Optics Communications 282 (2009) 3701–3705

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Utilization of four WDM channels with signal remodulation of OFDM-QAM for 10 Gb/s uplink passive optical networks

Chien Hung Yeh [a,*], Chi Wai Chow [b]

[a] Information and Communications Research Laboratories, Industrial Technology Research Institute (ITRI), Chutung, Hsinchu 31040, Taiwan
[b] Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan

ARTICLE INFO

Article history:
Received 31 March 2009
Received in revised form 10 June 2009
Accepted 10 June 2009

Keywords:
TDM
WDM
Passive optical networks (PONs)
OFDM

ABSTRACT

In this investigation, we experimentally investigate an extended reach (ER) time-division-multiplexed passive optical network (TDM-PON) using four wavelength-multiplexed channels to achieve 16 Gb/s downlink and 10 Gb/s uplink traffic. Each downlink signal uses the highly spectral efficient 4 Gb/s OFDM-QAM, and each uplink signal is generated by signal remodulating the downlink signal via a reflective semiconductor amplifier (RSOA) at 2.5 Gb/s non-return-to-zero (NRZ). In addition, the performance of the proposed ER TDM-PON has also been analyzed and discussed.

1. Introduction

Recently, huge bandwidth is required to support the rapid growth in demand of IP telephony, video on demand (VoD), HD-TV, IP-TV, and on-line gaming etc. Because of the requirement of huge capacity and bandwidth by end-users in fiber access networks, the cost of bandwidth service should be reduced [1,2]. The possible method is to simplify the fiber access architecture to accomplish the cost-effective access traffic. Thus, the number of equipment interfaces and optical devices can be reduced. Consequently, the extended reach (ER) fiber access technologies have also been proposed [2–6]. The ER access networks combine the optical metro and access networks into one system and provide the benefits of high speed, high capacity, high split-ratio passive optical network (PON) with a transmission length of more than 100 km [2].

Nowadays, the time-division-multiplexing PONs (TDM-PONs), such as Broadband PON (BPON), Ethernet PON (EPON) and Gigabit PON (GPON) were standardized and deployed by telecom carriers [7–9]. However, the data capacities of the present TDM-PONs cannot satisfy the bandwidth requirement for the future triple-play services. Thus, the current TDM-PONs need to be upgraded to 10 Gb/s or more. Furthermore, the 10G EPON and 10G GPON have also been discussed by the standardizations for the next generation 10G access network applications [10–12]. However, using a single distributed feedback (DFB) laser with 10 Gb/s data rate in each optical network unit (ONU) is still expensive. Moreover, the 10 Gb/s burst-mode receiver in optical line terminal (OLT) is still hard to perform and commercialize for receiving the busty uplink signal in the near future. Therefore, to reduce the cost and support the 10 Gb/s uplink traffic, using four WDM wavelengths with optical-injection method in each ONU to achieve this have been studied [11,12].

Besides, in order to increase the effective bandwidth based on the original light source, the orthogonal-frequency-division-multiplexing (OFDM) quadrature amplitude modulation (QAM) was used in PON system [12,13]. Furthermore, the frequency diversity transmission of OFDM signal would permit the simple equalization of frequency response and can effectively mitigate fiber chromatic dispersion [13].

In this study, we propose a simple ER TDM-PON system using four WDM wavelengths for both downlink and uplink traffic to achieve 16 and 10 Gb/s data rates, respectively. In this proposed architecture, each downlink wavelength uses 4 Gb/s OFDM-QAM format. Here, we investigate the four wavelength channels of OFDM-based downlink and the signal remodulated non-return-to-zero (NRZ) uplink by using reflective semiconductor optical amplifier (RSOA) in the ER TDM-PON. Error-free operations are achieved in the fiber transmission of 100 km without dispersion compensation.

2. Analysis and experiment

Fig. 1 shows the proposed architecture of ER TDM-PON system. In the OLT, four wavelengths are combined together by wave-

* Corresponding author. Address: ITRI, Rm. 300 V, Bldg. 14, 195, Sec. 4, Chung-Hsing Rd., Chutung, Hsinchu 31040, Taiwan.
E-mail address: depew@itri.org.tw (C.H. Yeh).

