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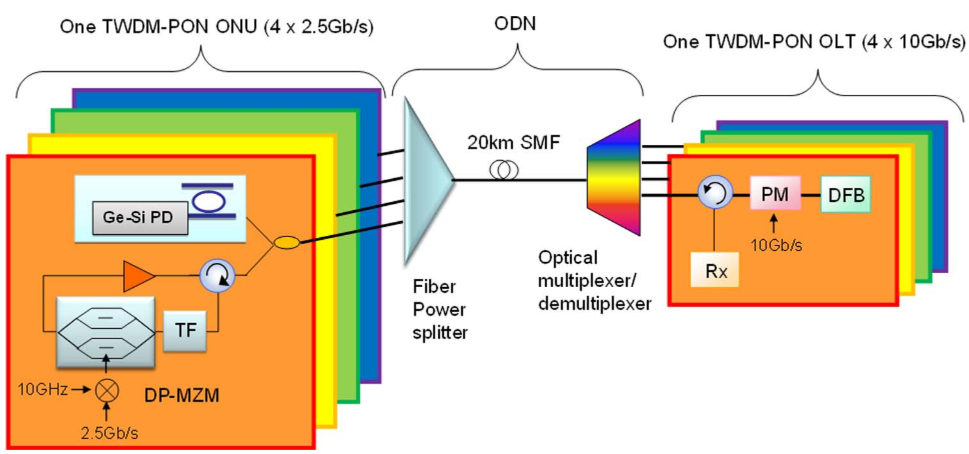

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TWDM-PON With Signal Remodulation and Rayleigh Noise Circumvention for NG-PON2

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Abstract: We propose and demonstrate a 40-Gb/s (4×10 Gb/s) downstream and 10-Gb/s (4×2.5 Gb/s) upstream time–wavelength-division-multiplexed passive optical network (TWDM-PON) using signal remodulation. Here, a downstream differential-phase-shift-keying (DPSK) signal and an upstream remodulated carrier-suppressed single-sideband non-return-to-zero (CS-SSB-NRZ) signal are used, which are wavelength shifted to circumvent Rayleigh backscattering (RB). A silicon-based optical microring resonator (MRR) filter is preinstalled at the optical networking unit (ONU) to select the desired downstream wavelength and simultaneously demodulate the downstream DPSK signal, which is then detected by a monolithic-integrated germanium-on-silicon (Ge-Si) photodiode (PD). Using silicon-based devices could be cost effective for the cost-sensitive ONU. The future monolithic integration of a silicon filter, a silicon detector, and a silicon modulator in the ONU is also discussed. The characteristics of the preinstalled silicon-based MRR and the Ge-Si PD are discussed. Error-free transmission (bit-error rate (BER) $< 10^{-9}$) is achieved in both downstream and remodulated upstream signals after propagating through 20 km of standard single-mode fiber (SMF).

Index Terms: Optical communications, noise mitigation, wavelength-division-multiplex passive optical network (WDM-PON), differential-phase-shift-keying (DPSK).

1. Introduction

A huge increase in bandwidth demand has been observed in recent years due to the introduction of different broadband applications. The traditional time-division-multiplexed passive optical networks (TDM-PON) could not satisfy this bandwidth demand. Hence, different organizations have proposed different network architectures to cope with the bandwidth demand. The Full Service Access Network (FSAN) has started to look for potential future-proof access solutions [1]. It has divided the PON evolution into two stages. The first stage is the next-generation PON (NG-PON1), which includes the XG-PON supporting the maximum downstream and upstream data rates of 10 Gb/s and 2.5 Gb/s, respectively. The second stage is the NG-PON2, which is required to provide a capacity of 40 Gb/s downstream and 10 Gb/s upstream. For, the NG-PON2, many network operators have proposed different solutions [2]. These solutions include using serial 40G TDM-PON [3], [4], orthogonal frequency division multiplexed (OFDM) PON [5], [6], and time-wavelength-division-multiplexed (TWDM) PON [7], [8]. Among these architectures, TWDM-PON is considered as a primary architecture for NG-PON2, and it can highly reuse the existing optical distribution network (ODN), with less destruction and less capital investment. A state-of-the-art TWDM-PON has been reported recently [9]. However, these proposals [7], [8] need tunable transmitters (Txs) and tunable receivers (Rxs) in the cost-sensitive optical networking units (ONUs).

