Rayleigh Backscattering Mitigation Using Wavelength Splitting for Heterogeneous Optical Wired and Wireless Access

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***Abstract*—We propose and demonstrate a heterogeneous optical access network using wavelength-splitting at remote-node to mitigate the Rayleigh backscattering (RB) noises. Two continuous-wave carriers are generated from each laser for wired and wireless applications, respectively. Results show that the scheme can effectively mitigate RB noises.**

***Index Terms*—Passive optical network (PON), radio-over-fiber (ROF) network, Rayleigh backscattering (RB).**

I. Introduction

THE convergence of optical wired and wireless networks is promising for offering subscribers with greater convenience [1], [2]. In the dense wavelength-division-multiplexing (DWDM) networks, one great challenge is to deploy the transmitter (Tx) at the optical networking unit (ONU)/remote antenna unit (RAU) cost-effectively. Hence, colorless ONU/RAU is desirable [3]. Although the carrier-distributed networks are attractive, Rayleigh backscattering (RB) is one of the most dominant impairments. For effective RB mitigation, we can reduce the spectral overlap between the upstream signal and the RB noise; hence, most of the electrical beat frequency will fall outside the electrical receiver (Rx) bandwidth at head-end. Using optical light source scrambling [4] has been proposed. However, the effect of suppressing both types of RB noises is limited. Advanced modulation formats [5]–[7] and optical carrier suppression with optical interleaver [8] have been proposed but they required complicated modulation and demodulation schemes. Here, we demonstrate a heterogeneous DWDM time-division-multiplexed (TDM) network using wavelength splitting (WS) for RB mitigation. The scheme only needs one modulator at the remote node (RN) for all the DWDM channels. Cost could be minimized by locating the erbium-doped fiber amplifiers (EDFAs) and modulator for WS at the RN, where power supply for temperature stabilizing the arrayed waveguide grating (AWG) could be already present. We believe that the improvement of signal quality and passive optical network (PON) split-ratio by significant mitigation of the RB noises could justify the additional cost of the scheme. It is worth mentioning that the scheme can only mitigate RB in the feeder fiber. Transmission experiments are performed by encoding the nonreturn-to-zero (NRZ) and orthogonal frequency-division-multiplexing–quadrature-amplitude-modulation (OFDM-QAM) data onto the upstream signals for PON and radio-over-fiber (ROF) applications, respectively. An extension of the network analysis with different split-ratios is presented in this letter and first results can be found in [9].

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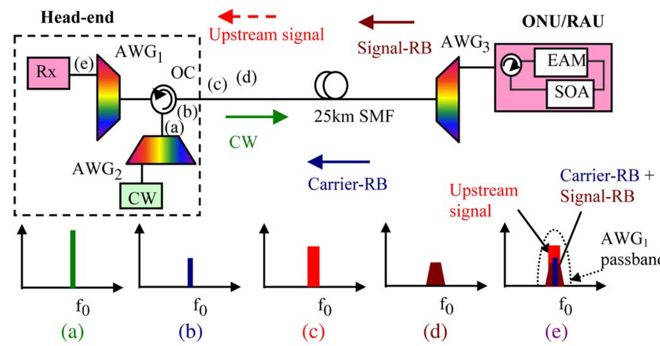

Fig. 1. Typical architecture of carrier distributed network with different schematic optical spectra at different locations.

II. Network Architecture and RB Contribution

For a typical carrier-distributed network, there are two types of RB noises, called carrier-generated RB (Carrier-RB) and signal-generated RB (Signal-RB). As shown in Fig. 1, the backscatter of the continuous-wave (CW) carrier [Fig. 1(a)] can produce the Carrier-RB [Fig. 1(b)]. At the output of the ONU/RAU, where the upstream data [Fig. 1(c)] is produced, the backscattered upstream signal re-enters the ONU/RAU and is launched towards the head-end Rx, forming the Signal-RB [Fig. 1(d)]. We can observe from Fig. 1(e) that the upstream signal, Carrier-RB, and Signal-RB have strong spectral overlapping.

