Tb/s Transmission and Routing Systems Using Integrated Micro-Photonic Components

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***Abstract*—Recent advances in the development of photonic switching and transmission systems that exploit high and low index contrast integration materials are reported. Micro-ring resonators, delayed interferometers and all-optical wavelength converters integrated in Si3N4-SiO2 and silica-on-silicon substrates are used for the regeneration and wavelength routing of amplitude and phase modulated optical signals. Micro-photonics is the key for elegantly squeezing terabits into a few mm^2 with optimum yield and at a low development cost.**

***Index Terms*—high-speed transmission, optical regeneration, photonic routing, all-optical wavelength conversion, photonic integration**

I. INTRODUCTION

Today we are witnessing a resurgence of the growth and increasing customer demand for capacity in optical networks. A major factor for this growth is an unprecedented deployment of optical access networks worldwide for providing ample bandwidth to the end-user in the >50Mb/s region. In this rationale, the growth rates of end-users take new meaning, compared to those in 2000. Before the telecom bubble, penetration rates in excess of 100% reported, fuelled massive technology investments in the core network. However, these growth rates always translated to new users with bandwidth of a few kb/s, since the access network was just not ready. Moreover, broadband applications were still in their infancy and the telecom world was still searching for the "killer application". The situation is very different today, with each new data connection translating to fast internet with combined voice and video. These new developments in the access networks are now exerting pressure on the metro and core networks that inevitably will always be "out-of-step" with the access networks, given that the genuine and sustainable market drivers for bandwidth are originating from the end-users.

Photonic integrated circuits are expected to play a central role in the development of new hardware to be included in next generation telecommunication systems.

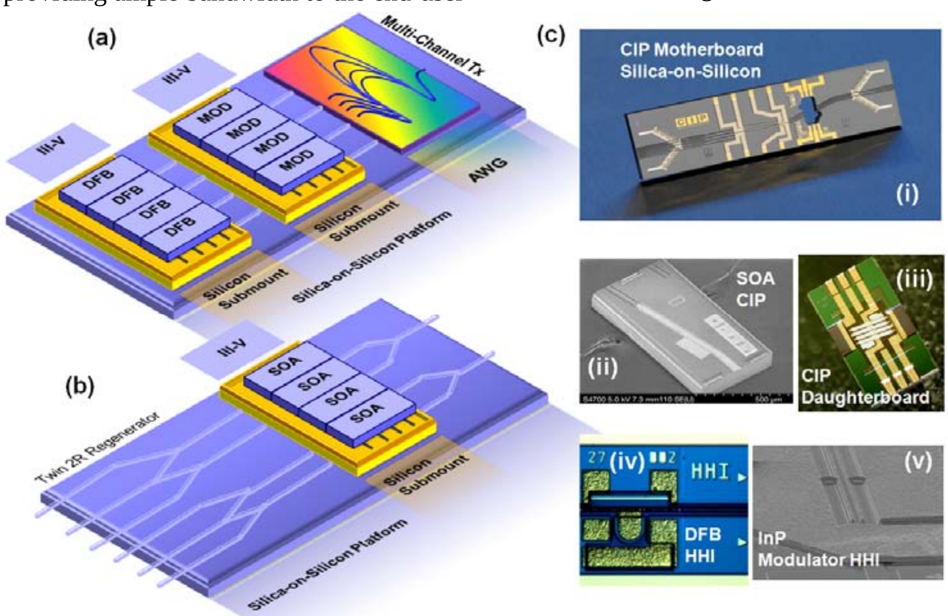

Figure 1. Systemic view of integration potential using Silica-on-Silicon hybrid integration technology for developing amplitude or phase modulated transmission links: (a) multi-wavelength, multi-format transmitter, (b) multi-format regenerator, (c) (i) Silica-on-Silicon motherboard, (ii) SOA, (iii) precision-machined silicon submount fabricated by CIP, (iv) DFB laser and (v) InP modulator developed by HHI.

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In this paper, potential upgrade paths are presented for increasing the throughput of transmission and routing systems utilizing micro-photonics fabricated on material systems that guarantee high integration scale and density. In this rationale, multi-material, multi-functional component integration on a single platform is achieved through optimum combination of monolithic and hybrid integration technologies that play equally important roles. Key milestones on this path are low development costs, integration technology scalability, power consumption and device footprint.

