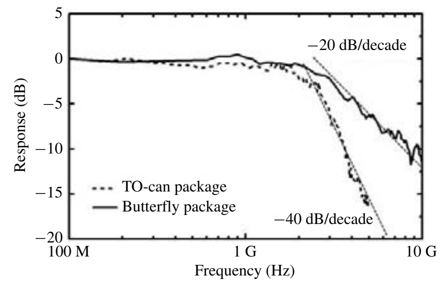

Fig. 1. Measured frequency responses of the TO-can packaged (dotted line) and butterfly-packaged (solid line) RSOAs.

In this letter, we propose and demonstrate a long-reach wavelength-division-multiplexed (WDM) PON capable of providing 100-Gb/s service to each subscriber. For the cost-effectiveness (as well as the colorless operation of ONUs), we implement this network in loopback configuration by using directly modulated reflective semiconductor optical amplifiers (RSOAs) operating at 25 Gb/s. Thus, the 100-Gb/s upstream signal is obtained by combining the outputs of four RSOAs at each ONU using the coarse WDM (CWDM) technique, as in the 100GBASE-LR4 specifications [5]. To operate the RSOA at 25 Gb/s, we mount it in a butterfly package (to minimize the electrical parasitics) and utilize the electronic equalization technique at the receiver [6]. The long-reach operation over >120-km long single-mode fiber (SMF) link is accomplished by using Erbium-doped fiber amplifiers (EDFAs) at the remote node (RN). The results show that we can achieve the error-free transmission of the 100-Gb/s signals (obtained by combining four 25-Gb/s CWDM channels) in the wavelength range of >35 nm with sufficient power margins. To the best of our knowledge, this result represents the first demonstration of the WDM PON capable of providing 100-Gb/s service to each subscriber.

II. Proposed Architecture of 100-Gb/s Long-Reach WDM PON Using Directly Modulated RSOAs at 25 Gb/s

Fig. 1 shows the measured frequency response of the RSOA used in this work. When we mounted this RSOA in a TO-can package, its modulation bandwidth was measured to be only ~2.2 GHz [7]. However, when we utilized a butterfly package to minimize the electrical parasitics, the modulation bandwidth

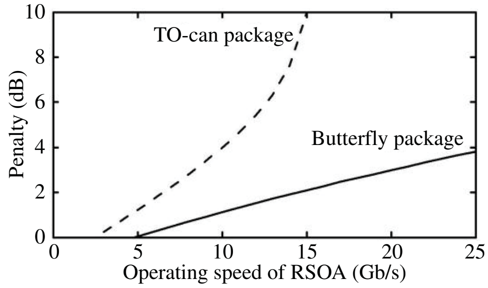

Fig. 2. Power penalties induced by the ideal decision-feedback equalizer of the TO-can packaged (dotted line) and butterfly-packaged (solid line) RSOAs as a function of operating speed.

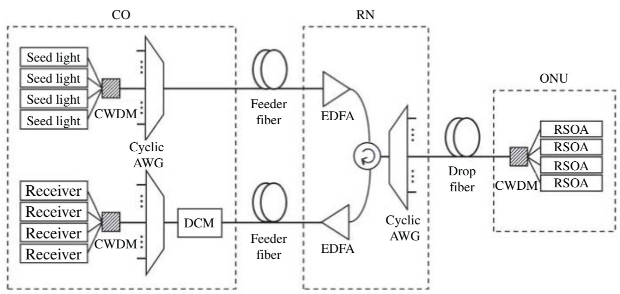

Fig. 3. Upstream link of the proposed long-reach WDM PON capable of providing 100-Gb/s service to each subscriber.