Fig. 2 shows the proposed network. The CW carrier at optical frequency f_0 [Fig. 2(a)] distributed from the head-end will be modulated by a Mach–Zehnder modulator (MZM) at the RN, which was electrically driven at Δf (25 GHz). The Carrier-RB will be generated by the CW carrier [Fig. 2(b)]. The MZM at the RN will produce two optical sidebands which is 50 GHz apart with suppression of the center wavelength

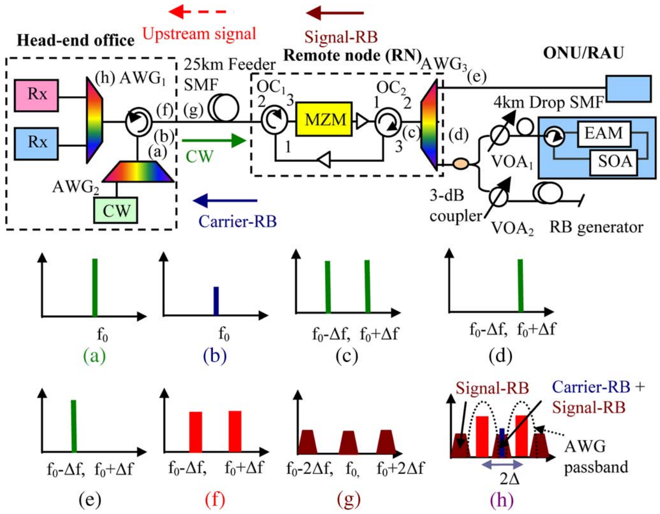

Fig. 2. Architecture of wired and wireless network using wavelength splitting, with different schematic optical spectra at different locations.

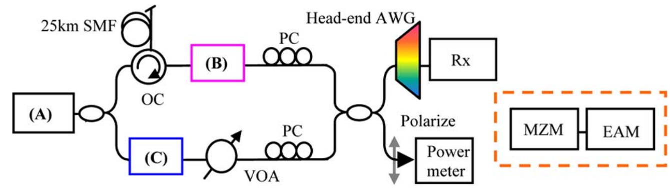

Fig. 3. Experimental setup for OSRNR analysis.

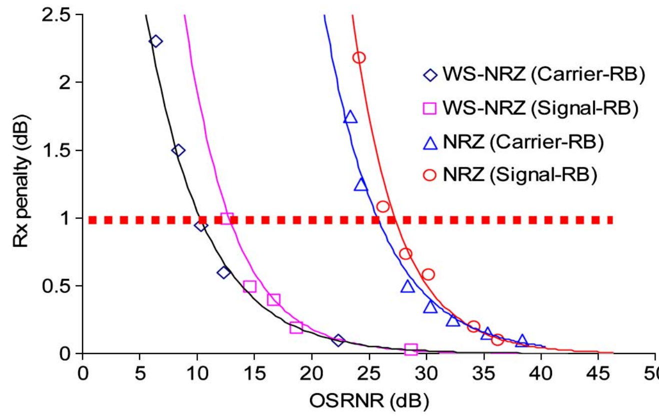

Fig. 4. RB performance at different OSRNRs of WS scheme and conventional NRZ signal.

[Fig. 2(c)]. The EDFAs and the MZM are located at the RN. Then, each sideband was filtered by a 50-GHz channel spacing arrayed waveguide grating (AWG_3), producing a pair of optical carriers $(f_0 + \Delta f, f_0 - \Delta f)$ [Fig. 2(d), (e)]. Polarization-insensitive MZM [10] can be used. AWG_1 and AWG_3 were aligned to $f_0 + \Delta f$, while AWG_2 was aligned to f_0. The two optical carriers $(f_0 + \Delta f, f_0 - \Delta f)$ will be modulated at the ONU/RAU, forming the upstream signals for PON and ROF, respectively [Fig. 2(f)]. Semiconductor optical amplifiers (SOAs) are used in the ONU/RAU to compensate the loss. The upstream signals will bypass the MZM in the RN by using the two optical circulators (OCs) configuration, and detected by the head-end Rx. The upstream data will also be backscattered by the single-mode fiber (SMF) towards the RN, where it will be wavelength split again, and blocked by the AWG_3. Back-reflection by the AWG_3 and the power leakage by the OC_2 will contribute to the Signal-RB launching to the head-end Rx [Fig. 2(g)]. As shown in the schematic optical spectra of Fig. 2(h) at the head-end before AWG_1, the Carrier-RB is at frequency f_0, while the double-modulated Signal-RB has the frequency components of f_0 and $f_0 \pm 2\Delta f$. This shows that ideally there is no spectral overlap between the upstream data and both types of RB. Besides, the frequency components of the RB will be highly attenuated by the AWG_1.