II. Multi-Format Photonic Integrated Transmission Systems

A. The need for integration scale increase

Current research efforts for developing new transmission systems in the core network now focus on cost-effective upgrade of transmission capacity using amplitude- and phase- modulated systems: this is where hybrid photonic integration can play a decisive role. The use of "monolithic-on-hybrid" integration approach can enable the increase of integration scale both vertically and horizontally without requiring outstandingly high yields and complex fabrication processes. Combination of high-speed indium phosphide (InP) monolithic arrays (vertical increase) can be on-chip interconnected (horizontal increase) using ultra low-loss silica-on-silicon motherboards [1]. These motherboards or Planar Lightwave Circuit Boards (PLCB) play the role of conventional Printed Circuit Boards (PCB) used in electronics. Using arrayed "all-semiconductor" active components can lead to cost effective, compact and low power consumption systems. On the other hand, the possibility to integrate these III-V components on a single low-loss circuit board can lead to multi-wavelength, multi-functional devices such as transmitters, receivers and regenerators capable of operating with OOK, DPSK and DQPSK formats, all sharing identical research and development costs. For example an InP-based modulator [2] requires 50% less power to operate and is one order of magnitude smaller than traditional discrete transmitters using LiNbO3. Moreover, considering arrays of such InP modulators hybrid integrated on the PLCB and on-chip interconnected with DFB laser arrays and filtering elements, a terabit capacity photonic integrated circuit becomes a realistic and competitive technology solution.

B. Phase- and amplitude- modulated regeneration systems using silica-on-silicon integration technology

Optical regeneration has the potential for data transparency and more cost-effective mitigation of transmission impairments bypassing the requirement for optical-electrical-optical systems. Hybrid integrated arrays of 2R or even 3R optical regenerators that share development and packaging costs are promising candidates for 40 Gb/s and 100 Gb/s systems, where the use of electronic repeaters becomes challenging, costly and significantly increases power consumption. Exploiting the versatility of the hybrid integration or platform, devices capable of operating with OOK, DPSK DQPSK can be developed using a common fabrication process. In addition, there is also the possibility for multi-functional devices: a single hybrid integrated device can be used for all the data formats Figure 2 shows experimental results of optical 2R regeneration at 40 Gb/s

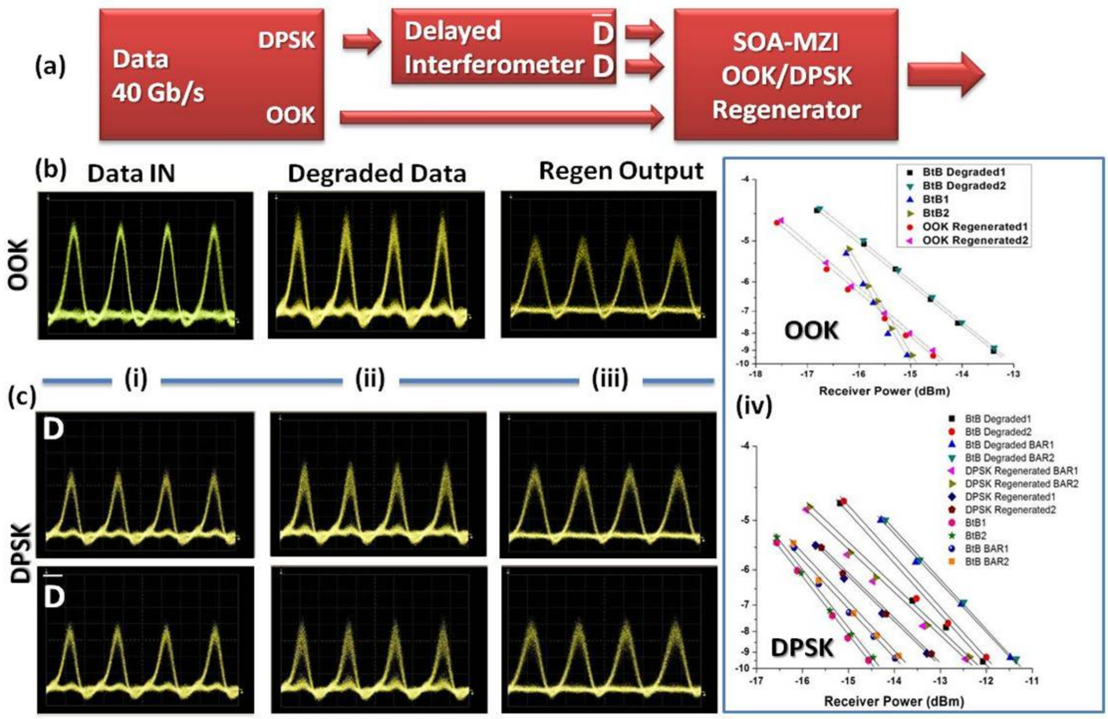

Figure 2. Optical regeneration for OOK and DPSK data (a) system functional blocks, performance evaluation of optical regeneration at 40 Gb/s with: (b) OOK and (c) DPSK data . Eye diagrams of (i) input data, (ii) degraded data, (iii) data at 2R regenerator output, (iv) BER performance for various levels of degradation (design, fabrication, pigtailing and packaging of devices by CIP Technologies).

with OOK and DPSK signals using a single device: a hybrid integrated Semiconductor Optical Amplifier Mach-Zehnder Interferometer (SOA-MZI). In order to assess the regenerating capabilities of the device, different levels of amplitude and phase degradations were introduced on the input signal that always resulted in more open eye diagrams and lower BER values for a specific input power to the receiver. Specifically, fig. 2(a) shows the basic functional blocks of the experimental setup, whereas fig. 2(b) and (c) shows experimental results when the SOA-MZI was operated as OOK and DPSK regenerator respectively. Eye diagrams and bit error rate (BER) measurements confirm the regenerative properties of the device, when degraded data are used as test signals.

