

Long-reach 10-Gb/s RSOA-based WDM PON employing QPSK signal and coherent receiver

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Abstract: We demonstrate a long-reach wavelength-division-multiplexed passive optical network (WDM PON) operating at the symmetric rate of 10.3 Gb/s. For the cost-effectiveness, we realize the upstream transmission by utilizing directly-modulated TO-can packaged reflective semiconductor optical amplifiers (RSOAs) and digital coherent receivers. In addition, to overcome the limited modulation bandwidth of this TO-can packaged RSOA (~2.2 GHz) and operate it at 10.3 Gb/s, we utilize the quadrature phase shift keying (QPSK) format and the electronic phase equalization technique. The result shows that we can extend the maximum reach of the 10.3-Gb/s RSOA-based WDM PON to ~80 km without using any remote amplifiers.

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1. Introduction

To further enhance the competitiveness of the wavelength-division-multiplexed passive optical network (WDM PON), we should be able to increase its operating speed and maximum reach cost-effectively [1]. Thus, it would be desirable to utilize the colorless light source at the optical network unit (ONU), while avoiding the use of the expensive external modulators and the remote optical amplifiers. One possible solution to satisfy these requirements is the WDM PON based on the directly-modulated reflective semiconductor optical amplifier (RSOA). However, its operating speed has been limited to ~2.5 Gb/s due to the inherently narrow bandwidth of the RSOA [2-3]. To overcome this limitation and operate the RSOA at >10 Gb/s, it has been proposed to utilize the multi-level modulation formats such as the 4-ary pulse amplitude modulation (PAM) and/or the electronic equalization technique [3-4]. On the other hand, the maximum reach of the RSOA-based WDM PON is typically limited by the power budget of the upstream signal due to its loopback configuration [5]. There have been many attempts to overcome this problem by using a remote Erbium-doped fiber amplifier (EDFA) [6-7]. However, the use of this amplifier tends to make the network highly vulnerable to the Rayleigh backscattering noises [8]. As a result, it becomes inevitable to utilize separate fibers for the upstream and downstream signals [7]. To solve this problem and extend the coverage of the central office (CO), we have recently developed a cost-effective coherent detection technique applicable to the access network [9]. In fact, by using this technique, we could demonstrate the RSOA-based WDM PON operating at the speed of 2.5 Gb/s with the maximum reach of >100 km without using any remote EDFA [5].

In this paper, our objective is to demonstrate the possibility of implementing a long-reach RSOA-based WDM PON operating at the per-wavelength speed of >10 Gb/s cost-effectively. We note that the maximum reach of this network will most likely be limited by the upstream signal due to its loopback configuration. Thus, we focus our efforts for the cost-effective implementation of the upstream transmission by using the directly-modulated TO-can packaged RSOAs and the digital coherent receivers recently developed for the use in the access network [9]. For the high-speed operation of this TO-can packaged RSOA at >10 Gb/s, we use the quadrature phase shift keying (QPSK) format together with the electronic phase equalization technique [10]. The results show that, due to the excellent sensitivity of the digital coherent receiver, the maximum reach of this network can be increased to ~80 km without using any remote EDFA.

2. Experiment and results

Figure 1 shows the experimental setup used to evaluate the performance of the proposed long-reach RSOA-based WDM PON operating at the simultaneous rate of 10.3 Gb/s. In this network, we assumed that the downstream transmission could be achieved by using an electro-absorption modulated laser (EML) array at the CO. However, due to the limited resources in our laboratory, we demonstrated the transmission of the 10.3-Gb/s downstream signal in non-return-to-zero (NRZ) format by using an externally modulated distributed feedback (DFB) laser and an avalanche photodiode (APD). On the other hand, for the upstream transmission, we utilized an RSOA at the ONU and a digital coherent receiver at the CO. A tunable laser operating at 1527.1 nm (linewidth: 170 kHz) was used for the seed light and local oscillator (LO). The optical power of the seed light was set to be + 1.6 dBm at the input of the feeder fiber. The optical power of the LO incident on the 3 × 3 coupler was set to

be + 3 dBm. The upstream and downstream signals were combined and separated by using the WDM filters placed at the CO and ONU, respectively. In addition, the cyclic arrayed waveguide gratings (AWGs), having a free-spectral range (FSR) of 23 nm, were placed at the CO and the remote node (RN). The insertion losses of these AWGs were ~ 4.2 dB. The optical power of the downstream signal was measured to be 0 dBm at the input of the feeder fiber. Figure 2 shows the bit-error rate (BER) curves of the downstream signal measured in the back-to-back condition and after the transmission over 80-km long single-mode fiber (SMF) link. The dispersion-induced power penalty was measured to be only 0.5 dB. Thus, there was no need to utilize any dispersion compensation techniques. Since the received optical power of the downstream signal at the ONU was -19.6 dBm, the power margin was ~ 4 dB.