0030-4018/$ - see front matter
doi:10.1016/j.optcom.2009.06.029

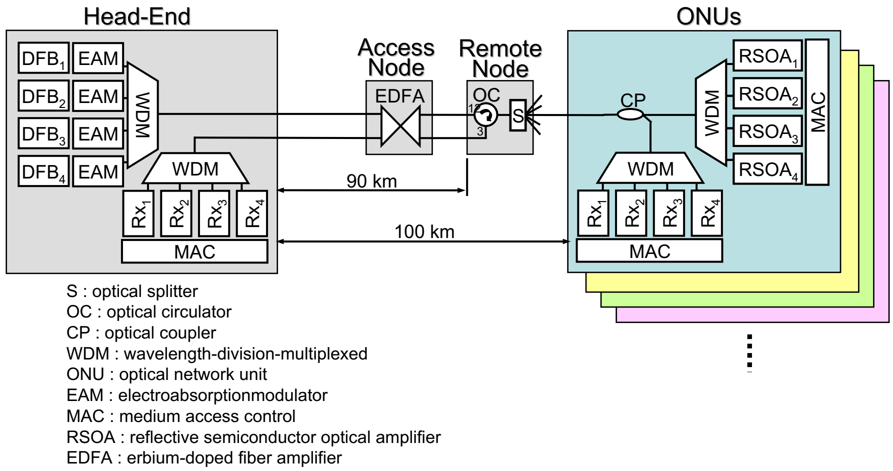

Fig. 1. The proposed experimental setup of ER TDM-PON system using OFDM-QAM and OOK remodulation for both downlink and uplink traffic.

length-multiplexer to generate the 16 Gb/s downlink data traffic for broadcasting to each ONU. That means that each downlink signal having 4 Gb/s data rate is modulated by OFDM format which is applied to an electro-absorption modulator (EAM) with proper bias via a bias-tee. An arbitrary waveform generator (AWG) with 4 GHz sampling rate is used to convert the baseband digital data to analog data, which then applied to the EAM for downlink traffic. The 4 Gb/s OFDM signal consists of 16 subcarriers, occupying nearly 1 GHz bandwidth. Each subcarrier is in 16-QAM format. The OFDM signal occupies the radio-frequency (RF) spectrum from 62.5 to 1125 MHz. The data pattern has 8192 OFDM symbols. In the experiment, we use four wavelengths, which are 1540.5, 1541.7, 1542.9 and 1544.1 nm, respectively, with 4 dBm average input power to the feeder fiber. Therefore, the 16 Gb/s downlink rate can be divided into the four downlink signals by the medium access control (MAC) to four wavelength channels, and each channel have a data rate of 4 Gb/s. As illustrated in Fig. 1, the transmission length between head-end (HE) and remote node (AN) is 90 km, and the distributed fiber length is 10 km. The bidirectional erbium-doped fiber amplifier (EDFA) in access node (AN) is employed to compensate the losses of fiber transmission and passive components. According to the current PON standard, we use 1×32 optical splitter in remote node (RN) for the measurement. At each ONU, the 10% downlink signal is tapped out and detected by the optically pre-amplifier receiver (Rx) consisting of a low-noise EDFA, an optical bandpass filter (BPF), and a PIN photodiode. A real-time 20 GHz sampling oscilloscope is used to act as an analog to digital converter for converting the downlink signal for demodulation. We use the computer software to perform the demodulation. Besides, we calculate the bit error rate (BER) performance of the ER TDM-PON by using the detected and demodulated error vector magnitude (EVM) [13]. Hence, the bandwidth of the EAM used at the OLT has the modulation bandwidth of 1.25 GHz. Since we are using the special efficient 16-QAM in the OFDM signal, the total 4 Gb/s data rate occupies 1 GHz bandwidth of the EAM. Hence this producing the 4×4 Gb/s signal when using four EAMs. In this paper, we used expensive equipments, such as the arbitrary waveform generator and the real-time scope, to generate and detect the OFDM signal respectively. However, as described in Ref. [13], >2 GHz high-resolution data converters are commercially available recently, and the OFDM detection can be integrated with the FEC modules. We believe that the OFDM signal may be a practical candidate for upgrading optical access networks in the future.