The scheme can only mitigate the RB in the feeder fiber (Fig. 2). However, most of the RB is generated in this fiber because it usually accounts for most of the access length, and because the RB generated in the drop fiber is attenuated by the fiber splitter. Although the RB noises, both Carrier-RB and Signal-RB, generated in the drop fiber are in-band, and still propagate to the head-end Rx, the overall RB power is greatly reduced.

III. Results and Discussion

By using the techniques described in [7], we can separately study the Carrier-RB and Signal-RB performances in terms of optical signal-to-Rayleigh-noise ratios (OSRNRs), as shown in Fig. 3. The OSRNR is defined as the ratio of the upstream signal power to the RB power measured prior to the head-end AWG (Fig. 3). WS signal $f_0 + \Delta f$ (encoded by 2.5-Gb/s NRZ data) was used to compare with the conventional NRZ signal without WS. For the Carrier-RB analysis, (A) was a CW signal, which was split by a 3-dB fiber coupler. The upper path was used to generate the Carrier-RB and hence (B) was a fiber patch cord. The Carrier-RB produced by a 25-km SMF, terminated with an angled connector, was extracted via an OC. In the lower path, the CW was modulated at (C), which was an MZM electroabsorption modulator (MZM-EAM) (inset of Fig. 3) to produce the WS-NRZ signal. A VOA was used to adjust the data power to generate different OSRNRs. The Carrier-RB and the data signal were then copolarized (highest beat noise case) by using the polarization controllers (PCs). They were combined and detected by the Rx. In the Signal-RB analysis, (A) consisted of a CW and the MZM-EAM to produce the WS-NRZ signal. In the upper path, the backscattered data signal by the 25-km SMF was modulated again at (B) by another set of MZM-EAM after the OC to generate the Signal-RB. In the lower path, (C) was just a fiber patch cord. The Signal-RB and the data signal from the lower path were then combined before being launched into the Rx.

Fig. 4 shows the Rx power penalties at a bit-error rate (BER) of 10^{-9} for different OSRNRs. The WS scheme significantly improves the required OSRNR ($\sim$13 dB) by wavelength shifting the upstream signal away from the center wavelength.

For the network experiment as shown in Fig. 2, the CW of 1549.5 nm, optical power of 7 dBm was launched from the head-end office. It entered the RN via an AWG (loss $=$ 5 dB), an OC (loss $=$ 0.5 dB), and 25-km standard SMF feeder fiber (attenuation $=$ 0.2 dB/km). The inset of Fig. 5 shows the experimental optical spectra produced by a 40-Gb/s $LiNbO_3$-based MZM (loss $=$ 5 dB) at the RN. It was electrically driven by a 25-GHz sinusoidal signal. The black curve indicates one of the sidebands for PON application. EDFAs (gain $=$ 27 dB, saturation power $=$ 23 dBm, noise figure $=$ 5 dB) were used at the RN to compensate the transmission loss. The ONU/RAU was constructed by an EAM (loss $=$ 6 dB) and an SOA (gain $=$ 18 dB, noise figure $=$ 7 dB). The head-end

