Heterogeneous radio-over-fiber passive access network architecture to mitigate Rayleigh backscattering interferometric beat noise

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Abstract: We propose and experimentally demonstrate a hybrid radio-over-fiber (ROF) wavelength division multiplexed and time division multiplexed passive optical network (WDM-TDM PON) architecture to mitigate Rayleigh backscattering (RB) interferometric beat noises. Here, only a single wavelength is needed at the central office (CO) to generate the downstream baseband data for optical wired application and optical millimeter-wave (mm-wave) signal for wireless application. The upstream signal is produced by remodulating the downstream signal. No optical filter is required at the optical network unit/remote antenna unit (ONU/RAU) to separate the optical wired and optical mm-wave signals. In the proposed network, 10 Gb/s differential phase shift keying (DPSK) signal is used for the downstream optical wired application and 2.5 Gb/s on-off keying (OOK) signal on 20 GHz carrier is used for the optical mm-wave signal. In each ONU, a reflective optical semiconductor amplifier (RSOA) is used to remodulate and produce a 2.5 Gb/s OOK format for upstream traffic. As the back-refection produced by the downstream DPSK signal and the upstream OOK signal is traveling in different fiber path, RB noise at the CO can be completely mitigated

OCIS codes: (060.2330) Fiber optics communications; (290.5870) Scattering, Rayleigh; (350, 4010) Microwaves.

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1. Introduction

Recently, time-division-multiplexed (TDM) and wavelength-division-multiplexed passive optical networks (WDM-PONs) have been extensively studied for fiber to the home (FTTH) access applications due to the advantages of high-speed, huge-capacity, and cost-effectiveness etc [1–2]. Because of the high bandwidth demand (towards Exabyte (10^{18})) in the future [3], the present TDM-PON could not support this requirement. To solve this issue, hybrid WDM-TDM PON will be clearly emerging technology for next-generation access [4]. However, in such WDM-PONs, multi-wavelength sources are required in central office (CO) to produce the downstream data to different optical network unit (ONU). And, each ONU also requires a specific-wavelength to match with the corresponding wavelength at the CO. Thus, a wavelength-tunable laser is demanded in each ONU for generating upstream signal [5]. Even though it is workable to employ a tunable laser source at each ONU, the laser source is still costly in WDM-PON access. It may also delay the development of WDM-PON. Hence, carrier-distribution PON access has been studied to overcome the high deployment cost in WDM-TDM PON [6,7]. In that PON, the upstream signal of ONU is generated by the laser source of central office (CO) for centralizing management. So, the "colorless" component or reflective modulator (R-MOD) can be used in each ONU. The WDM lasers located at CO can provide the optical carrier to each R-MOD of ONU to reuse the downstream for upstream link. That is to say, each ONU do not require the expensive tunable laser source for data traffic [8,9]. Due to the colorless ONU operation, it would lead to the Rayleigh backscattering (RB) interferometric beat noise, which is produced at the receiver at central office (CO). The RB beat noise could degrade the received signal to noise ratio (SNR) and reduce the received sensitivity [10]. To avoid and mitigate the RB noise in PONs, several technologies have been developed and reported, such as using phase and bias-current dithering, advanced modulation formats, and wavelength shifting [11–14]. However, the above methods either needed the complicated modulations or employing the dithering to broaden the upstream wavelength, which would decrease the dispersion tolerance. Furthermore, to increase the capacity and mobility in access area, the integration of wireless and optical fiber networks would be the powerful solution [15]. Hence, radio-over-fiber (ROF) technology has been proposed to integrate wireless and wired network and provide the broadband service everywhere [16,17]. Furthermore, to provide full-duplex ROF access in single wavelength, an optical filter should be used to filter baseband channel or remodulated wavelength in the past studies [18,19]. Moreover, these proposed ROF networks were also without RB noise mitigation.

In this investigation, the proposed ROF WDM-TDM PON architecture not only can provide baseband data and broadcasting millimeter (mm)-wave signal simultaneously, but

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also can mitigate the RB beat noises. Here, only a single wavelength at CO is used to generate the 10 Gb/s DPSK baseband downstream and 2.5 Gb/s data on 20 GHz mm-wave for video broadcasting to each ONU/RAU in 20 km single mode fiber (SMF) transmission without using any optical filter on the CO and each ONU/RAU. Besides, the DPSK downstream can be also remodulated by reflective semiconductor optical amplifier (RSOA) in each ONU for upstream traffic at 2.5 Gb/s OOK format. As a result, we can observe that the colorless upstream signal is not affected by the RB noises since the proposed architecture allows the back-reflected RB noises and the upstream signal travel in different fiber paths.