The remaining downlink power (90%) injects into the RSOA for signal remodulation. Here, there are four RSOAs in each ONU with the similar characteristics. They are injected by the corresponding wavelengths of the downlink signals, which then serve as the uplink signals. Fig. 2a presents the four downlink spectra at the wavelengths of 1540.5, 1541.7, 1542.9 and 1544.1 nm, respectively. Fig. 2b shows the four output spectra of uplink when the downlink signals are injected into RSOAs after 100 km transmission. For this measurement, a 2.5 Gb/s non-return-to-zero (NRZ) with pseudo random binary sequence (PRBS) pattern length of $2^{31}-1$ is used to directly modulate the RSOAs. Then the uplink wavelengths launch back to the HE Rx for eye diagram and bit error rate (BER) measurements through the second fiber path, as shown in Fig. 1. As a result, the 10 Gb/s uplink traffic can be performed by using four wavelength-multiplexed 2.5 Gb/s optical-injection RSOAs.

By reducing the extinction ratio of the downlink OFDM signal, higher residual optical signal can be provide for the uplink NRZ signal. We studied that by setting the extinction ratio of the OFDM signal to $\sim$4 dB, we can use the gain-saturation property of the RSOA to suppress the downlink OFDM signal and this will introduce negligible power penalty to the upstream remodulated NRZ signal.

To ensure the RSOA can be directly modulated at 2.5 Gb/s data rate, different optical injected-power level is used. We use the 1540.1 nm wavelength injecting into RSOA under different injection power. Fig. 3a–d shows the eye diagrams with the injected powers of −10, −12, −14 and −16 dBm, respectively. As shown in Fig. 3a, the clear wide open eye can be achieved with the injection power of −10 dBm. That is to say, if the RSOA want to achieve and maintain at 2.5 Gb/s modulation, the external-injection power must to be larger than −10 dBm at least.

Besides, compared with the past study [14], they proposed and demonstrated a RF up-converted OFDM signal remodulation network. The main different between their paper and our proposed scheme is that their OFDM downstream signal is 10 GHz RF up-converted, hence there are three dominant components in the optical spectrum (the centre wavelength and the first order upper and lower sidebands, as indicated in their paper). The upstream NRZ signal is then remodulated onto the three spectral components. At the upstream signal, a 2.5 GHz receiver can filter the higher frequency components and obtain the upstream 2.5 Gb/s NRZ signal. For our scheme, we are using the baseband OFDM signal. At the ONU, we are using the gain-saturation property of the RSOA to suppress the amplitude of the downstream OFDM signal. Hence, the upstream NRZ signal can be modulated onto the suppressed OFDM downstream signal.

In this measurement, the measured constellation diagrams of the downlink signal at back-to-back (B2B) and after transmission of 100 km SMF are shown in Fig. 4a. We can observe that the each