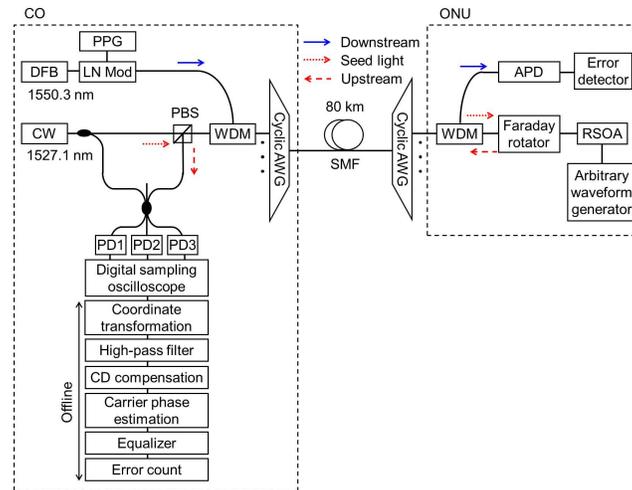


Fig. 1. Experimental setup to evaluate the performance of the proposed long-reach 10.3-Gb/s WDM PON implemented by using directly-modulated RSOAs and self-homodyne receivers.

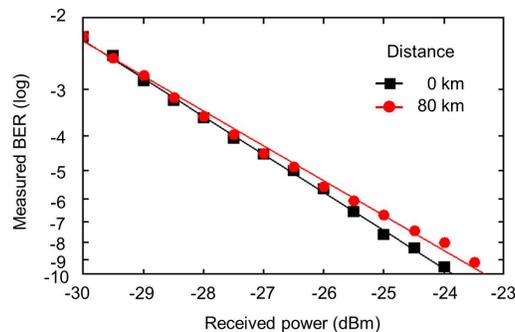


Fig. 2. Measured BER curve of 10.3-Gb/s downstream signal.

For the cost-effective implementation of ONU, we used a TO-can packaged RSOA as a colorless light source. However, the 3-dB modulation bandwidth of this RSOA was measured to be 2.2 GHz (roll-off slope: -40 dB/decade [3]), which was not sufficient to operate it at >10 Gb/s in NRZ format. We attempted to overcome this limitation by utilizing a multi-level modulation format. When we directly modulated the injection current of the RSOA, not only the amplitude but also the phase of its output signal was modulated (since both the gain and refractive index of an RSOA were dependent on the carrier density) [11]. In fact, as shown in Fig. 3, we observed that both the amplitude modulation (AM) and phase modulation (PM) indices were increased linearly as we increased the amplitude of the modulation current. Thus, we could obtain either the multi-level phase-modulated signal (such as QPSK) or intensity-

modulated signal (such as 4-ary PAM) from the directly-modulated RSOA. However, we decided to use the QPSK format since its sensitivity was superior to the 4-ary PAM format by 6.6 dB [12]. For this purpose, we directly modulated this RSOA with 4-level electrical signal to generate 10.3-Gb/s QPSK signal. The optical power of the seed light incident on the RSOA was -20 dBm. The bias and modulation currents of this RSOA were set to be 80 mA and 44 mA_{p-p}, respectively. Under these conditions, the gain of the RSOA was measured to be 18 dB. Figure 4 shows the resulting phasor diagram of the RSOA's output signal. As expected, due to the RSOA's chirp, the phasor was rotated as we modulated its injection current. However, unlike in the case of using the pure phase modulator (such as the LiNbO₃ phase modulator), the unwanted AM component caused by the modulation current changed the magnitude of the phasor and made its trajectory to have a spiral shape. As a result, the constellation of the QPSK signal became asymmetric, which, in turn, degraded the receiver sensitivity. The power penalty caused by this non-ideal QPSK signal was estimated to be ~ 1 dB regardless of the bit rates [12].

