High-Speed Coherent WDM PON for Next-Generation Access Network

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ABSTRACT
The wavelength-division-multiplexed passive optical network (WDM PON) is very attractive for the future broadband access network due to its capability of providing practically unlimited bandwidth to each subscriber. However, for the massive commercial deployment, its competitiveness is yet to be improved. In particular, we need to increase its operating speed and maximum reach, and, at the same time, enhance its cost-effectiveness. For these objectives, we have developed the high-speed WDM PON operating at per-wavelength speed of > 10 Gb/s by using reflective semiconductor optical amplifiers (RSOAs) and the digital coherent detection technique. We also evaluated the maximum operable speed of the RSOA-based WDM PON by using the classical Shannon theorem. This paper reviews these progresses achieved at KAIST.

Keywords: wavelength-division-multiplexed passive optical network (WDM PON), reflective semiconductor optical amplifier (RSOA), digital coherent detection.

1. INTRODUCTION

The wavelength-division-multiplexed passive optical network (WDM PON) has long been considered as an ultimate solution for the future optical access network capable of providing practically unlimited bandwidth to each subscriber [1]-[2]. On the other hand, it is still considered to be too expensive for the massive deployment. Thus, the competitiveness of WDM PON is yet to be improved for its commercial success. For this purpose, it is crucial to further increase the operating speed and maximum reach (or splitting ratio) of WDM PON. However, the increased speed and reach may not be helpful unless we can achieve these objectives cost-effectively. Thus, we assumed that it is vital to use colorless optical network units (ONUs) and bidirectional single-fiber systems. We also assumed that it is necessary to restrain the use of expensive external modulators and optical amplifiers. One of the most plausible configurations that can satisfy these assumptions is the WDM PON based on the reflective semiconductor optical amplifier (RSOA) [3]. Thus, we endeavor to develop cost-effective methods for increasing the per-wavelength speed of such a network to > 10 Gb/s and the maximum reach to > 80 km without using any remote optical amplifiers in the outside plant. This paper reviews some of these progresses. We also report on the maximum operable speed of the WDM PON implemented by using the bandwidth-limited RSOAs.

2. HIGH-SPEED COHERENT WDM PON BASED ON RSOA

The RSOA-based WDM PON is usually configured in loop-back architecture for the colorless operation of the ONU. Thus, the seed light, provided from the central office (CO), is modulated by the RSOA at the ONU, and then sent back to the CO as the 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 due to the limited gain of the RSOA. In principle, we can mitigate this limitation by increasing the optical power of the seed light and/or improving the receiver sensitivity. However, if we increase the optical power of the seed light, the performance of the upstream signal can be deteriorated by the reflection since the power of the reflected seed light is also increased [4]-[5]. Thus, it is better to improve the receiver sensitivity by utilizing either the coherent receiver or the optical amplifier. In fact, there have already been numerous attempts to increase the maximum reach of WDM PON by installing optical amplifiers in the outside plant [6]-[7]. However, the coherent receiver has not been widely used yet in WDM PON due to its cost and complexity [8]. To overcome this problem, we have recently demonstrated an RSOA-based WDM PON implemented by using a self-homodyne receiver [9]-[10]. Figure 1 shows a schematic diagram of the upstream link in such a network. Since this receiver utilizes a portion of the seed light as the local oscillator (LO), there is no need to use an additional laser for the LO and its frequency control circuitry. In addition, for the cost-effectiveness, we implement this receiver by utilizing an inexpensive 3×3 coupler as a 120º optical hybrid and 3 photodetectors instead of the 90º optical hybrid and 4 photodetectors. The polarization stability is achieved simply by placing a 45º Faraday rotator (FR) in front of the RSOA at the ONU [11]-[12]. Thus, we can detect the upstream signal by using a single-polarization coherent receiver instead of the complicated polarization-diversity (or polarization-tracking) technique. The results show that the proposed coherent receiver is extremely robust against the back-reflection of the seed light [10].

