# Rayleigh Noise Mitigation Using Single-Sideband Modulation Generated by a Dual-Parallel MZM for Carrier Distributed PON

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***Abstract*—Hybrid passive optical networks (PONs) with a centralized light source (CLS) could be a promising solution for the next-generation PON. However, the network with a loop-back architecture will give rise to interferometric noise caused by Rayleigh backscattering (RB). Here, we propose and demonstrate a colorless optical networking unit (ONU) using a dual-parallel Mach–Zehnder modulator (DP-MZM) to mitigate RB noise in a hybrid wavelength-division-multiplexing–time-division-multiplexing PON with CLS. Both dominant contributions of RB, carrier RB and signal RB, are experimentally characterized, for the first time, when using a DP-MZM as a reflective ONU. In addition, the split-ratio of a long-reach PON using the DP-MZM-based ONU is also investigated and analyzed, showing RB noise can be efficiently reduced.**

***Index Terms*—Hybrid passive optical networks (PONs), Rayleigh backscattering (RB), single sideband (SSB).**

## I. INTRODUCTION

HYBRID wavelength-division-multiplexing–time-division-multiplexing passive optical network (WDM-TDM PON) has attracted much attention recently. By integrating the WDM and TDM technologies, the challenges of upgrading the existing network capacity of tree topology TDM PON could be overcome by implementing WDM to extend the capacity of optical networks without drastically changing the fiber infrastructure. Due to the bandwidth-sharing nature of the TDM PON, hybrid WDM-TDM PON offers a relative lower per-subscriber cost than pure WDM PON by dividing a single wavelength channel to multiple subscribers, while still maintaining a relatively high per-subscriber bandwidth [1]–[3].

In a WDM system, one of the most critical issues is the cost of the laser source used in the cost-sensitive subscriber side where the wavelengths for subscribers should be precisely aligned with an associated WDM link. Recently, PON architecture with a centralized light source (CLS) has been proposed to reduce the cost by removing the laser source from the subscriber side. This can be achieved by employing a wavelength-insensitive reflective modulator at the customer optical networking unit (RONU) together with a seed light provided from the central office (CO) for wavelength addressing [4], [5]. By implementing the WDM-PON in a loop-back configuration, the CLS is modulated with the uplink data at the RONU and sent back to the CO. Thus, the cost of these carrier distributed WDM-PONs could be significantly decreased.

However, a loop-back network will suffer from the interferometric noise caused by Rayleigh backscattering (RB) and localized Fresnel back-reflections [6]–[8], which interfere with the uplink signal at the receiver (Rx) at the CO. Several methods have been proposed to improve the system performance, such as using a dual-feeder fiber approach together with a novel detuned filtering and spectral broadening scheme [8]; using a phase-modulation-induced spectral broadening and offset optical filtering scheme [9]; and using wavelength shifting in cascade modulators [10]. However, the methods mentioned above either require installation of new fibers or are not power-efficient for the power-budget-sensitive PON (more than half of the uplink power will be filtered out by the offset filtering schemes or high insertion loss in the cascade modulator scheme). When compared with [10], we used an integrated dual-parallel Mach–Zehnder modulator (DP-MZM) to replace the cascaded single-arm MZM and dual-arm MZM to reduce the insertion loss and the cost. In addition, we used commercially available DP-MZM (also called differential quadrature phase-shift-keying (DQPSK) modulator) for the demonstration, while [11] requires a special modulator design.

In this work, we propose and investigate the RB noise reduction by using a DP-MZM as the RONU in a hybrid WDM-TDM PON with CLS. By employing a single-sideband carrier-suppressed (SSB-CS) modulation scheme, the RB tolerance can be improved due to the reduced spectral overlap between the uplink signal and the RB noises. Both dominant contributions of RB: carrier RB (CB) and signal RB (SB) were experimentally characterized, for the first time, when using a DP-MZM as an RONU. In addition, numerical simulations are performed, and the results are in good agreement with the experiment. Finally, a full network experiment is performed using DP-MZM to mitigate the RB noises for the hybrid WDM-TDM PON and long-reach (LR) WDM-TDM PON.

