Colorless Optical Network Unit Based on Silicon Photonic Components for WDM PON

Lin Xu, Qi Li, Noam Ophir, Kishore Padmaraju, Lian-Wee Luo, Long Chen, *Member, IEEE*, Michal Lipson, *Senior Member, IEEE*, and Keren Bergman, *Fellow, IEEE*

***Abstract*— We demonstrate a low-cost colorless optical network unit (ONU) utilizing silicon photonic components for wavelength division multiplexed passive-optical-networks. At the ONU, a waveguide-coupled microring works as a demultiplexer for separating the downstream signal from the centrally distributed continuous-wave (CW) light. The 10-Gb/s downstream signal is received using a waveguide-integrated germanium photodetector while the CW light is further modulated at 5 Gb/s using a silicon microring modulator for upstream signal generation. Error-free transmission over 25-km single mode fiber is achieved with 0.2- and 0.4-dB power penalties for the downstream and upstream signals, respectively. Complementary metal-oxide semiconductor-compatible silicon photonic technology offers the potential for monolithic integration and mass production.**

***Index Terms*— Colorless ONU, silicon photonics, WDM-PON.**

I. Introduction

To COPE with the ever-increasing bandwidth demands in access networks, wavelength-division-multiplexed (WDM) passive-optical-networks (PONs) have been considered as a promising solution for the next generation broadband access network technology. Reducing the cost of WDM PONs will be the key challenge toward realizing broad deployment in the highly cost-sensitive optical network units (ONUs). Recent advancements in silicon photonics have introduced photonic devices including waveguides, modulators, switches and receivers [1]–[4]. CMOS-compatible silicon photonic technology offers the potential for compact, high-performance, energy-efficient and low-cost optical transceivers, rendering them attractive for access networks [5].

An ONU transceiver based on silicon photonics has been recently proposed, which envisions WDM filters, modulators and germanium photodetectors integrated on a single chip [6]. However, the lack of a silicon light source prevents the realization of fully integrated on-chip solution. A colorless ONU design has been suggested to overcome this problem and allow the same physical unit to be used irrespective of the local wavelength [7]. Following this path toward realizing a single chip silicon ONU, a transceiver based on Mach–Zehnder Interferometer (MZI) modulator has been demonstrated recently [8]. Compared to that device, microring based devices are more compact, power efficient, and require only CMOS-level driving voltages. In this letter, we demonstrate a colorless ONU transceiver based entirely on silicon photonic components, including a microring modulator, a germanium photodetector and a microring based WDM demultiplexer. The potential for single chip integration of this colorless ONU transceiver places it as a potentially attractive solution capable of meeting the stringent cost requirements for WDM PON.

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L. Xu, Q. Li, N. Ophir, K. Padmaraju, and K. Bergman are with the Department of Electrical Engineering, Columbia University, New York, NY 10027 USA (e-mail: lx2140@columbia.edu; ql2163@columbia.edu; ophir@ee.columbia.edu; kp2362@columbia.edu; bergman@ee.columbia.edu).

L.-W. Luo, L. Chen, and M. Lipson are with the School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853 USA (e-mail: ll399@cornell.edu; lc286@cornell.edu; ml292@cornell.edu).

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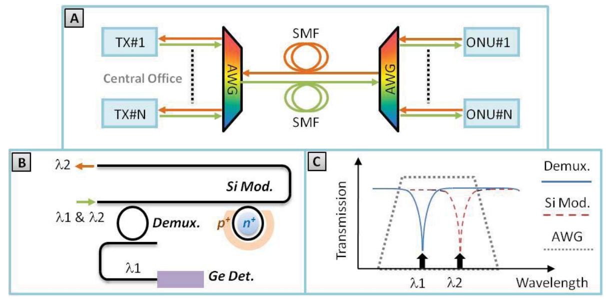

Fig. 1. (a) Architecture of the proposed WDM PON. (b) Configuration of the individual colorless ONU. (c) Transmission spectra of the AWG, microring demultiplexer (Demux), and the microring modulator (Si Mod), respectively.

II. Architecture and Device

In the proposed architecture Fig. 1(a), a dual-fiber link connects the transceivers located at the central office with the corresponding ONUs. The downstream fiber link carries downstream signals and centrally distributed continuous wave (CW) carriers for upstream modulations; the upstream fiber link carries upstream signals only. Each ONU Fig. 1(b) consists of a microring based demultiplexer for separating the downstream signal and the CW light, a photodetector for downstream signal detection, and a microring modulator for upstream signal generation. The transmission spectra Fig. 1(c) of the arrayed waveguide grating (AWG), microring based demultiplexer, and modulator depict the WDM channel positioning. The downstream signal (λ_1), which is on one resonance of the microring demultiplexer, is sent to the drop port and received by the photodetector. In parallel, the CW light (λ_2), which is off resonance of the microring demultiplexer while on the resonance of the microring modulator,

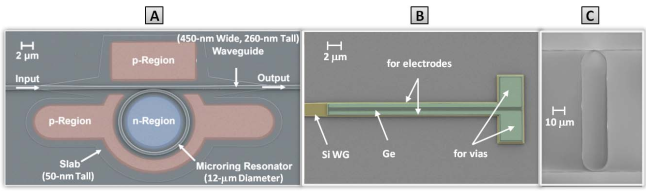

Fig. 2. Scanning-electron-microscope (SEM) image of (a) modulator, (b) photodetector, and (c) demultiplexer.

is sent to the through port and then modulated for upstream transmission. Both wavelengths are within the AWG passband. Since the resonance spectrum of microrings is periodic, the same components can be used for all ONUs.