was increased to ~3.2 GHz, which was still not sufficient for the operation at the speed of >10 Gb/s. However, the reduced roll- off characteristics achieved by using the butterfly package (i.e., from −40 dB/decade to −20 dB/decade) could play an important role if we attempt to overcome this limited bandwidth of RSOA by using the electronic equalization technique. For example, Fig. 2 shows the power penalties caused by operating the RSOA at the speed faster than its modulation bandwidth. In this calculation, we assumed that an ideal decision-feedback equalizer with an infinite number of taps was utilized [8]. The result shows that, when we used the TO-can packaged RSOA, the power penalty increased rapidly as the operating speed was increased. As a result, it was practically impossible to operate this RSOA at the speed of >15 Gb/s. However, when we used the butterfly-packaged RSOA, this penalty was estimated to be <4 dB even at 25 Gb/s. We have experimentally confirmed that it is indeed possible to operate the butterfly-packaged RSOA at >25 Gb/s [6]. Thus, for the realization of the cost-effective WDM PON capable of providing 100-Gb/s service to each subscriber, we propose to use the butterfly-packaged RSOAs operating at 25 Gb/s together with the CWDM technique as in the IEEE 100GBASE-LR4 specifications [5]. Fig. 3 shows the upstream link of the proposed 100-Gb/s long-reach WDM PON. (Here, we only show the upstream link since the downstream link is relatively simple. We assume that 100-Gb/s downstream links are realized simply by using integrated electro-absorption modulator lasers [9]). The proposed network is implemented in loopback configuration. To generate the 100-Gb/s upstream signal, we use four butterfly-packaged RSOAs operating at 25 Gb/s at the ONU. Thus, we need to send a set of four seed light to each ONU from the central office (CO). For this purpose, we assume to use cyclic arrayed waveguide gratings (AWGs) at the CO and RN, and the operating wavelengths of the seed light are separated by the free-spectral range (FSR) of the cyclic AWGs. Thus, a set of four seed light can be sent to each ONU through a single drop fiber. At the ONU, this set of four seed light is then separated by using a CWDM filter and directed to each RSOA (which is modulated at 25 Gb/s using the upstream signal). The modulated outputs of these RSOAs are combined again by the same CWDM filter, and sent back to the CO. However, we assume to use a pair of feeder fibers between the CO and RN to avoid the effects of Rayleigh backscattering [10]. To secure the sufficient power budget needed for the long-reach application, we use EDFAs at the RN. The effect of chromatic dispersion (CD) is suppressed by designing the transmission link to have a slightly negative dispersion value by placing a dispersion-compensation module (DCM) in front of the demultiplexing AWG at the CO [6].

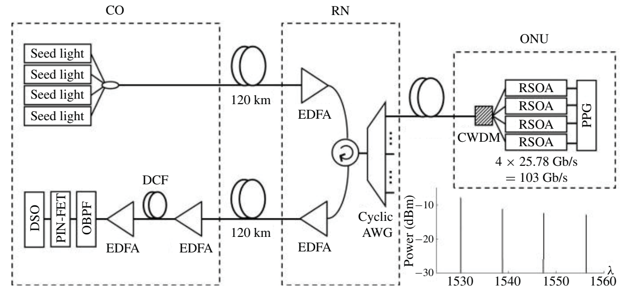

Fig. 4. Experimental setup used to demonstrate the 103-Gb/s 123.67-km reach WDM PON implemented by using directly modulated RSOAs. The inset shows the optical spectrum of the seed light measured in front of the ONU.

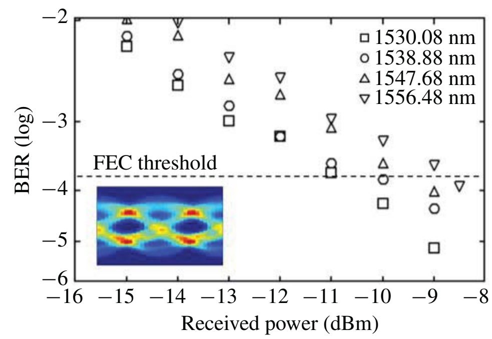

Fig. 5. Measured BER curves of four upstream CWDM channels after the transmission over 123.67-km-long SMF. The inset shows the eye diagram of the 25.78-Gb/s signal operating at 1530.08 nm.