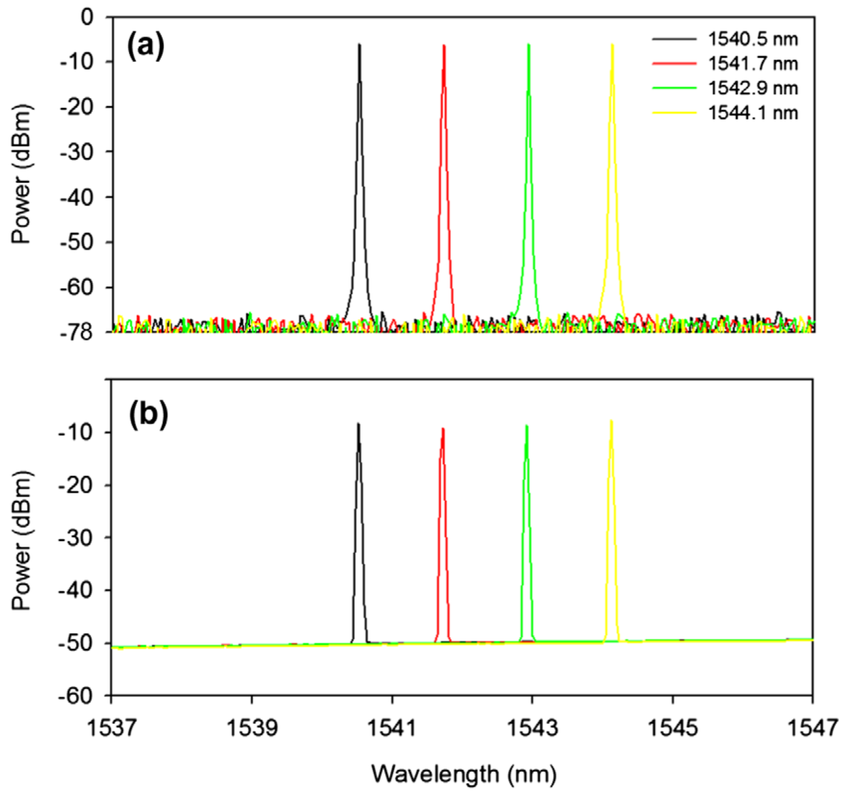

Fig. 2. (a) Four downlink spectra in OLT at the wavelengths of 1540.5, 1541.7, 1542.9 and 1544.1 nm, respectively. (b) Four output spectra of uplink when the downlink signals are injected into the RSOAs.

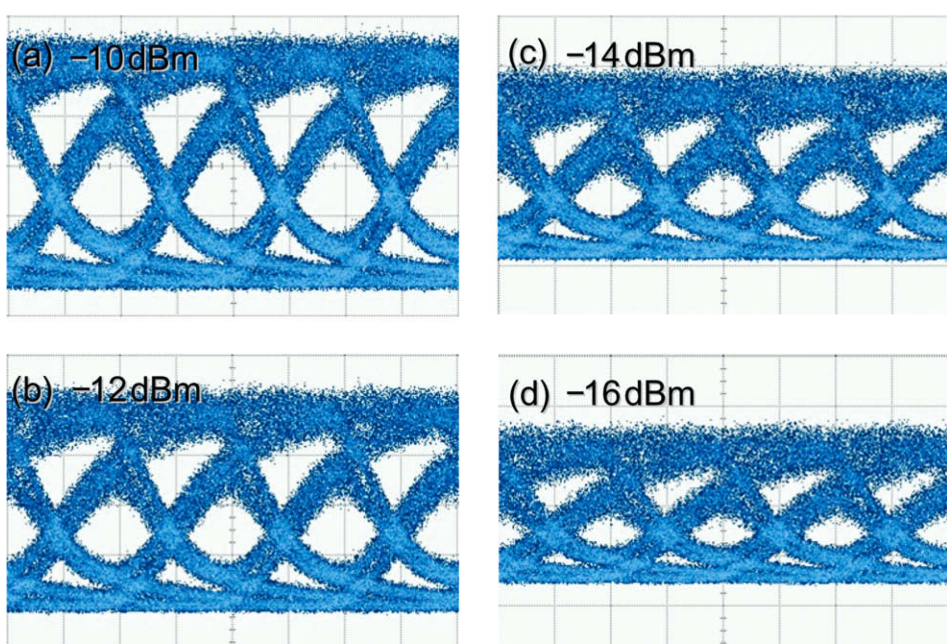

Fig. 3. The eye diagrams with the injected powers of (a) −10, (b) −12, (c) −14 and (d) −16 dBm, respectively.

constellation point, which is condensed, with good separation among others through 100 km fiber, even the extinction ratio of the OFDM signal is ∼4 dB. The results verify the baseband frequency domain equalizations have been successfully performed to demodulate the relatively low extinction ratio of the OFDM signal. Fig. 4b presents the output remodulated NRZ eye diagrams of uplink signal at B2B and 100 km transmission. It also shows the clear and wide eye open at B2B and 100 km.