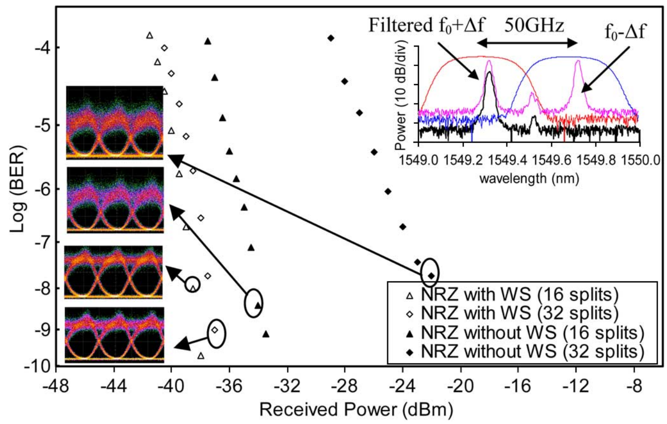

Fig. 5. BER of NRZ signals in the carrier distributed network with and without WS. Insets: corresponding eye diagrams. Inset: Optical spectra of the $f_0 - \Delta f$, $f_0 + \Delta f$ generated by the MZM.

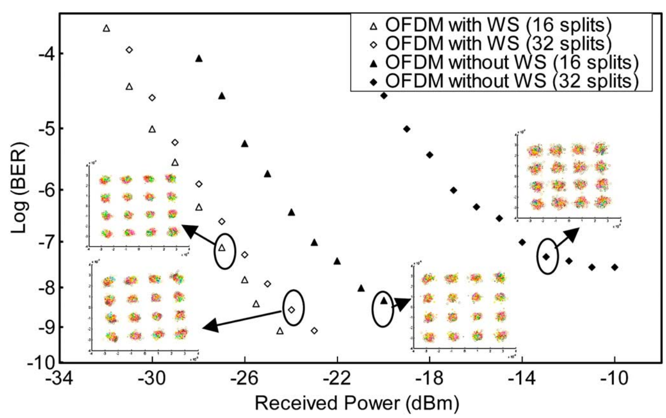

Fig. 6. BER of OFDM signals in the carrier distributed network with and without WS. Insets: corresponding constellation diagrams.

Rx was optically preamplified using EDFA (gain $=$ 23 dB, noise figure $= 4.5$ dB). We estimated the power budget for the OFDM signal at 32 splits is ~22 dB when an optically preamplified Rx was used.

We also evaluated the transmissions of the upstream signals by encoding the NRZ (for PON) and OFDM-QAM (for wireless) in the proposed network without and with using WS. A 2.5-Gb/s pseudorandom binary sequence (PRBS) $2^{31} - 1$ NRZ signal and 16-QAM OFDM signal were applied to the EAM, respectively. The OFDM signal consisted of 16 subcarrier symbols and in 16-QAM format, generated by an arbitrary waveform generator with 4-GHz sampling rate. The OFDM signal was RF up-converted, occupying ~1 GHz of RF spectrum (from 62.5 to 1125 MHz). The total data rate of the OFDM signal was 4 Gb/s. The BER performance of the OFDM was calculated from the measured error vector magnitude (EVM).

VOA_1 was used to emulate the split ratio of the DWDM-TDM PON. Attenuations (produced by the VOA_1 and the 3-dB coupler) of >12 and >15 dB emulated 16 and 32 split ratios, respectively. An RB noise generator consisted of VOA_2 and 25-km SMF described in [11] was used to emulate the RB generated from the 16 and 32 different TDM branches. Figs. 5 and 6 show the BER performances of the NRZ and OFDM signals with and without WS. A ~4-dB power penalty was observed in the NRZ signal (16 split-ratios) without WS. Error-floor at 10^{-8} was observed when the split-ratios were increased to 32. In Fig. 6, error-floors of 10^{-9} and 10^{-8} were observed in the OFDM signal with 16 and 32 splits, respectively, when WS was not used. Results show that the proposed scheme could significantly mitigate the RB noises. Since the scheme can only mitigate the RB in the feeder fiber (Fig. 2), we also evaluated different drop fiber lengths. We obtained similar BER results when using 200 m and 4-km SMF drop fibers between the VOA_1 and the ONU/RAU, showing that the scheme is effective under typical feeder and drop fiber lengths. The negligible effect introduced by the drop fiber is due to the much shorter length in the drop fiber (4 km) and the RB generated in the drop fiber is highly attenuated by the splitting (VOA_1).

