Transmission of 1.25-Gb/s PSK signal generated by using RSOA in 110-km coherent WDM PON

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Abstract: We generate the phase-modulated signal by utilizing the chirp characteristics of the directly-modulated reflective semiconductor optical amplifier (RSOA) for the cost-effective realization of a long-reach wavelength-division-multiplexed passive optical network (WDM PON). We first investigate the relation between the amplitude and phase modulation indices in a directly-modulated RSOA and optimize these modulation indices to maximize the symbol distance on the constellation diagram. The results show that, by operating the RSOA under this optimum condition, we can achieve the excellent receiver sensitivity of −49.8 dBm at 1.25 Gb/s. We implement a long-reach WDM PON by using the phase-modulated RSOAs and self-homodyne receivers, and demonstrate the error-free transmission of 1.25-Gb/s signal over a 110-km long link without using any optical amplifiers.

OCIS codes: (060.1660) Coherent communications; (060.2360) Fiber optics links and subsystems.

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1. Introduction

The wavelength-division-multiplexed passive optical network (WDM PON) based on the reflective semiconductor optical amplifier (RSOA) is one of the most promising candidates for the next-generation broadband access network [1–3]. This network is usually configured in loop-back architecture for the colorless operation of optical network units (ONUs). The seed light provided from the central office (CO) is directly modulated by the RSOA located at the ONU, and sent back to the CO as an upstream signal (i.e., the seed light is looped back.). As a result, the maximum reach of this network is often restricted by the power budget of the upstream signal. To overcome this limitation by improving the receiver sensitivity, we have recently demonstrated an RSOA-based WDM PON implemented by using a self-homodyne receiver [4,5]. The results show that we can transmit the 1.25-Gb/s upstream signal, obtained by directly modulating an RSOA, over 100 km of single-mode fiber without using any optical amplifiers. In this demonstration, however, we could not maximize the system's performance by utilizing a large extinction ratio due to the large chirp of the RSOA (i.e., the mark symbol in the constellation diagram becomes blurred as we increase the extinction ratio). In this paper, we solve this problem by generating the phase-shift-keying (PSK) signal instead of the conventional amplitude-shift-keying (ASK) signal from the directly-modulated RSOA.

When the RSOA is directly modulated, both the amplitude and phase of the output signal vary with the modulation current (due to the changes in the carrier density of the RSOA) [6]. Thus, we can consider the RSOA as an external phase modulator having a gain on the amplitude of the signal. The advantages of generating the PSK signal, instead of the ASK signal, from the directly-modulated RSOA are as follows. Firstly, it is possible to improve the receiver sensitivity since the symbol distance of the PSK signal is twice longer than that of the ASK signal. We also note that there is no significant difference in the complexities of the coherent receivers for the ASK and PSK signals. Secondly, we can reduce the modulation current and the power consumption required to generate the upstream signal (since it requires much less current to achieve the ideal phase modulation (PM) index of $\pi/2$ than the ideal amplitude modulation (AM) index of 1). Thus, we optimize the modulation current to achieve the maximum phase shift of π instead of maximizing the extinction ratio. However, when we utilize the RSOA as a phase modulator, the system's performance can in principle be deteriorated by the unwanted AM components. We evaluate this effect by estimating the symbol distances from the measured values of the AM and PM indices of the RSOA. The results show that we can obtain the maximum symbol distance at the PM index of $\sim\pi/2$, indicating that the power penalty caused by the unwanted AM components is negligibly small. Thus, even when we utilize the RSOA as a phase modulator, the receiver sensitivity is almost identical to the case of using the conventional external phase modulator (such as a LiNbO$_3$-based phase modulator). In fact, by using an RSOA as a phase modulator, we achieve the excellent receiver sensitivity of –49.8 dBm (@bit-error rate (BER) = 10^{-4}) at 1.25 Gb/s. We also demonstrate an RSOA-based WDM PON having the maximum reach of 110 km without using any optical amplifiers.