## II. EXPERIMENTS AND RESULTS

Fig. 1 illustrates the RB contributions in a hybrid WDM-TDM PON architecture using centrally distributed carrier and RONU. The CLS is distributed from the CO and passes through a single feeder fiber towards the RONU to

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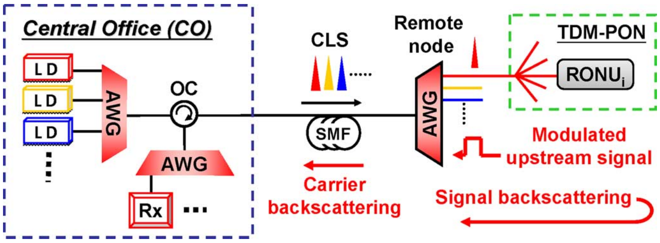

Fig. 1. RB contributions in a carrier distributed hybrid WDM-TDM PON architecture with RONU.

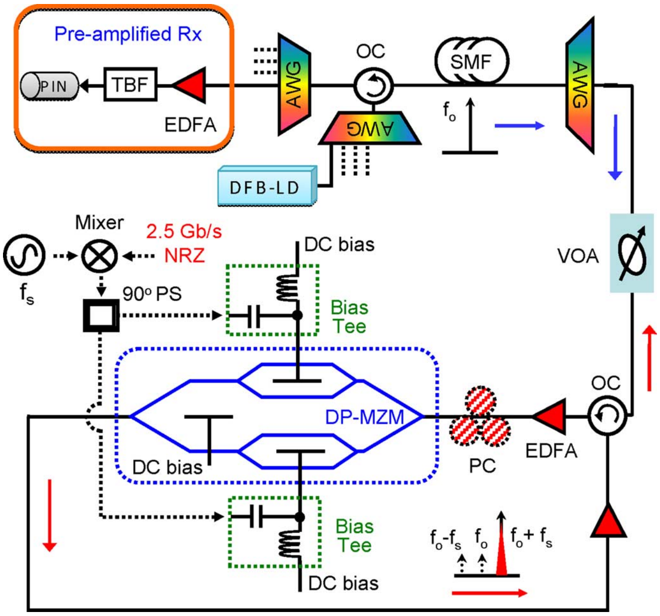

Fig. 2. Proposed carrier distributed PON using DP-MZM as RONU. EDFA: erbium-doped fiber amplifier; TBF: tunable bandpass filter; VOA: variable optical attenuator; OC: optical circulator; PC: polarization controller; PS: phase shifter; 90° PS: 90° hybrid power splitter.

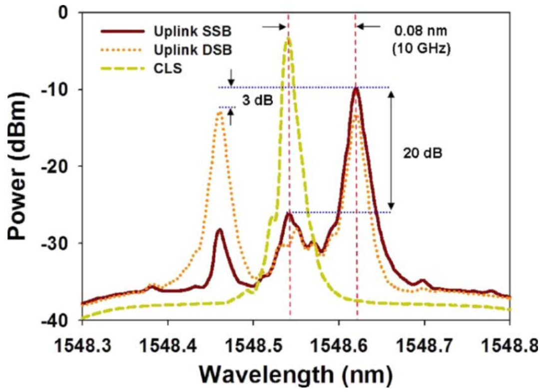

Fig. 3. Measured optical spectra. Solid line: SSB-CS uplink signal. Dotted line: DSB-CS uplink signal. Dashed line: CLS.

generate the uplink signal. There are two contributions to RB, which are generated by the intrinsic phenomenon in fiber propagation. The two contributions will beat with the uplink signal to generate interferometric noise at the Rx inside the CO. The first contribution, CB, is generated by the back reflection of the CLS seeding to the RONU. The second contribution, SB, is generated by the back reflection of the uplink signals at the output of the RONU. The backscattered light re-enters and is remodulated by the RONU, then launched towards the CO Rx.

