Transmission of 40-Gb/s QPSK upstream signal in RSOA-based coherent WDM PON using offset PDM technique

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Abstract: We demonstrate the 40-Gb/s upstream transmission in the 60-km reach wavelength-division-multiplexed passive optical network (WDM PON) implemented by using directly modulated reflective semiconductor optical amplifiers (RSOAs) and self-homodyne receivers. It is difficult to operate the RSOA at 40 Gb/s due to its limited modulation bandwidth. To overcome this problem and generate 40-Gb/s upstream signal, we utilize the quadrature phase-shift-keying (QPSK) format and the offset polarization-division-multiplexing (PDM) technique. For this purpose, we install two RSOAs at each ONU and provide the seed light for these RSOAs by polarization-multiplexing the outputs of two lasers with a small frequency offset (20 GHz). This frequency offset is used to separate the polarization-multiplexed seed light by using a simple delay-line interferometer (DLI), instead of the polarization-beam splitter and polarization controller, at the ONU. The separated seed light is modulated by each RSOA at 20 Gb/s in the QPSK format, and then combined again by the DLI before sent back to the central office (CO). The results show that this WDM PON can support the transmission of 40-Gb/s channels spaced at 50 GHz over 60 km without using any remote optical amplifiers.

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

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1. Introduction

To meet the ever-increasing demand for bandwidth, it will be necessary to develop the high-speed optical access network capable of providing >40-Gb/s service to each subscriber in the near future [1,2]. The wavelength-division-multiplexed passive optical network (WDM PON) is well suited for this purpose [2]. However, for its practical implementation, it is crucial to utilize colorless light sources and avoid the use of expensive external modulators, especially at the optical network units (ONUs). Previously, it has been demonstrated that the 40-Gb/s downstream transmission can be achieved by using a chirp-managed directly modulated laser in WDM PONs [1]. However, it is difficult to realize the high-speed (>40-Gb/s) upstream transmission by using the colorless light sources such as the reflective semiconductor optical amplifier (RSOA) and reflective electro-absorption modulator (REAM) due to their limited modulation bandwidths. Recently, there have been several efforts to overcome this problem by using the electronic equalization technique. For example, it has been demonstrated that the operating speeds of the RSOA and REAM could be increased to 25 Gb/s and 40 Gb/s, respectively, by using various electronic equalization techniques [3,4]. Recently, it has also been demonstrated that the 100-Gb/s WDM PON can be realized by utilizing 4 RSOAs (each operating at 25 Gb/s in non-return-to-zero (NRZ) format by using such electronic equalization techniques) in each ONU and the coarse WDM (CWDM) technique [5].

In this paper, we propose and demonstrate the 40-Gb/s upstream transmission in the 60-km-reach WDM PON implemented by using directly modulated RSOAs and self-homodyne receivers. To generate the 40-Gb/s upstream signal by using the RSOAs having a limited modulation bandwidth of only ~3.2 GHz, we utilize the quadrature phase-shift-keying (QPSK) format and the offset polarization-division-multiplexing (PDM) technique [6–8]. For this purpose, we multiplex the outputs of two seed light sources, operating with a small frequency offset (20 GHz), by using a polarization-beam splitter (PBS), and send to the ONU. This small frequency offset is used to separate the polarization-multiplexed seed light by using a simple delay-line interferometer (DLI) instead of a PBS and its associated polarization-control circuitry at the ONU. The separated seed light is then modulated by using two RSOAs at 20 Gb/s in the QPSK format. The modulated outputs of the RSOAs are combined again by the DLI and sent back to the central office (CO). The channel spacing of this network is set to be as narrow as 50 GHz, owing to the small frequency offset between the seed light and the compact optical spectra of the QPSK signals. Thus, if necessary, this WDM PON can accommodate a large number of 40-Gb/s subscribers. At the CO, the polarization-multiplexed 40-Gb/s upstream signals are separated by the PBS before the detection using self-homodyne coherent receivers. No polarization-diversity technique is used in these receivers as we install a Faraday rotator (FR) in front of each RSOA [9]. Also, due to the excellent sensitivity of these receivers, there is no need to utilize any remote optical amplifiers. The results show that 40-Gb/s WDM PON with the maximum reach of 60 km can be realized cost-effectively by using the proposed techniques.