2. PSK modulation by using directly-modulated RSOA

In a directly-modulated RSOA, both the amplitude and phase of the output signal vary with the modulation current (since the refractive index and gain of the RSOA are dependent on the carrier density) [6]. Figure 1(a) shows the complex electric field (or phasor) of the mark and space, E_1 and E_0, when the RSOA is directly modulated with a binary data signal. Due to the chirp of the RSOA, the phasor rotates as the injection current changes, and its trajectory becomes to have a spiral shape as shown by the dashed curve. If we define the AM index (γ) and PM index (θ) as $(|E_1|-|E_0|)/(|E_1| + |E_0|)$ and one half of the phase deviation between mark and space, respectively, E_1 and E_0 can be described as

$$E_1 = \sqrt{P_{avg}/(1+\gamma^2)}(1+\gamma)\exp(i2\theta) \text{ and } E_0 = \sqrt{P_{avg}/(1+\gamma^2)}(1-\gamma), \qquad (1)$$
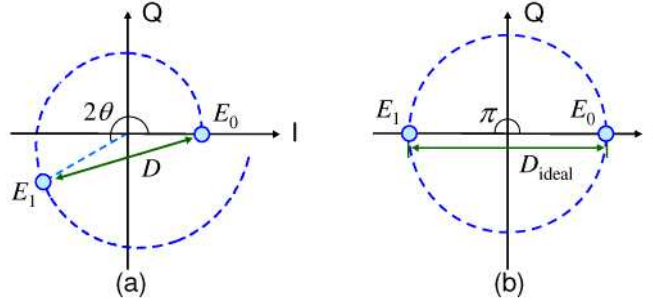

Fig. 1. Phasor diagrams of the output signals of the (a) directly-modulated RSOA and (b) ideal phase modulator.

where P_{avg} is an average power of the output signal. By using this equation, we can obtain the symbol distance D between E_1 and E_0 as

$$D = \sqrt{2P_{avg}\left[1 - \frac{1-\gamma^2}{1+\gamma^2}\cos(2\theta)\right]}. \qquad (2)$$

It is interesting to note that, when $\pi/2 < 2\theta < 3\pi/2$, the symbol distance is always longer than $\sqrt{2P_{avg}}$ (which is the symbol distance achievable by using an ideal intensity modulator with an infinite extinction ratio) and this property does not depend on the chirp characteristics of the RSOA. In other words, as long as we can rotate the phase by $>\pi/2$, it is always possible to achieve better receiver sensitivities by utilizing the PM effect of the directly-modulated RSOA regardless of its AM effect. In addition, if the relationship between γ and θ is known (which is often referred as the linewidth enhancement factor, $\alpha = -\partial\theta/\partial\gamma$ [7]), we can easily identify the optimum modulation current for maximizing the symbol distance by using Eq. (2). For example, if we assume that θ depends linearly on γ (i.e., $\theta = -\alpha\gamma$) [8], the optimum AM and PM indices (at which the symbol distance is maximized) can be easily calculated as a function of α (as shown in Fig. 2(a)). The result shows that, unless α is too small (<4.5), the optimum PM index can be approximated by $\pi/2$. Thus, the maximum symbol distance achievable by using a directly-modulated RSOA is obtained as

$$D_{RSOA} = 2\sqrt{P_{avg}/(1+\gamma_0^2)}, \qquad (3)$$

where $\gamma_0 = -(\pi/2)/\alpha$ represents the AM index when $\theta = \pi/2$. To evaluate the power penalty caused by the unwanted AM components generated in the directly-modulated RSOA, we compare the result with the symbol distance achievable by using an ideal phase modulator. Since the ideal phase modulator should not have any AM components (as shown in Fig. 1(b)), the maximum symbol distance achievable by using such a phase modulator, D_{ideal}, can be obtained by assuming $\gamma_0 = 0$ in Eq. (3).