We have recently demonstrated 110-km reach RSOA-based WDM PON by utilizing the differential phase-shift keying (DPSK) modulation of the RSOA and the proposed digital coherent detection technique [13]. However, the bit rate of this system has been limited to 1.25 Gb/s due to the inherently narrow modulation bandwidth of the RSOA. Thus, to further increase the operating speed of the RSOA, it is necessary to utilize the multi-level modulation formats and electronic equalization techniques. In fact, we have already reported that it is possible to increase the operating speed of the RSOA to > 10 Gb/s by using the 4-ary pulse amplitude modulated (PAM) format [14]-[15]. However, we note that the quadrature phase-shift keying (QPSK) signal is more attractive than the 4-ary PAM signal because of its superior sensitivity by 6.6 dB [16]. Thus, we increase the maximum reach and operating speed of the RSOA-based WDM PON by utilizing the coherent detection technique and QPSK modulation.

For the cost-effectiveness, we generate the QPSK signal by using a directly modulated RSOA. When the RSOA is directly modulated, both the amplitude and phase of the output signal are modulated at the same time [17]. Thus, we can generate the QPSK signal by directly modulating the RSOA with a proper 4-level electrical signal. However, unlike in the case of using the conventional phase modulator, the unwanted amplitude modulation (AM) component can distort the signal's constellation and degrades the receiver sensitivity. This degradation, which is dependent on the linewidth enhancement factor of the RSOA, is found to be very small (~1 dB for the RSOA used in our work). This result indicates that, in spite of the 1-dB penalty, the QPSK signal is better than the 4-ary PAM signal for the high-speed operation of the RSOA. Thus, by using the proposed technique, we generate 5-Gb/s QPSK signal and demonstrate the error-free transmission over 100-km long single-mode fiber (SMF) link without using any optical amplifiers and electronic equalizers [18]. In addition, by using this technique together with the electronic dispersion compensators and electronic equalizers, we demonstrate a long-reach WDM PON operating at per-wavelength speed of 10.3 Gb/s and the maximum SMF reach of 80 km without using any optical amplifiers [19]. Figure 2 shows an exemplary constellation diagram of the 10.3 Gb/s QPSK signal measured after the 80-km long SMF transmission.

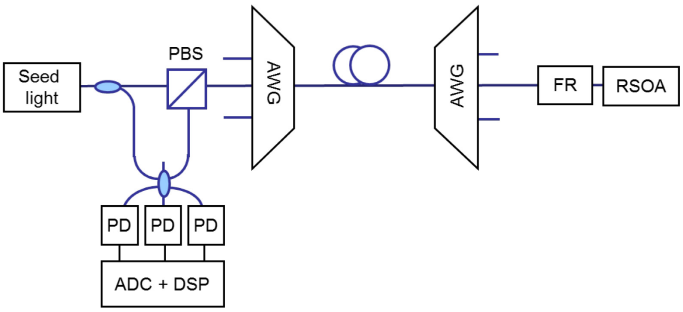


Figure 1. A schematic diagram of the upstream link of an RSOA-based WDM PON implemented by using a self-homodyne receiver.

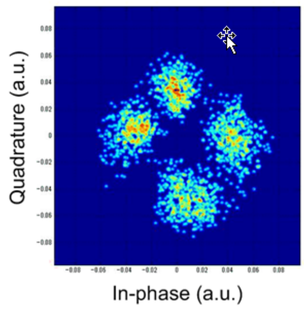
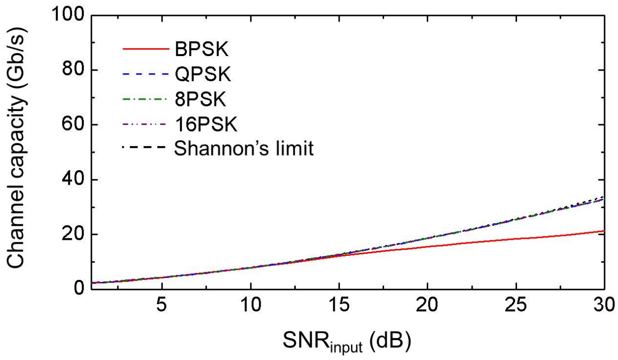