2. Experiment and results

Figure 1 shows the experimental setup used to demonstrate the 40-Gb/s upstream transmission in the proposed long-reach WDM PON implemented by using directly modulated RSOAs and self-homodyne receivers. The modulation bandwidth of the butterfly-packaged RSOA used in

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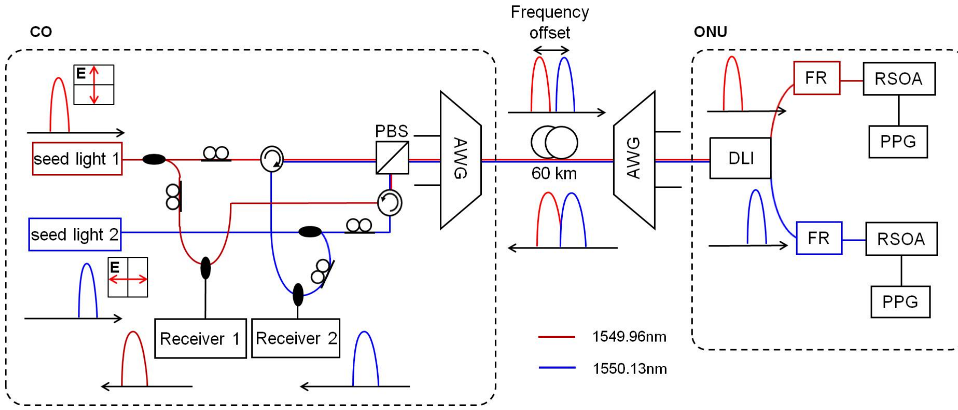

Fig. 1. Experimental setup used to demonstrate the 40-Gb/s upstream transmission in the proposed long-reach WDM PON using the offset PDM technique. (AWG: arrayed-waveguide grating, DLI: delay-line interferometer, FR: Faraday rotator, PPG: pulse pattern generator)

this experiment was only ~3.2 GHz [5]. Thus, to overcome this bandwidth limitation and achieve the 40-Gb/s upstream signal, we utilized the offset PDM technique and QPSK format. For this purpose, we installed two RSOAs at the ONU and sent two seed light (obtained by using two tunable lasers at the CO) in orthogonal polarization to each ONU. The operating wavelengths of these lasers were set to be 1549.96 nm and 1550.13 nm, respectively, and their outputs were polarization-multiplexed by using a PBS. Thus, the frequency offset between these two seed light was 20 GHz. This offset was used to combine/separate the polarization-multiplexed seed light simply by using a DLI at the ONU instead of using a PBS and its associated polarization-control circuitry. The arrayed waveguide gratings (AWGs), placed at the CO and remote node (RN), had flat-top passband and 50-GHz channel spacing. Thus, the 20-GHz offset was small enough for the polarization-multiplexed seed light to pass through these AWGs without significant excess losses. The output power of the seed light was set to be 3 dBm at the input of the 60-km long feeder fiber. After passing through a short section (~1 km) of the drop fiber, the polarization-multiplexed seed light was separated by using a DLI at the ONU. The insertion loss of the DLI was <1 dB. Since the free-spectral range (FSR) of this DLI was 40 GHz, it was well suited to combine/separate the PDM signals with 20-GHz offset. For example, Fig. 2(a) and 2(b) show the optical spectra of the polarization-multiplexed seed light with 20-GHz offset measured at the input and an output of the DLI, respectively. These figures showed that the polarization-multiplexed seed light could be separated by using this DLI with a suppression ratio of 22 dB. The optical power of the seed light incident on each RSOA was measured to be −15 dBm. The separated seed light was directly modulated by the RSOAs at 20 Gb/s in QPSK format using 4-level electrical signals, and then combined again by the DLI before sent back to the CO. Thus, the 40-Gb/s upstream signal was obtained by using two RSOAs, each modulated at 20 Gb/s in the QPSK format, at the ONU. Figure 2(c) shows the optical spectrum of the combined upstream signals measured after the DLI. Due to the small frequency offset between two seed light (i.e., 20 GHz), the optical spectra of the upstream signals broadened by the directly modulation of RSOAs at 20 Gb/s (10 Gbaud/s) slightly overlapped with each other. However, since these signals operated in the orthogonal polarizations, this spectral overlap would not cause any significant crosstalk problems at the receiver. For example, Fig. 2(d) shows the optical spectrum of an upstream signal measured in front of the coherent receiver at the CO. The combined upstream signals were well separated by the PBS with a suppression ratio of ~30 dB. The separated upstream signals were then detected by using self-homodyne receivers [6,7]. These coherent receivers were implemented by using inexpensive 3x3 couplers as 120°optical hybrids. There was no need to utilize the expensive polarization-diversity or polarization-tracking techniques in