The silicon photonic components used here include a microring modulator Fig. 2(a), a waveguide-integrated germanium metal-semiconductor-metal (MSM) photodetector Fig. 2(b), and a waveguide-coupled racetrack microring demultiplexer Fig. 2(c), all these components are fabricated at the Cornell Nanofabrication Facility. The waveguides dimensions of the microring modulator are 450-nm wide and 260-nm tall; the microring has a diameter of 12 μm with 50-nm slab that is doped to form a PIN diode structure. Modulation is accomplished by shifting the microring resonances due to carrier injection [2]. The detector is 30-μm long to ensure complete absorption of the light. The germanium cross-section is 1.5 μm $\times$ 0.26 μm, and the silicon region underneath the germanium is 1.8 μm $\times$ 0.26 μm. The planar electrodes are 0.35-μm wide with a spacing of 0.6 μm. Detection is accomplished by collecting photo-generated carriers in the germanium region. Such devices have been shown with 2.4-fF capacitance and 8.8-ps impulse response [4]. The waveguides of the demultiplexer are 450-nm wide and 250-nm tall. The racetrack length is 314.2 μm. Fig. 3 shows the output spectra of the resonant responses for the microring demultiplexer and modulator in the passive state when no voltage is applied.

III. Experiment and Results

Figure 4 depicts the experimental setup. CW light at 1534.4 nm from a tunable laser (TL_1) is modulated by an amplitude modulator (AM) driven with 10-Gb/s, $2^{31} - 1$ pseudorandom binary sequence (PRBS) pattern generated by a pulse pattern generator (PPG) for downstream signal generation. Meanwhile, CW light at 1535.4 nm from a second tunable laser (TL_2), working as a seed light for upstream signal modulation, is combined with the downstream signal using a 3-dB fiber coupler. They enter a 25-km single mode fiber (SMF) with an input power of 2 dBm each. After propagation, they pass through a polarizer (Pol) for transverse-electric (TE) polarization selection before entering a silicon chip. Note that a polarization-transparent approach can be implemented [9]. The external amplifiers and filters used in the experimental setup compensate for the extra insertion loss caused by the multiple coupling stages and would not be necessary in a fully integrated ONU with optimized inverse-taper edge couplers. In the experiment, an on-chip silicon microring demultiplexer, which has 17-dB extinction ratio for the through port and 15-dB extinction ratio for the drop port (Fig. 3), routes the downstream signal to the drop port. The CW light, which is at

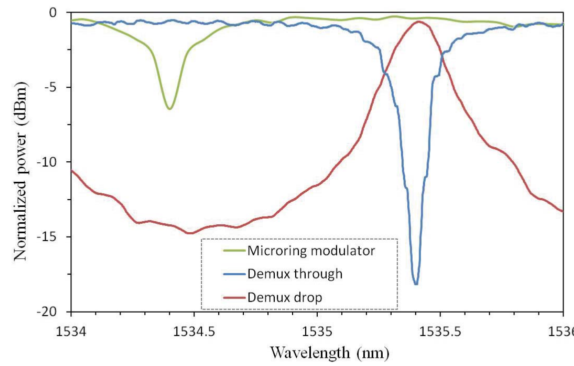

Fig. 3. Measured spectra of the microring demultiplexer and modulator.

off-resonance wavelength, egresses from the through port. The downstream signal is then amplified using an Erbium-doped fiber amplifier (EDFA), filtered (λ), tapped to record its optical eye diagram on a digital communications analyzer (DCA), and attenuated using a variable optical attenuator (VOA). A microring that satisfies critical coupling condition enables a higher extinction ratio and can fully separate the downstream signal from the CW light without using a filter. Tolerance to thermal drift and wavelength instability can be enhanced using a high-order microring or by integrating a thermal heater along with an active feedback loop [10].

After that, the CW light passes through a polarizer for TE polarization selection and is coupled into an on-chip photodetector. A bias tee (T) provides 1-V DC bias for the photocurrent generation. When the optical signal impinges on the photodetector, the generated electrical AC signal enters a high-sensitivity limiting amplifier (LA) followed by a bit-error-rate tester (BERT). The electrical eye-diagram at the LA's output is recorded on the DCA. We record BER curves (Fig. 5) and the respective electrical and optical eye diagrams (Fig. 5 inset) for the downstream signal. The back-to-back BER curve for the downstream signal is measured at the input of the first fiber-span (SMF_1) using the on-chip photodetector. A power penalty of 0.2 dB for the 10-Gb/s downstream signal is obtained with error-free operation after 25-km SMF propagation. The photodetector sensitivity is limited due to large waveguide loss for the device and coupling losses which can be improved in the future optimization. The receiver sensitivity can be improved by further optimization of the coupling, fabrication accuracy and monolithically integration of the discrete components with the electrical driving circuit on a silicon chip.

