10-Gb/s Access Network Architecture Based on Micro-Ring Modulators With Colorless ONU and Mitigated Rayleigh Backscattering

Lin Xu, Kishore Padmaraju, Long Chen, Michal Lipson, and Keren Bergman

***Abstract*—We demonstrate an optical access network architecture utilizing the wavelength-selective behavior of micro-ring modulators to achieve single-sideband (SSB) modulation, which generates a downstream signal and simultaneously provides a centrally distributed carrier for upstream phase-remodulation. Cascaded silicon micro-rings are capable for complementary metal–oxide–semiconductor (CMOS) integration and multi-channel SSB modulations which can help to significantly reduce the cost of the wavelength-division-multiplexed (WDM) passive optical networks (PONs). We further study the power penalty induced by Rayleigh backscattering from the centrally distributed carrier and show a power penalty of less than 0.6 dB when propagating 43 km of a single feeder fiber.**

***Index Terms*—Silicon micro-ring modulator, single-sideband (SSB) modulation, wavelength-division-multiplexed passive optical network (WDM-PON).**

I. Introduction

THE ever-increasing demand for bandwidth in optical access networks has driven the deployment of wavelength-division-multiplexing (WDM) in passive optical networks (PON). Reducing the cost of WDM PON is a key challenge toward realizing broad deployment. The employment of colorless optical network units (ONUs) enables the remodulation of downstream wavelength for upstream transmission, thus reducing the overall cost and management of remote ONUs [1]. Recently, the notch-filter like destructive port of a delay interferometer (DI) has been used to suppress Rayleigh backscattering (RBS) in carrier-distributed networks [2]. However, the scheme required additional laser diodes to provide the continuous wave (CW) carriers. Single-sideband (SSB) modulation can provide a downstream signal, a CW carrier distributed centrally for upstream remodulation as well as support radio-over-fiber [3]–[5]. However, SSB modulation schemes aforementioned are typically complicated due to the difficulties in optical sideband separation/combination, polarization alignment, power equalization and control of differential propagation delay.

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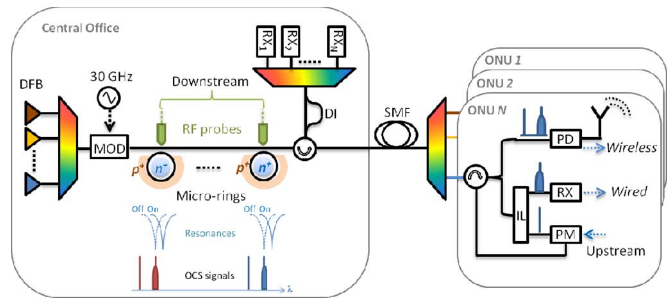

Fig. 1. Architecture of the proposed access networks with colorless remote units. Inset: conceptual diagram of SSB modulation.

The key feature in our proposed optical transceiver is the wavelength selective modulation function, uniquely enabled by the use of cascaded silicon micro-ring modulators [6]. Compact, low-energy silicon micro-ring modulators have been shown to be feasible for medium- and long-haul optical communications [7]. Their compatibility with existing complementary metal–oxide–semiconductor (CMOS) fabrication processes allows them to meet the stringent cost requirements of WDM PON. In this letter, we demonstrate a scheme based on SSB modulation using silicon micro-ring modulators for downstream and remodulation of the CW-like SSB carrier for upstream with mitigated RBS influenced degradation [8]. We further study the RBS suppression efficiency using the centrally distributed CW-like SSB carrier.

II. Working Principle

At the central office (Fig. 1), CW carriers from distributed feedback lasers are first multiplexed by an arrayed waveguide grating and then modulated by a shared Mach–Zehnder modulator driven with a 30-GHz RF signal. By tuning the DC bias of the modulator to the transmission minimum, optical carrier-suppressed (OCS) signals are generated, with the output of the modulator having first-order sidebands [9]. Multiwavelength operation can be optimized by adjusting the individual polarization properly. The all-optical upconversion for multiple channels are also demonstrated in [9], [10] while the bandwidth depends on phase matching conditions. Thus only one laser diode provides both downstream and upstream light sources centrally for the respective ONU. The modulator is followed by cascaded silicon micro-ring modulators, each one having its ra-

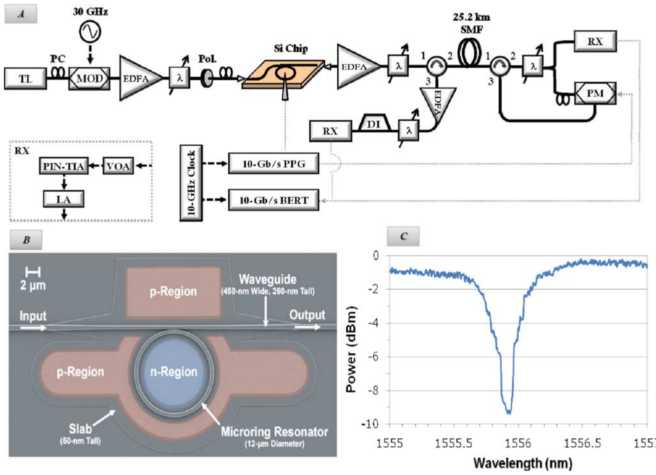

Fig. 2. (a) Experimental setup. RX: optical receiver. (b) SEM image of the micro-ring modulator. N and P doping are indicated. (c) Scanned spectrum of the resonance in its passive state.