III. Demonstration of 103-Gb/s 120-km Reach WDM PON Using Directly Modulated RSOA

Fig. 4 shows the experimental setup used to demonstrate the 103-Gb/s, long-reach WDM PON by using directly modulated RSOAs. The lengths of the feeder and drop fibers of this WDM PON were 120 km and 3.67 km, respectively. At the CO, we combined a set of four seed light (operating at 1530.08, 1538.88, 1547.68, and 1556.48 nm) and sent them to an ONU. These seed light were amplified by the remote EDFA at the RN. The cyclic AWG (channel spacing: 100 GHz) had

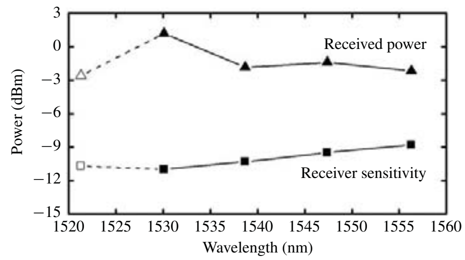

Fig. 6. Receiver sensitivities measured at the FEC threshold of the RS(255, 239) code (BER $= 1.8 \times 10^{-4}$) and the optical power incident on the receiver in the setup shown in Fig. 4.

a FSR of ~8.8 nm. Thus, since the operating wavelengths of the seed light were separated by the FSR of the AWG, all of them were directed to the same ONU through the same drop fiber, as shown in the inset of Fig. 4. At the ONU, we separated these seed light by using a 1×4 CWDM filter and sent to four butterfly-packaged RSOAs. For the upstream transmission, each of these RSOAs was directly modulated at 25.78 Gb/s. We combined these four 25.78-Gb/s channels by using the same CWDM filter, and sent back to the CO via the feeder and drop fibers. The effect of Rayleigh backscattering could be neglected in this experiment as we utilized a pair of feeder fibers and a short drop fiber. The CD accumulated in these fibers was compensated at the CO by using a dispersion-compensating fiber (DCF) module (dispersion: −2050 ps/nm at 1550 nm). The insertion loss of this DCF module was compensated by using additional EDFAs at the CO. However, it could be possible to avoid the use of these extra EDFAs by using a long-period fiber grating instead of the DCF for the dispersion compensation due to its small insertion loss [11]. We demultiplexed the upstream signals by using an optical bandpass filter (OBPF). The demultiplexed signal was first sent to a PIN-FET receiver, and then sampled by using a digital sampling oscilloscope (DSO) at 50 GS/s. The receiver's bandwidth was limited to be 18 GHz by the DSO. The sampled data was processed offline for the bit-error rate (BER) estimation. The electronic equalization was achieved by using 17-tap half-symbol-spaced feed-forward equalizer and 3-tap decision-feedback equalizer. The tap coefficients of these equalizers were determined according to the mean-square-error criterion [8]. After this equalization, we estimated the BER from the recovered data. Fig. 5 shows the results. The power penalties were larger for the channels operating at longer wavelengths due to the increased chirp of the RSOA. Nevertheless, these penalties were measured to be <2 dB for all the channels. Also, the BER performances of these 4 CWDM channels were better than the forward-error-correction (FEC) threshold of the RS(255, 239) code (i.e., BER $= 1.8 \times 10^{-4}$). Fig. 6 shows the receiver sensitivities measured at this FEC threshold for the 4 CWDM channels together with their received powers (closed symbols). The received power was slightly different from channel to channel due to the wavelength dependence of the EDFA's gain, RSOA's gain, and loss of the CWDM filter. However, the power margins were >6 dB for all 4 CWDM channels. The operable wavelength range of the proposed WDM PON is determined mostly by the gain bandwidth of the RSOAs and EDFAs. To estimate this range, we also measured the receiver sensitivity and received power at the wavelength of 1521.28 nm, as shown by the open symbols in Fig. 6. Using this result, we estimate that this network can support at least ten 103-Gb/s WDM channels (if the channel spacing of the cyclic AWG is 100 GHz).