IV. Conclusion

We demonstrated a heterogeneous DWDM-TDM access network using WS to mitigate the RB noises. Transmission experiments are performed for PON and ROF applications respectively. Results showed that the proposed network can effectively mitigate RB noises.

References

[1] G. K. Chang, J. Yu, Z. Jia, and J. Yu, "Novel optical-wireless access network architecture for simultaneously providing broadband wireless and wired services," presented at the Proc. OFC, Anaheim, CA, 2006, Paper OFM1.

[2] Z. Jia, J. Yu, A. Chowdhury, G. Ellinas, and G. K. Chang, "Simultaneous generation and delivery of independent wired and wireless services in radio-over-fiber systems using a single modulator," presented at the Proc. ECOC, Berlin, Germany, 2007, Paper 3.3.2.

[3] L. Y. Chan, C. K. Chan, D. T. K. Tong, F. Tong, and L. K. Chen, "Upstream traffic transmitter using injection-locked Fabry–Pérot laser diode as modulator for WDM access networks," *Electron. Lett.*, vol. 38, pp. 43–45, 2002.

[4] I. T. Monroy, E. Tangdiongga, R. Jonker, and H. de Waardt, "Interferometric crosstalk reduction by phase scrambling," *J. Lightw. Technol.*, vol. 18, no. 5, pp. 637–646, May 2000.

[5] Z. Li, Y. Dong, Y. Wang, and C. Lu, "A novel PSK-Manchester modulation format in 10-Gb/s passive optical network system with high tolerance to beat interference noise," *IEEE Photon. Technol. Lett.*, vol. 17, no. 5, pp. 1118–1120, May 2005.

[6] C. W. Chow, G. Talli, A. D. Ellis, and P. D. Townsend, "Rayleigh noise mitigation in DWDM LR-PONs using carrier suppressed subcarrier-amplitude modulated phase shift keying," *Opt. Express*, vol. 16, pp. 1860–1866, 2008.

[7] C. W. Chow, G. Talli, and P. D. Townsend, "Rayleigh noise reduction in 10-Gb/s DWDM-PONs by wavelength detuning and phase-modulation-induced spectral broadening," *IEEE Photon. Technol. Lett.*, vol. 19, no. 6, pp. 423–425, Mar. 15, 2007.

[8] A. Chowdhury, H.-C. Chien, M.-F. Huang, J. Yu, and G.-K. Chang, "Rayleigh backscattering noise-eliminated 115-km long-reach bidirectional centralized WDM-PON with 10-Gb/s DPSK downstream and remodulated 2.5-Gb/s OCS-SCM upstream signal," *IEEE Photon. Technol. Lett.*, vol. 20, no. 24, pp. 2081–2083, Dec. 15, 2008.

[9] C. W. Chow, L. Xu, F. Y. Shih, Y. F. Wu, C. H. Yeh, H. K. Tsang, and S. Chi, "Using wavelength splitting at the remote node to mitigate rayleigh backscattering for optical wired and wireless access networks," presented at the Proc. OFC 2010, San Diego, CA, Paper OWQ4.

[10] O. Leclerc, P. Brindel, D. Rouvillain, E. Pincemin, B. Dany, E. Desurvire, C. Duchet, E. Boucherez, and S. Bouchoule, "40 Gbit/s polarization-insensitive and wavelength-independent InP Mach–Zehnder modulator for all-optical regeneration," *Electron. Lett.*, vol. 35, pp. 730–732, 1999.

[11] G. Talli, C. W. Chow, E. K. MacHale, and P. D. Townsend, "Rayleigh noise mitigation in long-reach hybrid DWDM-TDM PONs," *J. Opt. Netw.*, vol. 6, pp. 765–776, 2007.