$$D_{ideal} = 2\sqrt{P_{avg}}. \qquad (4)$$

Thus, the power penalty caused by the unwanted AM components in a directly-modulated RSOA can be expressed by the ratio between D_{RSOA} and D_{ideal}. The solid line in Fig. 2(b) shows the ratio D_{RSOA}/D_{ideal} calculated as a function of α. The result shows that, as α increases, this ratio approaches to be unity. Thus, the power penalty caused by the unwanted AM components in the directly-modulated RSOA should be negligibly small. For example, the dashed curve in Fig. 2(b) shows the power penalty (= $20\log(D_{RSOA}/D_{ideal})$) calculated as a function of α. The power penalty is less than 0.5 dB when $\alpha > 4.5$.
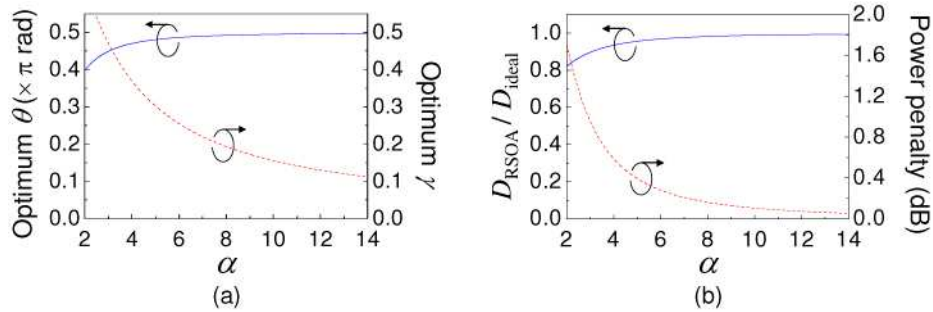
Fig. 2. Effects of the unwanted AM components. (a) Optimum PM and AM indices to achieve the maximum symbol distance. (b) D_{RSOA}/D_{ideal} and the power penalty caused by the unwanted AM components.
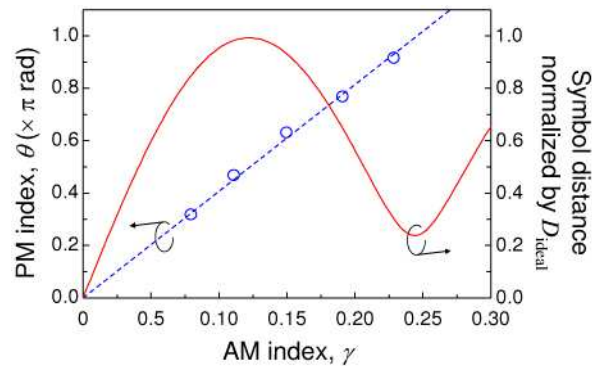

Fig. 3. Measured PM index (θ) and calculated symbol distance as a function of the AM index (γ) of the RSOA used in this experiment.

To verify the optimum operating condition of the RSOA for the phase modulation, we measured γ and θ for various modulation currents by using a self-homodyne receiver [4,5]. In this measurement, we directly modulated the RSOA by using a 750-MHz sinusoidal signal. The bias current was fixed to be 70 mA. At the receiver, we detected the output signal of the RSOA by using a 120-degree optical hybrid and three dc-coupled photo-detectors (PDs), and obtained the constellation diagram by sampling at the rate of 5 Gsample/s [4]. We then measured θ and γ from the obtained constellation diagram and the intensity of the output signal, respectively. The circles in Fig. 3 show the relation between θ and γ measured while changing the modulation current. This figure shows that θ increases linearly with γ. The dashed line was obtained by fitting the measured data using the least-mean square method. From the slope of this line, α was estimated to be 12.8 [8,9]. Thus, by using this result and Eq. (2), we obtained the symbol distance D between the mark and space. The solid curve in Fig. 3 represents the estimated symbol distances normalized by the ideal symbol distance, D_{ideal} (= $2\sqrt{P_{avg}}$). The maximum distance of 0.993 was obtained at $\gamma = 0.122$ and $\theta = 0.497\pi$. Thus, the difference from the value achievable by using an ideal PM modulator was extremely small and the power penalty caused by the unwanted AM components was calculated to be negligible (~0.07 dB). From this result, we concluded that the RSOA could be used as an excellent external phase modulator for the long-reach WDM PON application.

