A Simple Carrier-Phase Estimation Technique for High-Speed RSOA-based Coherent WDM PON

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Abstract: We propose a simple carrier phase estimation technique for the phase-modulated signal generated by using bandwidth-limited RSOA. By using this technique, we demonstrate 25.78-Gb/s QPSK upstream transmission in 60-km reach coherent RSOA-based WDM PON.

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1. Introduction
Recently, there have been many efforts to implement the long-reach, high-speed (>10 Gb/s) wavelength-division-multiplexed passive optical network (WDM PON) by modulating the reflective semiconductor optical amplifier (RSOA) in the quadrature phase-shift-keying (QPSK) format and utilizing the coherent detection technique [1]-[5]. In these RSOA-based coherent WDM PONs, various digital signal processing techniques are used for the dispersion compensation, carrier-phase estimation (CPE), and electronic equalization. In particular, to estimate the carrier phase of the QPSK signal generated by using a directly modulated RSOA, the M-th power algorithm has been used [6]. However, the performance of this algorithm deteriorates rapidly when the modulation speed is increased to be much higher than 10 Gb/s due to the limited modulation bandwidth of RSOA (which is typically in the range of 1~3 GHz). In this paper, we propose a simple CPE technique to overcome this problem. To utilize this technique, we first set the amplitude of the modulation current applied to the RSOA so that the modulated phase does not exceed a certain value, and then estimate the carrier phase of the QPSK signal simply by measuring the opening in the phasor diagram. By using this technique, we have successfully demonstrated the transmission of 25.78-Gb/s QPSK signal generated by directly modulating a bandwidth-limited RSOA (bandwidth: 3.2 GHz) in the 60-km reach coherent WDM PON. This result indicates that the proposed technique can be used for the implementation of the long-reach, high-speed (>25 Gb/s) WDM PON by using inexpensive RSOAs.

2. Proposed CPE algorithm for the phase-modulated signal generated by using bandwidth-limited RSOA
When we directly modulate the injection current of the RSOA, both the amplitude and phase of its output signal are modulated (since the gain and refractive index of the RSOA are dependent on the carrier density). Thus, we can obtain the QPSK signal by directly modulating the RSOA with a 4-level electrical signal. A coherent receiver can be used for the detection of this QPSK signal. However, when we modulate the RSOA in the QPSK format at the speed much faster than its modulation bandwidth, it is difficult to estimate its carrier phase properly by using the conventional M-th power algorithm. To describe this problem, we evaluate the performance of this algorithm by numerical simulations using 10.3-Gb/s and 25.78-Gb/s QPSK signals generated by directly modulating an RSOA. In these simulations, we assume that the 3-dB modulation bandwidth and its roll-off characteristics of the RSOA are 3.2 GHz and ~20 dB/decade, respectively, which are identical to the experimentally measured values of the RSOA used in this work [7]. For the simplicity, we ignore the amplitude modulation (AM) components of the directly modulated RSOA. We then evaluate the effects of using the bandwidth-limited RSOA on the performance of the M-th power algorithm by applying a lowpass filter (which has the same passband characteristics with the RSOA) to the 4-level electrical drive signal. Fig. 1(a) shows the simulated phasor diagram of the QPSK signals generated by directly modulating the RSOA at 10.3 Gb/s. Its corresponding eye diagram of the drive signal is shown in Fig. 1(b). To utilize the M-th power algorithm for this signal, we first select the center samples in this phasor diagram (which are resulting from the data at the center of the eye diagram) from the oversampled data as shown in Fig. 1(c), and then calculate the fourth power to cancel out the phase modulation information as shown in Fig. 1(d). Thus, the phase is averaged out to zero when we sum up these complex amplitudes. This result confirms that, when the RSOA is modulated at 10.3 Gb/s in the QPSK format, we can accurately estimate its carrier phase by using the M-th power algorithm. However, this algorithm cannot properly estimate the carrier phase when the bit rate is increased to 25.78 Gb/s. For example, Fig. 1(e) and (f) show the phasor and eye diagrams of the 25.78-Gb/s QPSK signal obtained by using the same RSOA, respectively. Unlike in the case of modulating the RSOA at 10.3 Gb/s, the eye diagram is nearly closed even at the center of the eye due to the extremely limited modulation bandwidth of the
RSOA (emulated by the lowpass filter in this simulation) for the operation at 25.78 Gb/s. As a result, as shown in Fig. 1(g), each phase of the QPSK signal is seriously broadened. Fig. 1(g) also shows that these broadened phases can exceed their boundaries (i.e., $\pm \pi/4$ from each constellation point), as shown in the dotted box, which, in turn, causes significant errors in the process of averaging out the fourth-powered data shown in Fig. 1(h). To solve this problem, we develop a simple carrier phase estimation technique based on the opening in the phasor diagram of the QPSK signal. We set the amplitude of the modulation current applied to the RSOA in a way that its phase can be changed only between $0 \sim 3\pi/2$ in the phasor diagram. Thus, the shape of the phasor diagram is not dependent on the bit rate, as shown in Fig. 1(a) and (e). As a result, we can identify the phase of the center vector simply by measuring the opening in the phasor diagram (which is always $-\pi/4$, as shown by the dashed arrows in Fig. 1(a) and (e)). Thus, by using this technique, we can accurately estimate the carrier phase of the QPSK signal generated by the bandwidth-limited RSOA even when its operating speed is much higher than 10 Gb/s.

3. Experiment and results

Fig. 2 shows the experimental setup to demonstrate the transmission of the 25.78-Gb/s upstream signal obtained by using a directly modulated RSOA in the long-reach coherent WDM PON by using the proposed CPE algorithm. A tunable laser operating at 1549.87 nm was used for the seed light. The optical power of the seed light was set to be 2.2 dBm at the input of the feeder fiber. At the optical network unit (ONU), we modulated this seed light (by directly modulating an RSOA using a 4-level electrical signal) to generate the 25.78-Gb/s QPSK upstream signal. The modulation bandwidth of this butterfly-packaged RSOA was measured to be 3.2 GHz. At the central office (CO), this upstream signal was detected by using a self-homodyne receiver. In this receiver, a portion of the seed light was used as the local oscillator (LO) and a 3x3 coupler was used as a 120° optical hybrid. The optical power of the LO incident on the 3x3 coupler was 3 dBm. Since we placed a Faraday rotator (FR) in front of the RSOA at the ONU, there was no need to utilize the polarization-diversity receiver [2]. The output signals from the 3x3...
coupler were detected by using three PIN photodiodes, and then sampled at 40 GS/s by using a digital sampling oscilloscope. We obtained the I- and Q-components of the QPSK signal by using the coordinate transformation. A highpass filter was used to filter out the low-frequency components caused by Rayleigh backscattering. The effect of the chromatic dispersion was compensated by applying Fourier transform of the inverse fiber dispersion function [8]. We then applied the proposed CPE algorithm to estimate the carrier phase of the 25.78-Gb/s QPSK signal. The electronic equalization technique is used to compensate for the limited modulation bandwidth of the RSOA [3]. We then applied the proposed CPE algorithm to estimate the carrier phase of the 25.78-Gb/s QPSK signal. The results showed that the proposed technique could properly estimate the carrier phase of the QPSK signal generated by using a bandwidth-limited RSOA even when we increased the bit rate to 25.78 Gb/s.

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5. References