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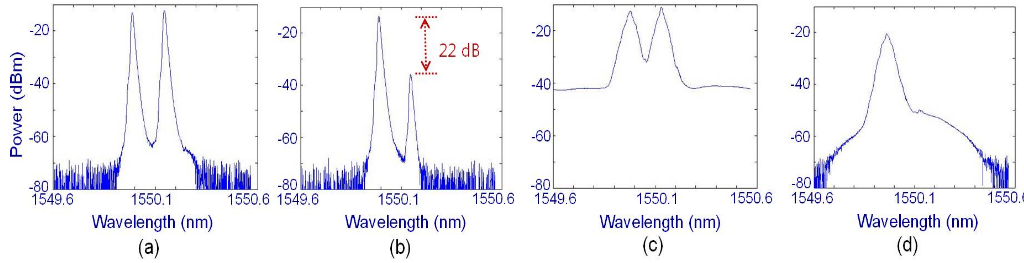

Fig. 2. Optical spectra of (a) two seed light measured in front of the DLI (b) separated output after DLI (c) the combined upstream signals measured after the DLI after the modulation by RSOAs, and (d) the separated upstream signal by the PBS measured in front of the coherent receiver.

these receivers since we stabilized the state-of-polarization (SOP) of the upstream signals by placing a FR in front of each RSOA at the ONU [9]. As a result, the SOP of the upstream signal became orthogonal to that of the seed light at the input of the PBS at the CO at all times. For the self-homodyne coherent detection, we utilized portions of the seed light 1 and 2 as local oscillators for the coherent receivers 1 and 2, respectively, as shown in Fig. 1. The output powers of these local oscillators were set to be 3 dBm. The output signals of the 3x3 coupler at each coherent receiver were detected by using three PIN photodiodes. The detected signals were sampled at 40 GS/s by using digital sampling oscilloscopes. 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. We then applied Fourier transform of the inverse fiber dispersion function to the received signals for the dispersion compensation [10]. However, the carrier phases of the received QPSK signals could not be recovered accurately by using the conventional m-th power algorithm [11]. This was because the modulation bandwidth of the RSOA was too narrow (i.e., 3.2 GHz) for the generation of the 20-Gb/s QPSK signal. As a result, the received signal became seriously distorted for the accurate estimation of the carrier phase. To solve this problem, we set the amplitude of the modulation current applied to the RSOA so that its phase could be changed only between 0 ~$3\pi/2$ in the phasor diagram. Thus, we could estimate the carrier phase of the QPSK signal simply by measuring the opening between $3\pi/2$ ~0 in the phasor diagram. By using this technique, we adjusted the carrier phase of the received QPSK signal in every 350 symbols. We then utilized the electronic equalization technique to compensate for the limited modulation bandwidths of the RSOAs. 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, we applied the electronic equalization technique (consisted of half-symbol-spaced 19-tap feed-forward equalizer and 10-tap decision-feedback equalizer) only to the phase portion of the modulated signal [7]. Figure 3 shows the BER curves of the 20-Gb/s QPSK signal measured by using the coherent receivers 1 and 2 at various transmission distances. The receiver sensitivity (@ BER = 10^{-4}) was measured to be −28.2 dBm under the back-to-back condition, and −26.3 dBm after the transmission over the 60-km long single-mode fiber (SMF) link. There was no significant difference between the measured sensitivities of two coherent receivers, as shown in Fig. 3(a) and 3(b). The power penalties observed after the transmission were attributed mostly to the reduced optical powers incident on the RSOA. To evaluate the effect of the proposed offset PDM technique on the receiver sensitivity, we also measured the BER curves of an upstream signal while turning off the other part of the upstream signal operating in the orthogonal polarization. The result showed that the power penalty caused by the offset PDM technique was <0.5 dB as shown in Fig. 3(a) and 3(b).