Fig. 5 shows the BER measurements of both downlink and uplink traffic of the OFDM 16-QAM and NRZ remodulation at 4 and 2.5 Gb/s data traffic, respectively, at the wavelength of 1540.1 nm. About 1.8 and 1 dB power penalties of OFDM-QAM

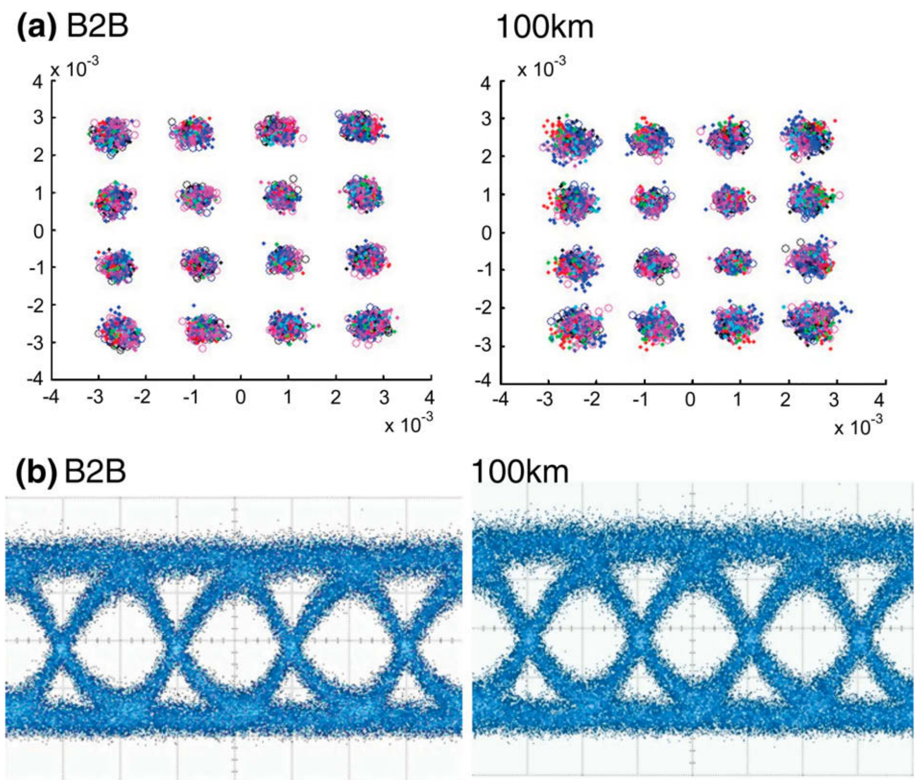

Fig. 4. (a) Constellation diagrams of OFDM signal at B2B and 100 km. (b) Output remodulated NRZ eye diagrams of RSOA at B2B and 100 km.

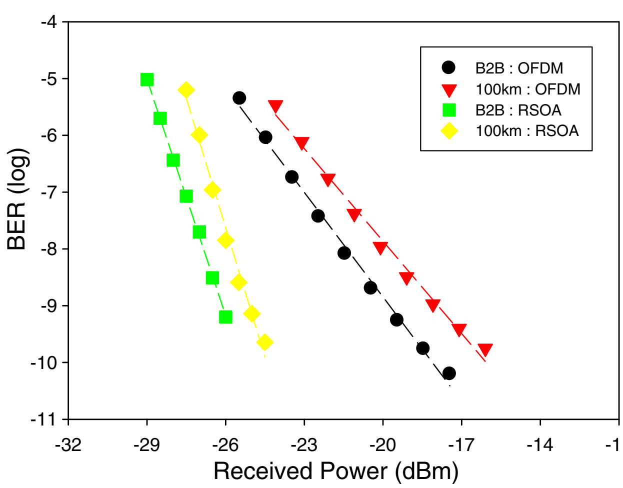

Fig. 5. BER measurements of both downlink and uplink signals with OFDM 16-QAM and NRZ remodulation with 4 and 2.5 Gb/s data traffic, respectively.

downlink and remodulated NRZ signals are observed at BER of 10^{-9} after 100 km transmission distance without dispersion compensation. The proposed ER TDM-PON architecture can be a potential candidate for the new generation 10G TDM-PON systems.