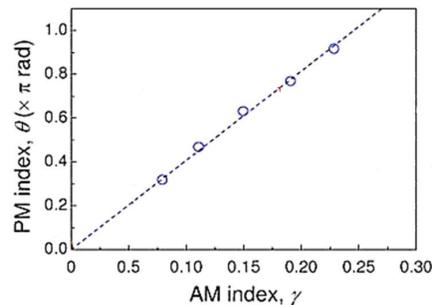


Fig. 3. Relationship between PM index and the AM index of the optical signal generated by directly-modulated RSOA.

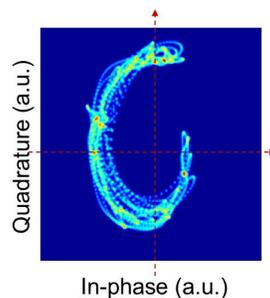


Fig. 4. Measured phasor diagram of the 10.3-Gb/s QPSK signal generated by using a directly-modulated RSOA.

The upstream signal was detected by using the self-homodyne coherent receiver placed at the CO. This coherent receiver was implemented by using a 3x3 coupler as a 120-degree optical hybrid. There was no need to utilize the expensive polarization-diversity receiver since we stabilized the state-of-polarization (SOP) of the upstream signal by placing a Faraday rotator in front of the RSOA at the ONU [5]. There was no problem in utilizing this technique in the proposed long-reach WDM PON since the roundtrip time over the 80-km long fiber link (~ 0.8 ms) was much shorter than the fastest polarization fluctuation time occurred in this link (> 20 ms) [5, 13]. The output signals of the 3×3 coupler were detected by using three PIN photodiodes. The detected upstream signal was sampled at 40 GS/s by using a digital sampling oscilloscope. We obtained the I- and Q-components by using the coordinate transformation [9]. For the BER estimation, 2.6×10^5 symbols were used. We filtered out the low-frequency components resulting from the Rayleigh backscattering by using a high-pass filter (HPF) having a cutoff frequency of 20 MHz [9]. However, this HPF could also cut off

the low-frequency components of the upstream signal itself and degrade its performance. To solve this problem, we encoded the upstream signal using 64B/66B code (pattern length: 8382 bits). We then applied Fourier transform of the inverse fiber dispersion function to the received signal for the chromatic dispersion (CD) compensation [14]. The carrier phase of the QPSK signal was estimated by using the M-th power algorithm [15]. We then utilized the electronic equalization technique to compensate for the limited modulation bandwidth of the RSOA. The electric field of the QPSK signal, detected by the coherent receiver, could be expressed as $e^{ig\{d(t)\}}$, where d and g were the transmitted symbol and the function representing the bandwidth-limited electrical-to-optical response of the RSOA, respectively. Thus, if an ideal electronic equalizer having an inverse function of g (i.e., g^{-1}) were used to compensate for the limited modulation bandwidth of the RSOA, the equalized signal could be different from the original signal since

$$g^{-1}[e^{ig\{d(t)\}}] \neq e^{id(t)}. \quad (1)$$

To solve this problem, we applied the electronic equalizer only to the phase portion of the signal after its detection in the coherent receiver. When we utilized the RSOA as a phase modulator (to generate the QPSK signal), the phase variation of the RSOA's output signal was proportional to its intensity variation. Thus, by using the phase portion of the signal, we could achieve the electronic equalization in the digital coherent receiver since the equalized signal could be expressed as

$$g^{-1}[g\{d(t)\}] = d(t). \quad (2)$$

However, since the absolute value of the phase of the QPSK signal should be in the range of $0 \sim 2\pi$, a sudden jump could occur (due to the noise) in the phases at the boundary between the lowest and highest levels. For example, Fig. 5 shows the phase changes of the transmitted and received QPSK signal. As shown in the middle of Fig. 5, abrupt changes were observed in the measured phases by using a digital coherent receiver. Since these abrupt phase changes could disrupt the discrimination between the lowest and highest levels of the QPSK signal, we treated the phase similar to the intensity (i.e., neglected the boundary of $0 \sim 2\pi$) and applied the electronic equalizer only to the phase portion of the modulated signal. For this purpose, we added or subtracted 2π to the measured data whenever we observed an abrupt change by assuming the slowly-varying phase from the oversampled data. The triangles in Fig. 5 show the resulting converted intensity. This converted intensity was then directed to the electronic equalizer consisted of a half-symbol-spaced 16-tap feed-forward equalizer and a 10-tap decision-feedback equalizer.