IV. Conclusion

We have experimentally demonstrated the upstream link of 103-Gb/s, 123.67-km reach WDM PON implemented by using directly modulated RSOAs. For this experiment, we mounted the RSOA in a butterfly package to minimize the electrical parasitics. As a result, the modulation bandwidth of this RSOA was improved to 3.2 GHz and its frequency response was rolled off at a rate of −20 dB/decade. We directly modulated these RSOAs at 25.78 Gb/s with the help of electronic equalization technique. For the 103-Gb/s upstream transmission per ONU, we combined the outputs of 4 RSOAs operating at 25.78 Gb/s by using a CWDM filter at the ONU. The output wavelengths of these RSOAs (determined by the wavelengths of the seed light sent from the CO) were separated by the FSR of the cyclic AWG used at the RN. Thus, we could still ensure the colorless operation of the ONU. The 123.67-km reach was achieved by using EDFAs at the RN and the DCF module at the CO. The results show that the error-free transmission could be achieved for all four 25.78-Gb/s channels. To the best of our knowledge, this result represent the first demonstration of WDM PON capable of providing >100-Gb/s service to each subscriber.

References

[1] H. Kimura, N. Iiyama, Y. Sakai, and K. Kumozaki, "A WDM-based future optical access network and support technologies for adapting the user demands' diversity," *IEICE Trans. Commun.*, vol. E93-B, no. 2, pp. 246–254, Feb. 2010.

[2] D. Qian, N. Cvijetic, J. Hu, and T. Wang, "108 Gb/s OFDMA-PON with polarization multiplexing and direct-detection," in *Proc. Tech. Dig. OFC 2009*, San Diego, CA, Mar. 2009, pp. 1–3, paper PDPD5.

[3] D. Qian, N. Cvijetic, Y.-K. Huang, J. Hu, and T. Wang, "Single-wavelength 108 Gb/s upstream OFDMA-PON transmission," in *Proc. ECOC 2009*, Vienna, Austria, Sep. 2009, pp. 1–2, paper PD3.3.

[4] N. Cvijetic, D. Qian, and J. Hu, "100 Gb/s optical access based on optical orthogonal frequency-division multiplexing," *IEEE Commun. Mag.*, vol. 48, no. 7, pp. 70–77, Jul. 2010.

[5] O. Ishida, "40/100 GbE technologies and related activities of IEEE standardization," in *Proc. Tech. Dig. OFC 2009*, San Diego, CA, Mar. 2009, pp. 1–29, paper OWR5.

[6] K. Y. Cho, B. S. Choi, Y. Takushima, and Y. C. Chung, "25.78-Gb/s operation of RSOA for next-generation optical access networks," *IEEE Photon. Technol. Lett.*, vol. 23, no. 8, pp. 495–497, Apr. 15, 2011.

[7] K. Y. Cho, Y. Takushima, and Y. C. Chung, "10-Gb/s operation of RSOA for WDM PON," *IEEE Photon. Technol. Lett.*, vol. 20, no. 18, pp. 1533–1535, Sep. 15, 2008.

[8] J. G. Proakis, *Digital Communications*, 4th ed. New York: McGraw Hill, 2001.

[9] T. Sugawara, *et al.*, "High-speed optical/electrical devices and their integration for highly-efficient l00 GbE," in *Proc. Tech. Dig. OFC 2010*, San Diego, CA, Mar. 2010, pp. 1–3, paper OThS4.

[10] P. Ossieur, *et al.*, "A 135-km 8192-split carrier distributed DWDM-TDMA PON with $2 \times 32 \times 10$ Gb/s capacity," *J. Lightw. Technol.*, vol. 29, no. 4, pp. 463–474, Feb. 15, 2011.

[11] S. Ramachandran, *et al.*, "All-fiber grating-based higher order mode dispersion compensator for broad-band compensation and 1000-km transmission at 40 Gb/s," *IEEE Photon. Technol. Lett.*, vol. 13, no. 6, pp. 632–634, Mar. 2001.