After conducting the downstream signal detection, we continue to conduct the upstream signal generation and transmission. The CW light egressing from the through port of the microring demultiplexer is amplified using an EDFA, filtered and TE polarized before entering an on-chip microring modulator. The 1-Vpp modulator drive signal (5 Gb/s, $2^7 - 1$ PRBS) generated by a PPG goes through a pre-emphasis circuit to improve modulator response. The use of a short pattern is to avoid having long consecutive ones that heat up the ring. This can be avoided by using 8B/10B coding that there are not more than five consecutive 1s or 0s in a row. Active stabilization can also be achieved

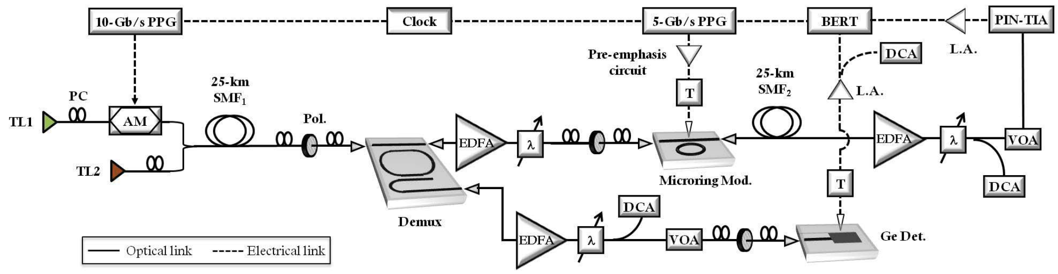

Fig. 4. Experimental setup.

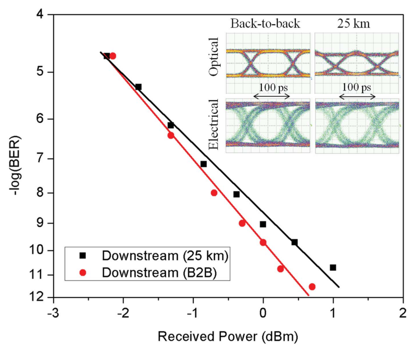

Fig. 5. BER measurement of the 10-Gb/s downstream signal. Inset: optical and electrical eye diagrams of the back-to-back and 25-km fiber transmission case.

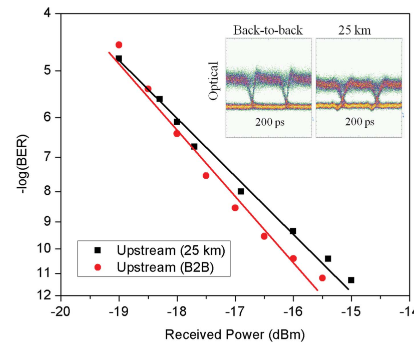

Fig. 6. BER measurement of the 5-Gb/s upstream signal. Inset: optical eye diagrams of the back-to-back and 25-km fiber transmission case.

leveraging a feedback loop circuit to compensate for dynamic temperature and bias voltage fluctuations [10]. Athermal and thermal isolation solutions will potentially minimize the power consumption of active stabilization. A bias tee is used to add a 0.4-V DC bias to the signal. The resonance extinction ratio of the microring modulator is ~6 dB (Fig. 3), and the data is encoded onto the CW light through resonance shifting. The optical signal egressing from the chip passes a 25-km SMF and is further amplified by an EDFA, filtered, attenuated by a VOA, and detected using a photodetector (PIN-TIA) followed by a LA, and examined on a BERT. A portion of the optical signal is tapped to the DCA to record its eye diagram. A central clock is distributed to all the devices. We also record BER curves (Fig. 6) and the respective optical eye diagrams (Fig. 6 inset) for the upstream signal. The generated signal has ~5-dB extinction ratio. The back-to-back BER curve for the upstream signal is measured at the input of the second fiber-span (SMF_2) using the PIN-TIA followed by a LA. The optical eye diagrams show clear eye opening with some noise coming from low signal noise ratio after EDFA amplification. This can be improved by using a device with lower insertion loss. Power penalty of 0.4 dB for the 5-Gb/s upstream signal is obtained with error-free operation after 25-km propagation.

IV. Conclusion

We have demonstrated a colorless ONU based entirely on silicon photonic components. The 10-Gb/s downstream signal detected by the waveguide-integrated germanium photodetector and 5-Gb/s upstream signal generated by the microring modulator were achieved with 0.2-dB and 0.4-dB power penalties. Rayleigh backscattering effects were avoided by using the dual fiber scheme. The different slopes of the BER curves were due to modulation chirp and filtering effect. With the CMOS compatibility of silicon photonics, the discrete components can be further integrated with the electrical driving circuit potentially on a single silicon chip which would offer an attractive solution under the stringent cost and power budget requirements of WDM PONs.

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