3. Conclusion

This work shows and experimentally investigates an ER-TDM-PON using four wavelength-multiplexed wavelengths to achieve 16 Gb/s downlink and 10 Gb/s uplink traffic. Here, the total data rate can be divided into four wavelengths for both downlink and uplink signals. Each downlink signal uses the highly spectral efficient 4 Gb/s OFDM-QAM modulation format, and each uplink signal is generated by remodulating the OFDM downlink signal via a reflective semiconductor amplifier (RSOA) at 2.5 Gb/s directly modulation. In this experiment, nearly 1.8 and 1 dB power penalties of OFDM-QAM downlink and remodulated NRZ signals are observed respectively at BER of 10^{-9} after 100 km transmission distance without dispersion compensation. We believe that the proposed access network scheme is the promising solution for next generation ER PON applications.

Acknowledgement

This work was supported in part by the National Science Council of ROC (Taiwan) under contract NSC 96-2218-E-009-025-MY2 and 97-2221-E-009-038-MY3.

References

[1] K. McCammon, S.W. Wong, Experimental validation of an access evolution strategy: smooth FTTP service migration path, in: OFC, 2007, Paper NThB3.
[2] P.D. Townsend, G. Talli, C.W. Chow, E.M. MacHale, C. Antony, R. Davey, T. De Ridder, X.Z. Qiu, P. Ossieur, H.G. Krimmel, D.W. Smith, I. Lealman, A. Poustie, S. Randel, H. Rohde, Long reach passive optical networks, in: IEEE LEOS Annual Meeting, 2007, Invited Paper.
[3] D.P. Shea, J.E. Mitchell, J. Lightwave Technol. 25 (2007) 685.
[4] A.B. Ruffin, J.D. Downie, J. Hurley, Purely passive long reach 10 GE-PON architecture based on duobinary signals and ultra-low loss optical fiber, in: OFC, 2008, Paper OThL4.
[5] A. Chowdhury, H.C. Chien, M.F. Huang, J. Yu, G.K. Chang, IEEE Photon. Technol. Lett. 20 (2008) 2081.
[6] C.W. Chow, C.H. Yeh, C.H. Wang, F.Y. Shih, C.L. Pan, S. Chi, Opt. Express 16 (2008) 12096.
[7] Broadband Optical Access Systems Based on Passive Optical Network (PON), ITU-T, Recommendation G. 983.1, 1998.
[8] Gigabit-capable Passive Optical Network (GPON): General Characteristics, ITU-T, Recommendation G. 984.1, 2003.
[9] Ethernet in the First Mile Task Force, IEEE 802.3ah, Draft 3.0b, 2004.
[10] 10G EPON Study Group Public Articles, <http://grouper.ieee.org/groups/802/3/av/index.html>.

[11] H.C. Chien, M.F. Huang, A. Chowdhury, J. Chen, S. Chi, G.K. Chang, A novel hybrid 10G/1G coexisted TDM-PON using central office controlled reflective transmitters for low-cost upstream 10G services, in: LEOS, 2007, Paper ThW4.
[12] C.H. Yeh, C.W. Chow, C.H. Wang, F.Y. Shih, Y.F. Wu, S. Chi, Opt. Express 16 (2008) 18857.
[13] Y.M. Lin, Demonstration and design of high spectral efficiency 4 Gb/s OFDM system in passive optical networks, in: OFC, 2007, Paper OThD7.
[14] J. Yu, M.F. Huang, D. Qian, L. Chen, G.K. Chang, IEEE Photon. Technol. Lett. 20 (2008) 1545.