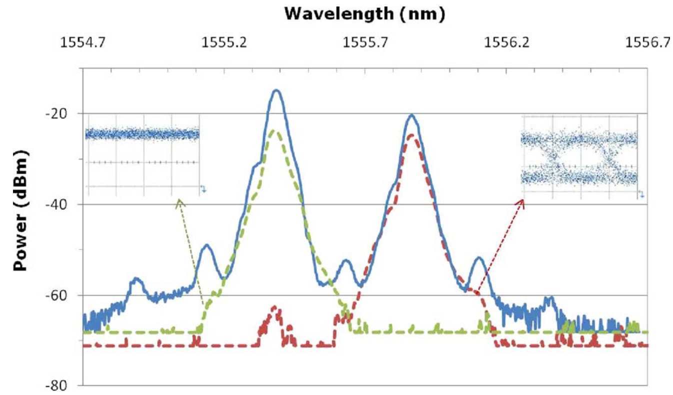

Fig. 3. Spectra of SSB modulated signal (solid line) after the chip and individual sideband after filtering (dashed line). Inset: waveform of the respective sideband in time domain.

dius tuned to correspond to a particular CW carrier. Cascaded micro-rings have been demonstrated as cost effective modulators for WDM systems [6]. To produce SSB modulation, one sideband of each generated OCS signal is aligned with the resonance of the micro-ring (Fig. 1 inset), taking advantage of its wavelength selectivity. The 60-GHz spacing between the first-order sidebands ensures that there is no modulation crosstalk on the unmodulated sideband from the micro-ring [11]. Power equalization, polarization alignment and differential delay control are not necessary between the two sidebands. The signals are sent from the central office to ONUs through a single-mode fiber (SMF). At the ONU, an interleaver separates the two sidebands. The data carried by the modulated sideband is detected for downstream wired service while the CW-like unmodulated sideband is remodulated with DPSK by a phase modulator for upstream transmission. It is worth to mention that in parallel, a data-modulated mm-wave carrier can be created for wireless service by heterodyne detection using a high-speed photodetector since the two sidebands are coherent [3]–[5], [9], [10]. At the central office, a common DI demodulates all the upstream DPSK signals due to its periodic frequency response. The notch-filter like destructive port of the DI considerably suppresses Rayleigh-backscattering from the downstream CW SSB carriers.

III. Experiment and Results

Fig. 2(a) shows the experimental setup. A CW signal from a tunable laser (TL) is modulated by a $LiNbO_3$-based intensity modulator, which is electrically driven with a 30-GHz sinusoidal RF signal and biased at transmission minimum. The generated OCS signal, having 60-GHz spacing between its first-order sidebands, is then amplified, filtered and set to TE polarization before being launched from a tapered fiber into the waveguide. Fig. 2(b) and (c) show the scanning-electron-microscope (SEM) image and spectrum of the micro-ring device, further described in [6], [7]. The silicon chip has a fiber-to-fiber loss of 22 dB, with the micro-ring having an extinction of 8 dB. However, the insertion loss of the pass-band between the adjacent micro-rings comes from the waveguide loss and coupling loss which can be much lower with improved fabrication process. The sideband whose wavelength overlaps with the resonance is modulated with 10-Gb/s nonreturn to zero (NRZ) $2^7 - 1$ pseudorandom bit sequence (PRBS) using a pattern generator (PPG) and a micro-ring modulator. The use of a short pattern is to avoid having long consecutive ones that heat up the ring. The micro-ring modulator is driven electrically using a high-speed RF probe with a 0.85-V voltage bias and 2.1-Vpp electrical signal.

The optical signal egressing from the waveguide (Fig. 3 solid line) is amplified and filtered to a power of 3-dBm before propagating in 25.2-km SMF. Fig. 3 (dashed line) shows the spectrum and respective waveform in time domain by filtering each sideband using 0.22-nm (3-dB bandwidth) filters after the chip. The unmodulated sideband retains a CW characteristic while the modulated sideband shows a clean eye-diagram.