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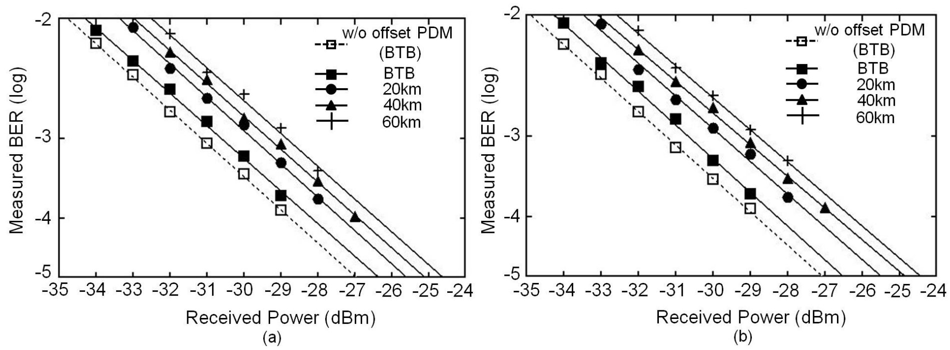

Fig. 3. Receiver sensitivities of the upstream signal measured by using the (a) receiver 1and (b) receiver 2 in Fig. 1.

3. Summary

We have demonstrated the transmission of the 40-Gb/s upstream signal over 60-km long SMF link in the proposed WDM PON implemented by using directly-modulated RSOAs and self-homodyne receivers. To overcome the limited modulation bandwidth of the RSOA and generate the 40-Gb/s upstream signal, we utilized the QPSK format and the offset PDM technique. For this purpose, we sent two seed light in orthogonal polarizations with a small frequency offset (20 GHz) to each ONU. These seed light were separated by using a simple DLI at the ONU and modulated by two RSOAs at 20 Gb/s each in QPSK format. These two modulated QPSK signals were then combined again by using the DLI at the ONU and sent back to the CO. At the CO, these polarization-multiplexed upstream signals were separated by using a PBS and then detected by a pair of inexpensive self-homodyne receivers. In these receivers, there was no need to utilize additional lasers for the local oscillators (since portions of the seed light were used as local oscillators) or the polarization-diversity technique (since we installed a FR in front of each RSOA). In addition, due to the excellent sensitivity of these receivers, we could achieve the 60-km reach at 40 Gb/s without using any remote optical amplifiers. The channel spacing of this WDM PON was 50 GHz. Thus, the achieved spectral efficiency was 0.8 bit/s/Hz, indicating that a large number of 40-Gb/s channels could be supported in this WDM PON. From these results, we concluded that it would be possible to implement 60-km-reach, 40-Gb/s WDM PON cost-effectively by using the directly modulated RSOA (together with the QPSK format and offset PDM technique) and the inexpensive self-homodyne receivers.

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