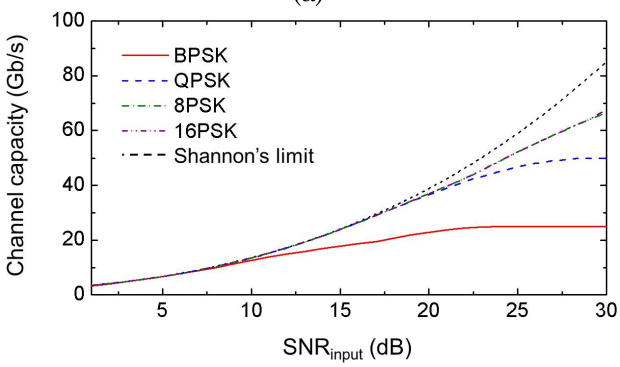
Figure 2. Measured constellation diagram of the of the 10.3-Gb/s QPSK signal measured in the 80-km reach RSOA-based coherent WDM PON.

3. MAXIMUM OPERABLE SPEED OF RSOA-BASED WDM PON

For the cost-effective realization of the next-generation WDM PON operating at the per-wavelength speed faster than 10 Gb/s, it is critical to overcome the limitation caused by the narrow modulation bandwidth of the RSOA (which is typically in the range of 0.6 ~ 3.2 GHz) [20]-[24]. Recently, there have been many attempts to achieve this objective by utilizing the electronic equalization techniques and/or multi-level modulation formats [15], [19], [21]-[24]. However, it is not clear yet what the maximum operating speed achievable by using such bandwidth-limited RSOAs together with these equalization techniques and multi-level formats is. To answer this question by evaluating the maximum operable speed of the RSOA, we assume a short-reach WDM PON implemented without using any remote optical amplifiers. Thus, the maximum operable speed is mostly determined by the signal-to-noise ratio (SNR) of the received signal deteriorated by the limited modulation bandwidth of the RSOA. We estimate this speed by using the classical Shannon's capacity theorem [25]-[27]. In this estimation, we limit the channel bandwidth and the SNR of the driving signal applied to the RSOA to be 25 GHz and 25 dB, respectively, to obtain the practically achievable values. The results in Fig. 3 show that we can, in principle, increase the operating speed of the RSOA to ~60 Gb/s when its modulation bandwidth is 3.2 GHz. However, when the modulation bandwidth of the RSOA is extremely limited (< 3 GHz), the use of the multi-level modulation formats higher than the QPSK format is not very effective for increasing its operating speed due to their requirements of the high SNR. The results also show that it is possible to increase the operating speed of the RSOA to 100 Gb/s if its modulation bandwidth can be increased to > 5.8 GHz.



(a)



(b)

Figure 3. Channel capacities achievable by using multi-level formats when the WDM PON is implemented by using (a) TO-can packaged RSOAs (modulation bandwidth: 2.2 GHz, roll-off: -40 dB/decade) and (b) butterfly-packaged RSOAs (modulation bandwidth: 3.2 GHz, roll-off: -20 dB/decade).

4. SUMMARY

We reviewed the recent advancement in the WDM PON technology achieved at KAIST. In particular, we reported the progresses in the high-speed and long-reach WDM PON based on the RSOA and digital coherent detection technique. For the cost-effectiveness, we utilized directly modulated RSOA for the generation of the QPSK signal. The coherent receiver was implemented by using a portion of the seed light as a local oscillator and a 3×3 coupler as an optical hybrid. The polarization stability was achieved simply by placing a Faraday rotator in front of the RSOA. By using these techniques, we could transmit 5-Gb/s QPSK signal over 100 km of SMF without using any optical amplifiers. We could also demonstrate the transmission of 10-Gb/s QPSK signal over 80 km of SMF with the help of the electronic equalization technique. In addition, we evaluated the maximum operable speed of the WDM PON implemented by using the bandwidth-limited RSOAs by using the classical Shannon theorem. The results showed that we could increase the operating speed of the RSOA to ~60 Gb/s even when its modulation bandwidth was only 3.2 GHz. This speed could be further increased to 100 Gb/s if the modulation bandwidth of the RSOA could be increased to 5.8 GHz. The results also showed that, if the modulation bandwidth of the RSOA was limited to be < 3 GHz, the use of the higher-level modulation formats than QPSK was not very helpful for increasing the channel capacity due to their high SNR requirements.

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