At the ONU, the two sidebands are separated using 0.22-nm (3-dB bandwidth) filters instead of an interleaver for this proof-of-principle demonstration. The modulated sideband is detected while the CW-like sideband is modulated by a phase modulator driven with a 10-Gb/s $2^{31} - 1$ PRBS to generate upstream DPSK signal and launched to the same fiber via an optical circulator. At the central office, the upstream signal is amplified and filtered before demodulation using a 100-ps DI with 28-dB extinction ratio. Both downstream and upstream signals are detected using a variable optical attenuator (VOA), a photodetector (PIN-TIA) followed by a limiting amplifier (LA), and examined on a BER tester (BERT). We record BERs and eye-diagrams for downstream and upstream signals as shown in Fig. 4. Power penalties of 2.5 dB for downstream NRZ signal and 1.5 dB for upstream DPSK signal are experimentally obtained with error free operation in the single feeder fiber scheme.

To investigate the tolerance to RBS, we compare the performance of the two schemes shown in Fig. 5(a) and (b). An OCS signal with 60-GHz spacing between the two sidebands is generated and only one sideband is selected by passing through a narrowband filter. The CW-like sideband with 3-dBm input power transmits in a L-km SMF after which it is modulated by a phase modulator to generate a 10-Gb/s DPSK signal. For scheme A, it

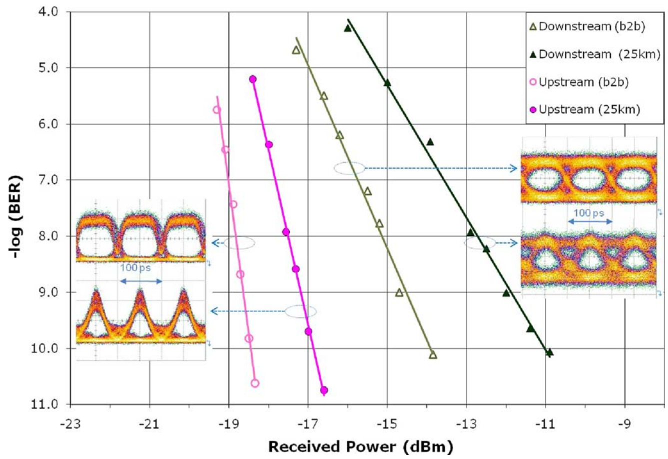

Fig. 4. BER measurement of downstream NRZ signals and upstream DPSK signals for both back-to-back (b2b) and 25.2-km transmission cases. Inset: respective eye diagrams.

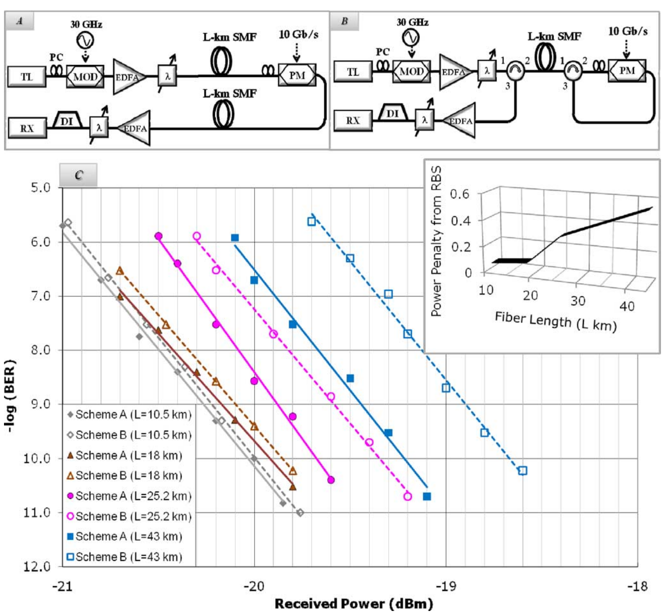

Fig. 5. Experimental setup of (a) scheme A, (b) scheme B, and (c) BER measurements of upstream DPSK signals for both schemes at different fiber lengths. Inset: Power penalty induced by RBS as a function of fiber length.

is routed back to the receiver via another L-km SMF to mimic the dual feeder fiber scenario. For scheme B, it is routed back to the receiver via the same fiber to mimic the single feeder fiber scenario. The BER curves are recorded as shown in Fig. 5(c) for varied fiber lengths ($L = 10.5, 18, 25.2, 43$ km). The power penalty between scheme A and B at a BER of 10^{-9} (Fig. 5(c) inset) shows that there is less than a 0.6-dB power penalty induced by RBS for the upstream DPSK signal after 43-km single feeder fiber transmission using centrally distributed SSB carrier.

IV. Conclusion

We have demonstrated a silicon micro-ring modulator enabled SSB modulation scheme for WDM PON with colorless ONU. The scheme can provide broadband downstream signals and centrally distributed SSB carriers for upstream remodulations. The use of destructive port of DI can mitigate the impairment from RBS of distributed SSB carriers with single feeder fiber. The CMOS compatibility of the silicon micro-ring modulators adheres to the stringent cost requirements of WDM PON.

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