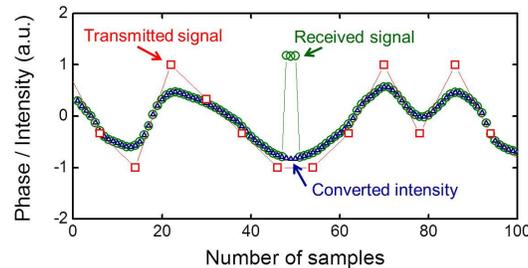


Fig. 5. The phases of the transmitted (\square) and received signals (\circ), and the converted intensities (\triangle) by assuming the slowly-varying phase.

Figure 6 shows the measured BER curve in back-to-back condition. The result showed that, by using the proposed electronic phase equalizer, we could overcome the limited modulation bandwidth of the RSOA and achieved the BER of $<10^{-4}$. We then measured the constellation diagrams of the upstream signal after the transmission over 80-km long SMF link. Figure 7(a) and 7(b) show the results obtained after the carrier phase estimation (CPE)

and electronic phase equalization, respectively. The optical power of the upstream signal incident on the 3×3 coupler of the self-homodyne receiver was measured to be -34.5 dBm. The BER of the upstream signal estimated after the CPE and electronic phase equalizer were 2.8×10^{-2} and 1.1×10^{-3} , respectively. Thus, we should be able to achieve the error-free transmission (i.e., $\text{BER} < 10^{-12}$) by using the Reed-Solomon (255,223) code without increasing the line rate, as in the 10-Gb/s Ethernet PON (10G-EPON) standards [16]. Although there was no system margin in this result, it could be improved easily by using the high-power seed light, optical pre-amplifier, and enhanced forward-error correction (FEC) code, etc.

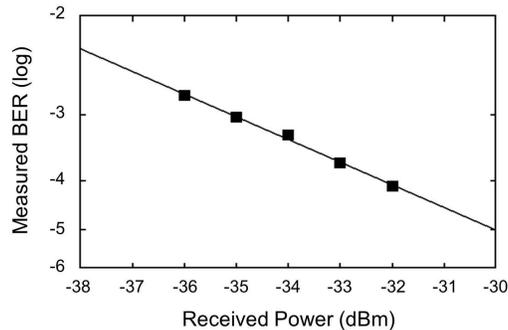


Fig. 6. Measured BER curve of 10.3-Gb/s QPSK signal in the back-to-back condition.

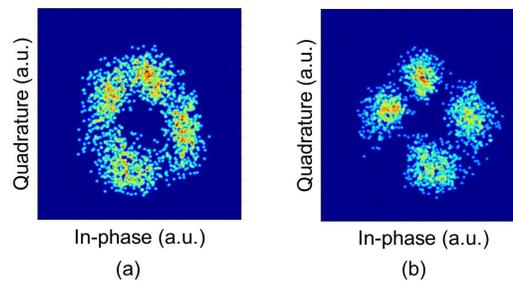


Fig. 7. Constellation diagrams of the 10.3-Gb/s QPSK signal measured (a) before and (b) after the electronic phase equalizer.

3. Summary

We have demonstrated the 10.3-Gb/s, 80-km-reach RSOA-based WDM PON without using any remote optical amplifiers. The downstream transmission was realized simply by using an externally modulated DFB laser and an APD receiver. For the upstream transmission, we generated the 10.3-Gb/s QPSK signal by directly modulating a TO-can packaged RSOA at the ONU and detected it by using a cost-effective self-homodyne receiver at the CO. In addition, we utilized the electronic phase equalizer to compensate for the limited modulation bandwidth of the TO-can packaged RSOA (~ 2.2 GHz). The results showed that we could implement a long-reach WDM PON operating at the per-wavelength speed of 10.3 Gb/s cost-effectively by using the QPSK signals (obtained by directly modulating TO-can packaged RSOAs), self-homodyne receivers, and digital signal processing techniques.

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