2. Experiment and discussions

Figure 1 shows the proposed heterogeneous ROF WDM-TDM PON with RB beat noise mitigation. At the CO, the 1550.1 nm continuous-wave (CW) lightwave was split into two paths via a 1×2 and 50:50 optical coupler (CP) to generate the baseband and mm-wave signals, as illustrated in Fig. 1. We employed a single-arm Mach-Zehnder modulator (MZM) with modulation speed of 12 GHz to generate 20 GHz mm-wave signal by double side-band carrier suppression (DSB-CS) modulation for wireless video broadcasting. Here, the 2.5 Gb/s non-return-to-zero (NRZ) data, at pseudo random binary sequence (PRBS) of 2^{31}–1 pattern length, was up-converted via a RF mixer with an electrical sinusoidal signal at 10 GHz frequency. The polarization controller (PC) could be utilized to adjust the properly polarization state to keep the maximum and optimum output of the MZM. We drove the MZM to generate the DSB-CS signal by optimally adjusting the driving voltage. In Fig. 1, the erbium-doped fiber amplifier (EDFA) with 17 dBm saturated power and 5 dB noise figure was employed to compensate the losses of passive component and fiber transmission. Figure 2 shows the output spectra of the CW lightwave and mm-wave signal, observed by an optical spectrum analyzer (OSA) with a 0.05 nm resolution. The dashed and solid lines are the CW lightwave of 1550.1 nm and DSB-CS signal when the RF is driven at 10 GHz, observed at the input and output of DP-MZM, respectively.

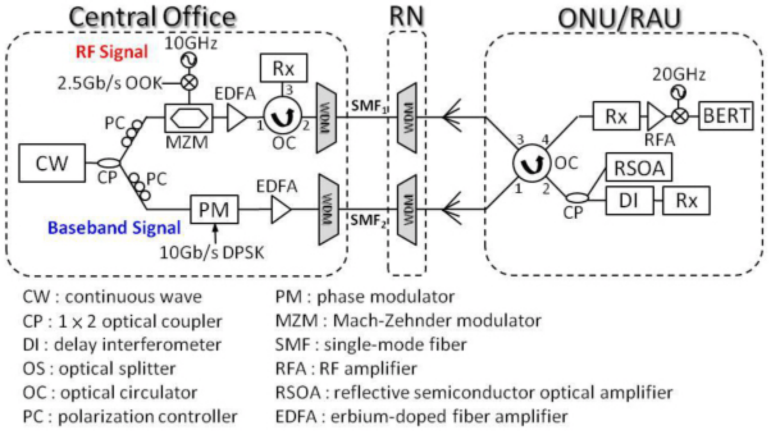

Fig. 1. Proposed hybrid ROF WDM-TDM PON system with RB noise mitigation.

The DSB-CS signal was sent from the CO via the upper fiber path (F_1) and propagated into ONU via optical circulator (OC) (port 3 → port 4) to the 40 GHz PIN receiver (Rx) for wireless broadcasting after 20 km SMF fiber propagation, as seen in Fig. 1. In the experiment, the 20 GHz mm-wave signal was down-converted to baseband for measuring the bit error rate (BER) performance in ROF-PON system. Figure 3 presents the BER curve of at the down-converted 2.5 Gb/s OOK signal at back-to-back (B2B) and 20 km fiber transmission. Thus, nearly 0.2 dB optical power penalty is obtained in Fig. 3. The inserts of Fig. 3 are the corresponding eye diagrams under B2B and 20 km fiber transmission. And, the measured eye is still wide and clear opening after 20 km fiber propagation. And, since the fiber length is

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only 20 km and the radio-over-fiber signal is only 20 GHz, the RF fading effect is negligible in this transmission length.

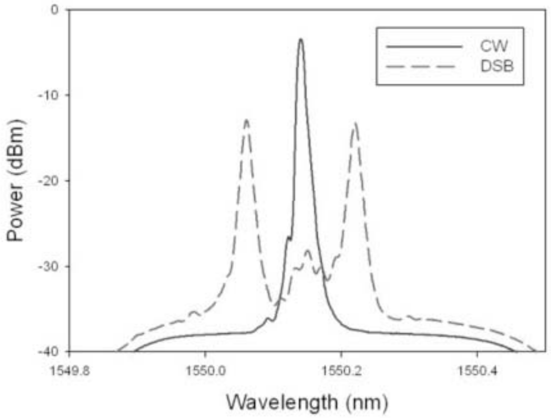

Fig. 2. Output spectra of 20 GHz mm-wave signal and CW lightwave.