Fig. 2 shows the experimental setup of the fully passive carrier distributed PON using DP-MZM as the RONU. A distributed-feedback laser diode (DFB-LD) set at 1548.54 nm ($f_0$) was used as a CLS. The CLS was transmitted through 25- or 75-km standard single-mode fiber (SMF) towards the RONU, via an arrayed waveguide grating (AWG) (Gaussian-shaped 3-dB width of 50 GHz). There is no active component between the CO and the ONU, and the carrier distributed PON is fully passive. A variable optical attenuator (VOA) was used to emulate the PON split-ratio. In the colorless ONU, a loop-back configuration was achieved by an optical circulator (OC). A polarization controller (PC) was used to control the polarization state to maintain the optimum modulation of our proposed DP-MZM. The DP-MZM was commercially available with a modulation speed of 12 GHz. The baseband 2.5-Gb/s non-return-to-zero (NRZ) data at pseudorandom binary sequence (PRBS) $2^{31} - 1$ was up-converted via a radio-frequency (RF) mixer with an electrical sinusoidal signal at frequency $f_s$ (10 GHz) generated by an RF signal synthesizer. The 2.5-Gb/s upstream data was used due to the bandwidth limitation of the mixer. It is worth mentioning that this scheme could be operated at a higher data rate. The up-converted NRZ data was then split into two paths by a 90° hybrid power splitter (PS) before being launched into the DP-MZM. The DP-MZM was driven in-phase and quadrature-phase, at arm 1 and arm 2, respectively, by the up-converted NRZ data with proper dc biases. Then the optical SSB-NRZ can be optimized by adjusting the driving voltage of arm 3. Erbium-doped fiber amplifiers (EDFAs) (gain = 23 dB, noise figure = 5 dB) were used in the ONU to compensate the losses of the fiber transmission. For LR and/or high split-ratio networks, optical amplifiers, such as EDFA, or semiconductor optical amplifier (SOA), are usually considered [8]. In this proof-of-concept demonstration, a commercially available LiNbO$_3$-based modulator was used, but alternative schemes using polarization-insensitive semiconductor modulators could be more practical [12]. Cost can be reduced by integrating the SOA with the semiconductor modulator. The uplink signal was then sent back to the CO through the same SMF. An optical preamplified Rx at the CO, consisting of an EDFA, a tunable bandpass filter (TBF) (3-dB width of 50 GHz), and a PIN (bandwidth of 3 GHz), was used to receive the uplink signal. No dispersion compensation was used in the experiment.

Fig. 3 shows the optical spectra measured by an optical spectrum analyzer with a resolution of 0.01 nm. The dashed line is the distributed CLS at a wavelength of 1548.54 nm measured at the input of the DP-MZM. The solid and dotted lines are the SSB-CS and double-sideband (DSB)-CS NRZ modulated uplink signals with RF driven at $f_s = 10$ GHz measured at the output of the DP-MZM. We can observe that the SSB-CS signal can save ~3-dB power when compared with the DSB-CS signal. This implies that the split-ratio of the PON could be improved when compared with the DSB-CS modulation with offset optical filtering [9], [13]. For the SSB-CS uplink signal, the power ratios of the upper sideband to the lower sideband and center wavelength are >20 dB. Since the RB tolerance depends on the interferometric beat noise falling within the Rx bandwidth, the RB tolerance of the SSB-CS modulation can be significantly improved due to the reduced spectral overlap with the CLS.