3. Demonstration of long-reach RSOA-based WDM PON

We first evaluated the BER performances of the phase-modulated signal by using the directly-modulated RSOA in a typical WDM PON configuration. Figure 4 shows the experimental setup. We used a tunable laser diode (TLD) having a linewidth of 170 kHz to provide the seed

light for the RSOA placed at the ONU. The optical power of the seed light incident on the transmission fiber (after the arrayed waveguide grating (AWG) at the CO) was measured to be 0 dBm. The bias current of the RSOA was set to be 70 mA. We directly modulated the RSOA at 1.25 Gb/s (pattern length = 2^{11}-1). We applied Manchester coding to avoid the penalty caused by the loss of the low-frequency components due to the use of the high-pass filter (HPF) in the self-homodyne receiver. (This HPF was needed to improve the reflection tolerance drastically, as discussed in [4, 5].) The modulated upstream signal was sent back to the CO and detected by using the self-homodyne receiver. To enhance the cost-effectiveness of the proposed scheme, we implemented this self-homodyne receiver by using a 3x3 fiber coupler instead of the 90-degree optical hybrid [10,11] and reused the seed light source to obtain the local oscillator (LO). The optical power of the LO launched into the 3x3 fiber coupler was 3 dBm. The excess loss of the 3x3 fiber coupler was <0.65 dB. In the receiver, we first detected the output signals from the 3x3 coupler by using three ac-coupled PDs. The detected signals were sampled by using a real-time sampling oscilloscope at a rate of 7.46 Gsample/s. We then demodulated the upstream data by using the delay-detection method in the offline processing. Since the linewidth of the LO was sufficiently narrow (i.e., 170 kHz), we could ignore the effect of the phase noise on the delay detection [11]. In this experiment, the measurable BER was limited to 10^{-5} due to the limitation of the time and memory size of the offline processing. However, this BER is sufficiently low for the discussion of the error-free condition under the assumption of using the forward-error correction (FEC) code such as Reed-Solomon (255, 239) code [12], where the BER threshold for the error-free condition is 10^{-4} before FEC.
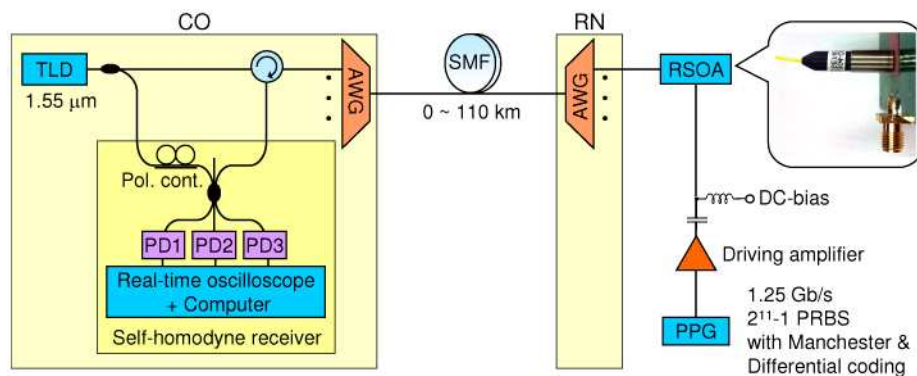
Fig. 4. Experimental setup.

We first measured the back-to-back BER performance while changing the modulation current of the RSOA and evaluated the relation between the receiver sensitivity and the AM index, γ. Figure 5 showed that the best receiver sensitivity (–49.8 dBm) was obtained at $\gamma =$ 0.115, which agreed well with the optimum value obtained in Fig. 3 (i.e., $\gamma = 0.122$).