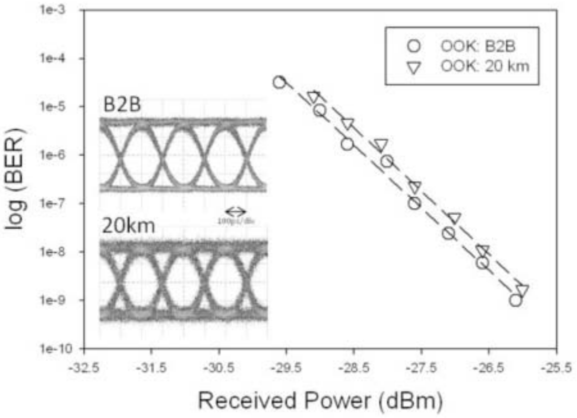

Fig. 3. BER performance of 20 GHz mm-wave signal. The insert are corresponding eye diagrams.

In baseband (downstream) traffic, the 1550.1 nm CW lightwave was modulated at 10 Gb/s DPSK format by a $LiNbO_3$ phase modulator (PM), encoding with a differentially precoded NRZ data with $2^{31}–1$ pattern length, and transmitted through the lower fiber path (F_2) into the ONU, as illustrated in Fig. 1. And the DPSK downstream signal was launched into the RSOA via an OC (port 1→ port 2). Half of the optical power was received by an optically pre-amplified receiver, which constructed by a variable optical attenuator (VOA), EDFA, delay interferometer (DI) for DPSK demodulation, and 10 GHz PIN receiver. We then measured the 10 Gb/s DPSK downstream signal received at the ONU after 20 km fiber transmission. Figure 4 shows the measured BER performance of the downstream traffic at B2B and 20 km fiber transmission. The power penalty of 1 dB was measured at the BER of 10^{-9} after 20 km fiber link. And the measured eye diagrams, which are observed in the inserts of Fig. 4, are clear and wide opening at B2B and 20 km transmission. Moreover, as shown in Fig. 1, the output power sending from the CW source at the central office was 9 dBm. Then the power was split by a 3-dB fiber coupler and hence only 6 dBm were launched to produce the RF and the baseband signals respectively. Under this power level, we have not observed any nonlinear effects that will affect the phase modulation.

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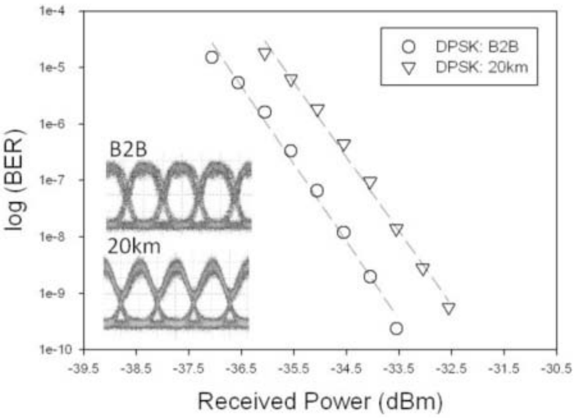

Fig. 4. BER performance of 10 GB/s DPSK downstream signal. The inserts are corresponding eye diagrams.

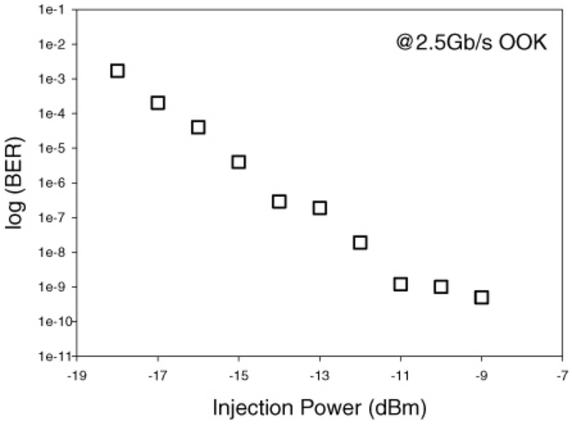

Fig. 5. BER performances versus different DPSK injection powers.