In this work, we propose and demonstrate a 40 Gb/s (4×10 Gb/s) downstream and 10 Gb/s (4×2.5 Gb/s) upstream TWDM-PON using signal remodulation. Signal remodulation [10]–[12] reuses the downstream signal to generate the upstream signal; hence, only one wavelength is needed for both upstream and downstream signals. This can simplify the wavelength management. Colorless ONU can be implemented using reflective optical modulator. Here, downstream differential-phase-shift-keying (DPSK) signal and upstream remodulated carrier-suppressed single-sideband non-return-to-zero (CS-SSB-NRZ) signal are used. The optical spectrum of the upstream CS-SSB-NRZ signal is wavelength-shifted to circumvent Rayleigh backscattering (RB) [13]. A silicon-based optical micro-ring resonator (MRR) filter is pre-installed at the ONU to select the desired downstream wavelength and simultaneously demodulate the downstream DPSK signal, which is then detected by a monolithic-integrated germanium-on-silicon (Ge-Si) photodiode (PD) [14]. Using silicon-based devices could be cost-effective for the cost-sensitive ONU. Future monolithic integration of silicon filter, silicon detector and silicon modulator in the ONU is also discussed. Part of the downstream DPSK signal is remodulated to produce the upstream CS-SSB-NRZ signal sending to the optical line terminal (OLT). The characteristics of the pre-installed silicon-based MRR and the Ge-Si PD are discussed. Error-free transmission (bit-error-rate (BER) $< 10^{-9}$) is achieved in both downstream and remodulated upstream signals after propagating through 20 km of standard single mode fiber (SMF) without dispersion compensation.

The architecture of the proposed TWDM-PON using signal remodulation is presented in Section 2. The experimental results and analysis for the downstream DPSK demodulation and detection by the monolithic integrated silicon MRR and Ge-Si PD are given in Section 3. The design and fabrication parameters of the silicon devices are also presented in Section 3. The experimental results and analysis of the upstream CS-SSB-NRZ signal with RB circumvention are discussed in Section 4. Finally, a conclusion is given in Section 5.

2. Architecture of the Signal Remodulated TWDM-PON

The system architecture of the proposed signal-remodulated TWDM-PON is shown in Fig. 1. In order to simplify the figure, only one OLT and one ONU for the TWDM-PON are included in the figure. Inside each OLT, four sets of Tx modules at different wavelengths are stacked. A continuous-wave (CW) signal emitted from a distributed feedback laser (DFB) is encoded by a 10 Gb/s, PRBS $2^{23} - 1$ DPSK downstream signal via a phase modulator (PM) in each Tx module. Four different wavelengths of the DPSK signals are combined by an optical multiplexer to produce the 40 Gb/s downstream signal. They are then transmitted through 20 km SMF to the ONU.

In each ONU, four sets of Rx modules are used. Inside each Rx module, the downstream DPSK signal is divided by a 3-dB fiber splitter. One half of the downstream signal is launched into a monolithic-integrated silicon-based MRR filter and a Ge-Si PD. The MRR filter can select the desired downstream wavelength and simultaneously demodulate the DPSK signal. Another half of the downstream signal will be selected by a tunable filter (TF) and then launched into a commercially available dual-parallel Mach-Zehnder modulator (DP-MZM). A 10 GHz radio-frequency (RF) up-converted 2.5 Gb/s NRZ signal are applied in-phase and quadrature-phase to the upper and lower MZMs of the DP-MZM. By properly adjusting the dc-bias to the DP-MZM, a CS-SSB-NRZ upstream signal can be generated. The optical spectrum of the remodulated upstream NRZ signal is wavelength-shifted by 10 GHz away from the wavelength of the downstream DPSK signal for effective RB circumvention.