We demonstrated a long-reach RSOA-based WDM PON by setting γ to be 0.115. For this demonstration, we inserted various lengths of single-mode fiber ranging from 0 to 110 km between the CO and remote node (RN) in Fig. 4. The average loss of the fibers and AWGs were 0.23 dB/km and 4.5 dB, respectively. Figure 6 shows the measured BER curves as a function of the transmission distance. As a reference, we added a BER curve obtained by using a LiNbO$_3$-based phase modulator, instead of the RSOA, in back-to-back condition. In this case, the receiver sensitivity was measured to be –50.0 dBm (@BER = 10^{-4}). However, when we utilized the RSOA, the back-to-back receiver sensitivity was measured to be –49.8 dBm. Thus, the power penalty caused by using the RSOA as a phase modulator was only ~0.2 dB. When the transmission distance exceeded ~80 km, the power penalty increased gradually. This was mainly because of the fact that the optical power incident on the RSOA decreased as

the transmission distance increased, and, as a result, the optical signal-to-noise ratio (OSNR) of the upstream signal was degraded. Nevertheless, we could achieve the transmission distance of 110 km. To the best of our knowledge, this represents the longest transmission distance achieved without using any remote optical amplifiers among the WDM PONs utilizing colorless light sources. In this demonstration of 110-km reach WDM PON, the loss budget (i.e., the difference between the RSOA's output power and the receiver sensitivity required for the error-free transmission using FEC) and the link margin were 40.9 dB and 6.2 dB, respectively. It should also be noted that we could further extend the maximum reach by increasing the optical power of the seed light.
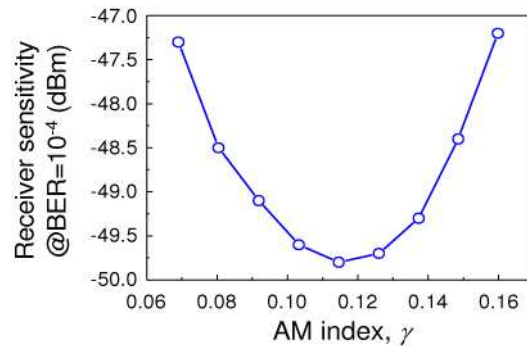

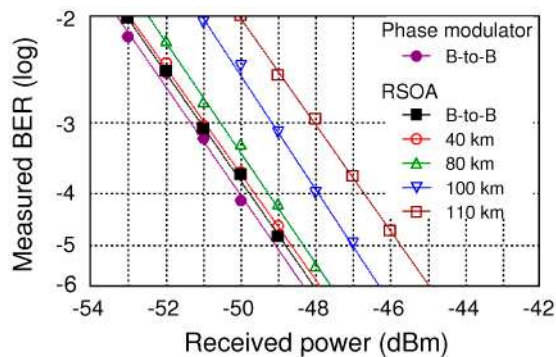Fig. 5. Measured receiver sensitivities as a function of the RSOA's γ.

Fig. 6. Measured BER curves as a function of the transmission distance.

4. Summary

In this paper, we have demonstrated a long-reach WDM PON implemented by using the PSK modulated RSOAs and self-homodyne receivers. To evaluate the performance of the PSK signal generated by directly modulating an RSOA, we first calculated the symbol distance as a function of the PM and AM indices, and then obtained the conditions required to achieve the maximum symbol distance. The results showed that we could achieve this maximum symbol distance at the PM index of $\sim\pi/2$ (since the linewidth enhancement factor of the RSOA was sufficiently large). In addition, by measuring the PM and AM indices of the RSOA, we showed that the maximum symbol distance obtained in this experiment was almost identical to the value achievable by using an ideal phase modulator. As a result, we could obtain the excellent receiver sensitivity of -49.8 dBm (@BER $= 10^{-4}$) for 1.25-Gb/s signal by using the PSK-modulated RSOAs and self-homodyne receivers. Using this setup, we demonstrated that the maximum reach of the RSOA-based 1.25-Gb/s WDM PON could be extended to >110 km without using any optical amplifiers.

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