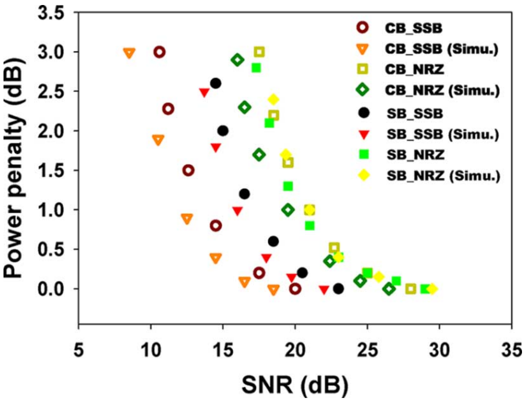

Fig. 4. CB and SB performances at different SNR.

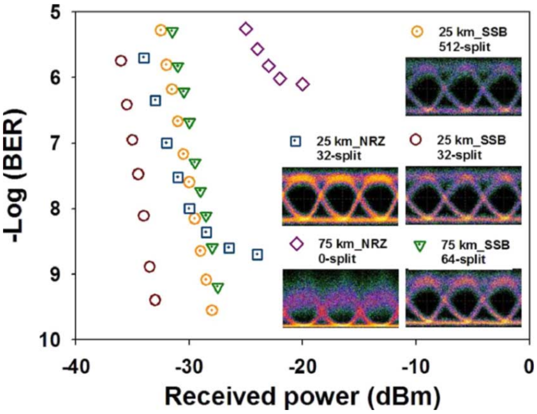

Fig. 5. BER performances of uplink SSB-NRZ (case 1) and conventional NRZ (case 2) signals with different split ratios in the transmission link. Insets show the corresponding eye diagrams.

The RB tolerance by using the experimental setup described in [9] was performed in terms of optical signal power to RB noise power ratio (SNR). The Rx power penalties at a bit-error rate (BER) of $10^{-9}$, as shown in Fig. 4, were measured by experiment and confirmed by numerical simulation (VPI Transmission Maker V7.5). The SSB-CS NRZ modulation improves the SNR by 6.5 and 3.5 dB in the CB and SB cases, respectively, at 1-dB power penalty when compared to a conventional NRZ signal. For the conventional NRZ signal, due to the entire spectral overlap between the uplink signal and the RB components, the BER can be seriously degraded even at relatively low levels of RB.

Here, the split-ratio of our proposed scheme was also investigated and compared. Fig. 5 shows the BER performances of the SSB-CS NRZ with $f_s = 10$ GHz and the conventional NRZ signals with a different split-ratio in the transmission link, in the loop-back network, as shown in Fig. 2. The results show that the power penalties of SSB-CS NRZ signals were significantly improved when compared to the conventional NRZ signal. The corresponding eye diagrams are shown in the insets. For the SSB-CS NRZ signal, a high split-ratio of 512 was achieved after transmission of 25-km SMF, and also can reach up to 64-split after transmission of 75-km SMF. For the conventional NRZ signal, the error-floor appears when the split-ratio is 32 after 25-km SMF transmission, and the signal can hardly be detected after 75-km SMF transmission. For the network experiment (Fig. 2), it is difficult to separately analyze the effects of CB, SB, and the total back reflections introduced by different optical components. For the 75-km SMF and 64-split transmission, due to the additional attenuation by the SMF and the split-ratio, the SNR is much lower than the case of 25-km SMF and 32-split. Because of the low SNR, high power penalty and error-floor appear for the NRZ signal at 75-km SMF and 64-split transmission, as shown in Fig. 5. A 10-Gb/s data rate of the NRZ signal is also possible. However, since 10-Gb/s data has a higher bandwidth, the frequency shift ($f_s$) should be increased correspondingly to reduce the spectral overlap between the uplink signal and the RB noises.

## III. CONCLUSION

Using DP-MZM to mitigate RB noises in a fully passive bidirectional carrier distributed PON was demonstrated. By employing SSB-CS modulation, the RB tolerance is efficiently improved by 6.5 and 3.5 dB for CB and SB, respectively, when compared with the conventional NRZ signal. A high spilt ratio of 512 and 64 was achieved in the SMF transmission of 25 and 75 km, respectively. The results show that our proposed scheme could be a potential candidate for RB mitigation.

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