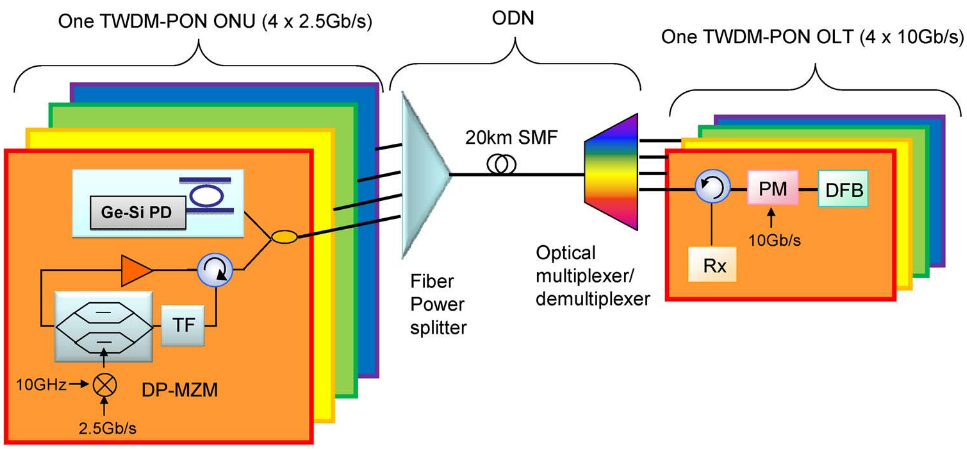

Fig. 1. Proposed signal-remodulated TWDM-PON with RB noise circumvention. DFB: distributed feedback laser, PM: phase modulator, Rx: receiver, SMF: single mode fiber, OLT: optical line terminal, ODN: optical distribution network, ONU: optical networking unit, TF: tunable filter.

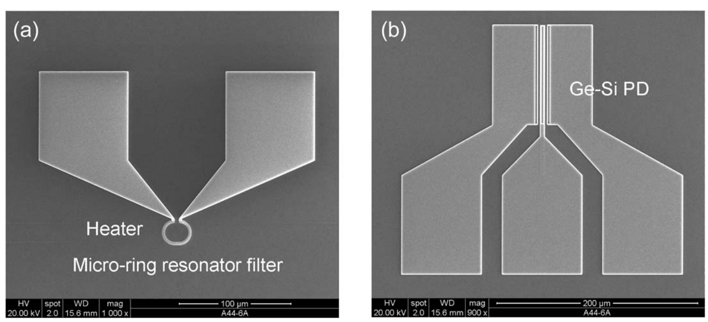

Fig. 2. SEM images of (a) silicon MRR filter for wavelength selection and DPSK demodulation and (b) Ge-Si PD for downstream detection.

3. Results of Downstream DPSK Demodulation and Detection

In each Rx module in the ONU, there was a monolithic-integrated silicon-based MRR filter and a Ge-Si PD. The scanning electron microscope (SEM) images of the MRR and the Ge-Si PD are shown in Fig. 2(a) and (b), respectively. The MRR filter selects the desired downstream wavelength and simultaneously demodulates the DPSK signal. In the experiment, the downstream DPSK was at the wavelength of 1544.7 nm. The optical signal was coupled to the MRR filter via a tapered waveguide grating coupler with about 5 dB coupling loss, which can be further minimized if apodized grating structure were used [15]. The device was fabricated at the Institute of Micro-electronics (IME). Recently, new foundry service for silicon photonic chips has been established, allowing researchers working on different projects in the world to share the cost of silicon photonic fabrication [16].

The Rx was fabricated on a silicon-on-insulator (SOI) wafer, having the thickness of the top silicon and buried oxide (BOX) of 220 nm and 2 μm, respectively. The silicon single-mode waveguide connecting the grating coupler and the MRR has a dimension of 500 nm $\times$ 160 nm. For the MRR filter, the coupling length, the gap distance between the waveguide and the MRR, and the MRR radius are 4 μm, 200 nm, and 7.5 μm, respectively. A thermal heater on the MRR was used for tuning the resonance wavelength. The thermal heater was produced by deposition of a 120 nm thick titanium nitride (TiN) layer on top of the silicon MRR. Fig. 3(a) and (b) shows the measured transmission spectrum of the MRR, with the applied dc-bias voltage from 0 V to 4 V, and the corresponding power consumption, respectively. When the applied dc bias voltage was increased