Next, the rest of the DPSK downstream power was launched into the RSOA, which operated at 80 mA, to generate the upstream signal. The upstream signal of RSOA could be remodulated at 2.5 Gb/s OOK format with the NRZ PRBS data with pattern length of $2^{31}-1$. However, the modulation rate is limited by the RSOA, higher data rate is possible in the proposed scheme. To investigate the relationship of downstream injected-power level and output performance of remodulated upstream signal first, different powers of DPSK downstream signal were injected into the RSOA for upstream remodulation. Figure 5 shows the measured BERs under different injected-power levels at 2.5 Gb/s OOK modulation, in 20 km fiber transmission. Figure 5 presents that the better BER performance depends on larger injection power. As a result, to achieve 2.5 Gb/s remodulation at the BER of 10^{-9}, the downstream injection must be larger than –10 dBm.

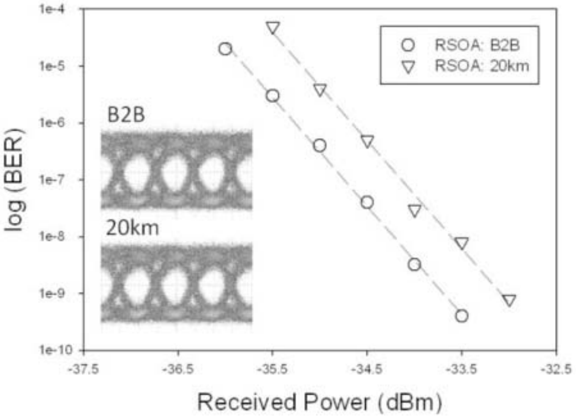

Fig. 6. Measured BERs of RSOA-based ONU at 2.5 Gb/s OOK modulation in 20 km fiber transmission. The inserts are corresponding eye diagrams.

The remodulated 2.5 Gb/s upstream signal would travel via OC (port 2 → port 3) of ONU and propagate through the upper fiber path F_1 into CO. Therefore, we can observe that the upstream signals are not affected by the RB noises since the back-refection produced by the downstream DPSK signal and the upstream OOK signal is traveling in different fiber path, illustrated in Fig. 1. Figure 6 shows the BER measurement of RSOA-based upstream signal at 2.5 Gb/s OOK modulation at B2B and 20 km fiber transmission. The power penalty of 0.5 dB is obtained at the BER of 10^{-9}, as shown in Fig. 6. The inserts of Fig. 6 are the corresponding eye diagrams at B2B and 20 km fiber link and these eyes are wide and clear opening. Acting as a modulator, the RSOA can also provide optical gain for the upstream signal. We measured that the output power of the RSOA is about 3 dBm when the input injection power is –10 dBm. By considering the insertion losses of the OC, AWG, CP and SMF are 0.5 dB, 5 dB, 3 dB and 4 dB (0.2dB/km × 20 km) respectively, and the upstream receiver sensitivity is –32 dBm (as shown in Fig. 6), we can have a power budget of about 17 dB. This implies that a typical PON split-ratio of 32 can be achieved for TDM access. Besides, for the present FTTH or FTTB architectures, 1 or 2 pairs of fibers have already been reserved for connecting to the ONU. Hence, we believe that our proposed architecture will not add extra burden to the access network.

3. Conclusion

We have proposed and experimentally demonstrated the hybrid ROF WDM-TDM PON architecture to mitigate RB noises. Here, only a single wavelength is needed at the CO to generate the downstream baseband data for optical wired application and optical mm-wave signal for wireless application. The upstream signal is produced by remodulating the downstream signal. No optical filter is required at the ONU/RAU to separate the optical wired and optical mm-wave signals. In the proposed network, 10 Gb/s differential phase shift keying (DPSK) signal is used for the downstream optical wired application with power penalty of 1 dB after 20 km SMF transmission; and 2.5 Gb/s on-off keying (OOK) signal on 20 GHz carrier is used for the optical mm-wave signal with negligible power penalty measured at the down-converted OOK signal. In each ONU, a reflective optical semiconductor amplifier (RSOA) is used to remodulate and produce a 2.5 Gb/s OOK format for upstream traffic with power penalty of 0.5 dB after 20 km SMF transmission. As the backrefection produced by the downstream DPSK signal and the upstream OOK signal is traveling in different fiber path, RB noise at the CO can be completely mitigated. As a result, the proposed WDM-TDM PON network presents the simple configuration and good transmission performance.

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