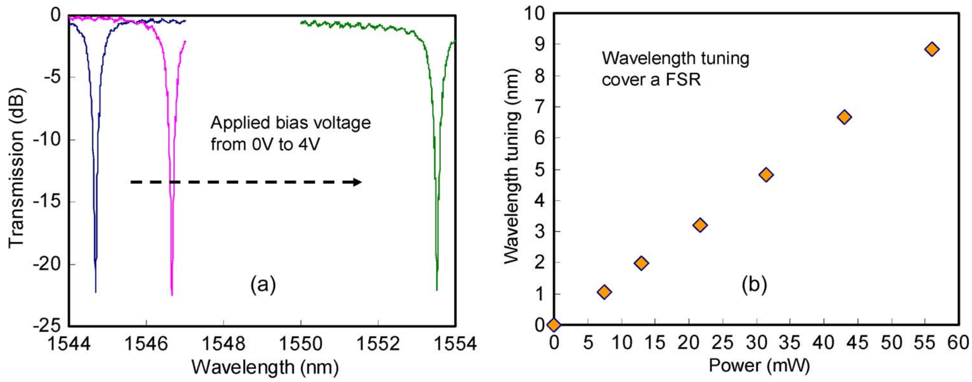

Fig. 3. (a) Measured transmission spectrum of the MRR with the applied DC-bias voltage from 0 V to 4 V, and (b) the corresponding power consumption.

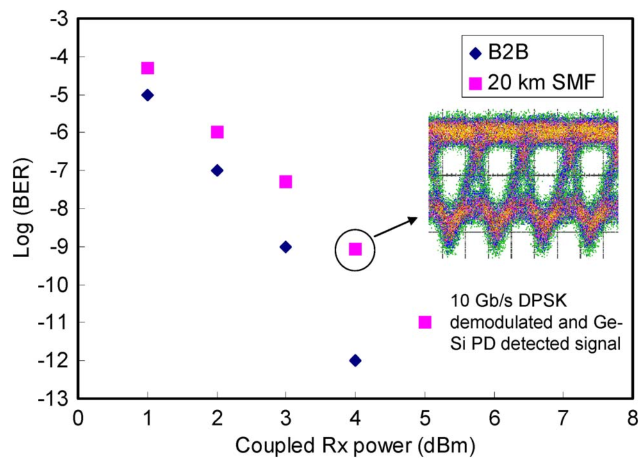

Fig. 4. Measured BER of the 10 Gb/s DPSK demodulated and Ge-Si PD detected downstream signal. Inset: detected eye-diagram after 20 km SMF transmission.

from 0 V to 4V, it produces a wavelength tuning of 8.9 nm, covering about a free-spectral range (FSR) of the MRR. The Q and the extinction ratio of the MRR are ~3500 and 22 dB, respectively.

The MRR demodulated downstream DPSK signal was then directly launched to the Ge-Si PD via a tapered single-mode single waveguide. The Ge region has the thickness, length, and width of 800 nm, 6 μm, and 90 μm, respectively. After the optical-to-electrical conversion in the PD, the downstream signal was measured by a BER tester (BERT) connected via a signal-ground-signal (SGS) electrical probe. The responsivity and bandwidth of the Ge-Si PD are 0.7 A/W (at bias of −3 V) and 12.5 GHz, respectively. Shrinking the Ge window size to increase the PD bandwidth and using balanced detection will be considered in the next version of the Rx.

Then, BER measurements were performed for the 10 Gb/s DPSK demodulated and Ge-Si PD detected downstream signal at back-to-back (B2B) and after 20 km SMF transmission without any dispersion compensation. A ~1 dB power penalty was measured at BER of 10^{-9}, with wide-open eye-diagram shown in the inset of Fig. 4.

4. Results of Upstream CS-SSB-NRZ Generation With RB Circumvention

The signal-remodulated upstream CS-SSB-NRZ signal was generated by a commercially available DP-MZM (also known as different quadrature-phase-shift-keying (DQPSK) modulator), which was used as the colorless upstream modulator in the ONU. The DP-MZM was electrically driven by a

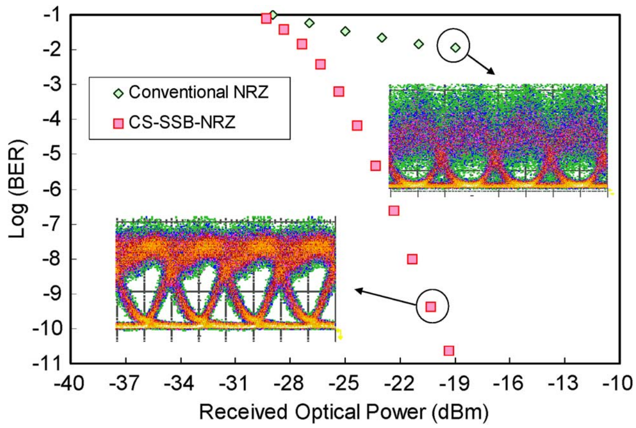

Fig. 5. Measured BER of the signal-remodulated conventional NRZ signal and the proposed CS-SSB-NRZ signal, showing RB noise can be successfully circumvented. Inset: corresponding eye-diagrams.

10 GHz RF up-converted 2.5 Gb/s NRZ signal at in-phase and quadrature-phase respectively applied to the upper and lower MZMs of the DP-MZM. At the output of the DP-MZM, a 10 GHz CS-SSB-NRZ signal-remodulated optical upstream signal was produced. The original center wavelength at 1544.7 nm was suppressed, producing an upstream NRZ signal at wavelength of 1544.78 nm. The signal-remodulated upstream signal was then sent back to the OLT through the same fiber path and then was measured using a BERT.

Fig. 5 shows the measured BER of the signal-remodulated conventional NRZ signal and the proposed CS-SSB-NRZ signal. These two upstream signals were generated from the remodulation of the downstream DPSK signal, which have propagated through a total of 40 km SMF. We can observe that the conventional NRZ signal (without wavelength-shifting) was highly degraded by the RB at the OLT Rx, with an error-floor at BER of 10^{-2}. The proposed signal-remodulated CS-SSB-NRZ signal can significantly circumvent the RB noise, and error-free transmission (BER $< 10^{-9}$) was successfully achieved. In a typical signal remodulation network, the RB generated by the downstream signal and the remodulated upstream signal are propagating in the same direction toward the Rx at OLT. The RB and the upstream signal will produce the interferometric beat noise, which will be at the baseband and fall within the Rx bandwidth, degrading the upstream signal. In the proposed scheme, the upstream signal is wavelength shifted by 10 GHz; hence, the beat noise will be shifted and will fall outside the Rx bandwidth (the Rx 3-dB bandwidth is 2.5 GHz). As a result, the RB can be mitigated.

In practical case, the upstream signal is operated in burst mode (transmitting the TDM optical packets); hence, the Rx at OLT should be gated to only measure the payload of the optical packets. As the wavelength of the upstream signal is shifted to mitigate the RB, we believe that the RB mitigation efficiency should be similar to that shown in Fig. 5 (in continuous mode). It is also worth pointing out that although the lithium niobate ($LiNbO_3$) based DP-MZM was used in the proof-of-concept demonstration, it is also believed that this modulator can be fabricated in SOI platform [17]. Hence, the MRR, PD, and the modulator can be monolithic integrated in the ONU to reduce cost.

5. Conclusion

TWDM-PON is a cost-effective and primary solution for the NG-PON2. It is also particularly desirable for the brown-field deployment, in which the conventional TDM-PON has already been built. In this work, we proposed and demonstrated a TWDM-PON using signal remodulation. The downstream DPSK signal was divided into two parts in the ONU; one part of the downstream DPSK signal was remodulated to produce the upstream CS-SSB-NRZ signal sending to the OLT. The optical spectrum of the upstream CS-SSB-NRZ signal was wavelength-shifted by 10 GHz to circumvent RB. The experimental results showed that the proposed signal-remodulated CS-SSB-NRZ signal can significantly circumvent the RB noise with error-free transmission (BER $< 10^{-9}$), while the conventional signal-remodulated NRZ had an error floor at BER of 10^{-2}. Another part of the downstream DPSK signal was demodulated by a silicon-based optical MRR filter, which had the Q and extinction ratio of $\sim$3500 and 22 dB, respectively. A TiN thermal heater was deposited on top of the silicon MRR for wavelength tuning. By applying a dc-bias voltage from 0 V to 4 V, the wavelength tuning can cover the FSR of the MRR (8.9 nm), with power consumption $<$ 60 mW. Then, the demodulated DPSK signal was detected by a monolithic-integrated Ge-Si PD, which had the responsivity and bandwidth of 0.7 A/W (at bias of -3 V) and 12.5 GHz, respectively.

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