III. Next Generation Photonic Integrated Routing Systems

A. Switching systems based on "CMOS photonics"

Increasing the transmission of point-to-point links within the core network cannot translate to useful bandwidth increase in the remaining network chain of metro and access networks, unless core routing systems cope with corresponding upgrade steps. Responding to the call for bandwidth coming from the access networks, system vendors have commercialized new generation of routing systems, following aggressive research and development investments. New terabit routing systems are equipped with 40Gb/s linecards and total throughput of 640 Gb/s. These state-of-the-art routing systems can be upgraded to multi-terabit capacities using multiple interconnected racks in expense of non-linear increase in power consumption, space, size and cooling requirements.

In order for photonics to penetrate into next generation routing systems, several critical milestones need to be achieved: low switching power requirements, small device footprints, low development costs and in the case of routing systems, CMOS-compatible fabrication that may allow merging electronics with photonics on a single platform. The TriPleX^{TM} waveguide technology – developed by Dutch company LioniX BV and now commercialized by XiO Photonics BV – is capable of meeting all these requirements [3]. The TriPleX^{TM} waveguides consist of alternating layers of silicon nitride (Si_3N_4) and silicon dioxide (SiO_2) formed by CMOS compatible low-pressure chemical vapor deposition (LPCVD). Figure 3(a) and (b) show the waveguide geometry; - a low-index SiO_2 core is surrounded by a high-index Si_3N_4 cladding. This material configuration ensures tight waveguide bends and consequently the fabrication of ultra-small structures that can be densely integrated on a single photonic chip. As such, TriPleX^{TM}

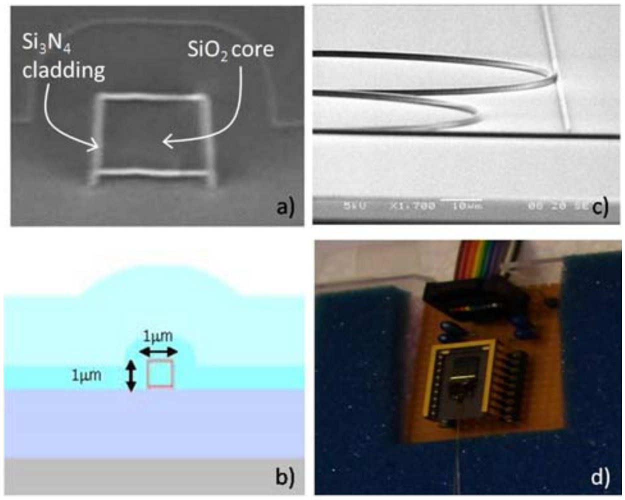

Figure 3. (a) and (b) TriPleX^{TM} waveguide geometry, (c) SEM image of coupled micro-ring resonators, (d) packaged and pigtailed device. Fabrication by LioniX BV, characterization and pigtailing by XiO Photonics BV.

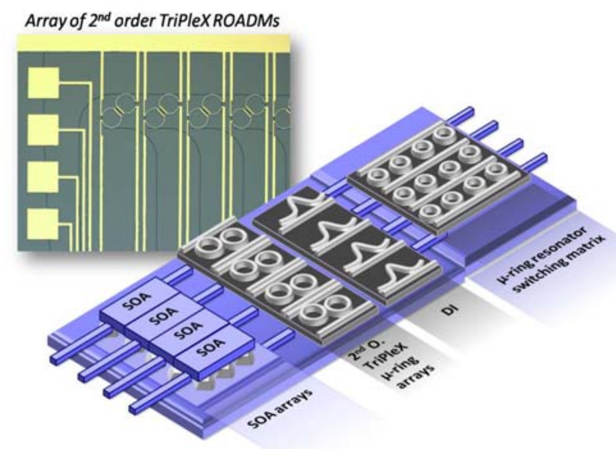

Figure 4. Wavelength router implementation using micro-ring resonator arrays

can provide photonic chips with a high aggregate throughput that can be efficiently cascaded due to the low insertion (~0.15 dB) and waveguide (<0.006 dB/cm) loss [4]. Figure 3(c) shows a scanning electron microscope (SEM) image of a TriPleX^{TM} ROADM. The component consists of two coupled micro-ring resonators with a ring radius of 50 um and with a capability for independent tuning through integrated heaters. This compact component can be the building block for realizing all the wavelength selective functionalities of a photonic wavelength router offering fine tunability, enhanced chip real estate efficiency and lower cost with respect to mainstream Arrayed Waveguide Grating (AWG) components.

Taking as an example the simplified architecture of Figure 4, a wavelength router consists of:

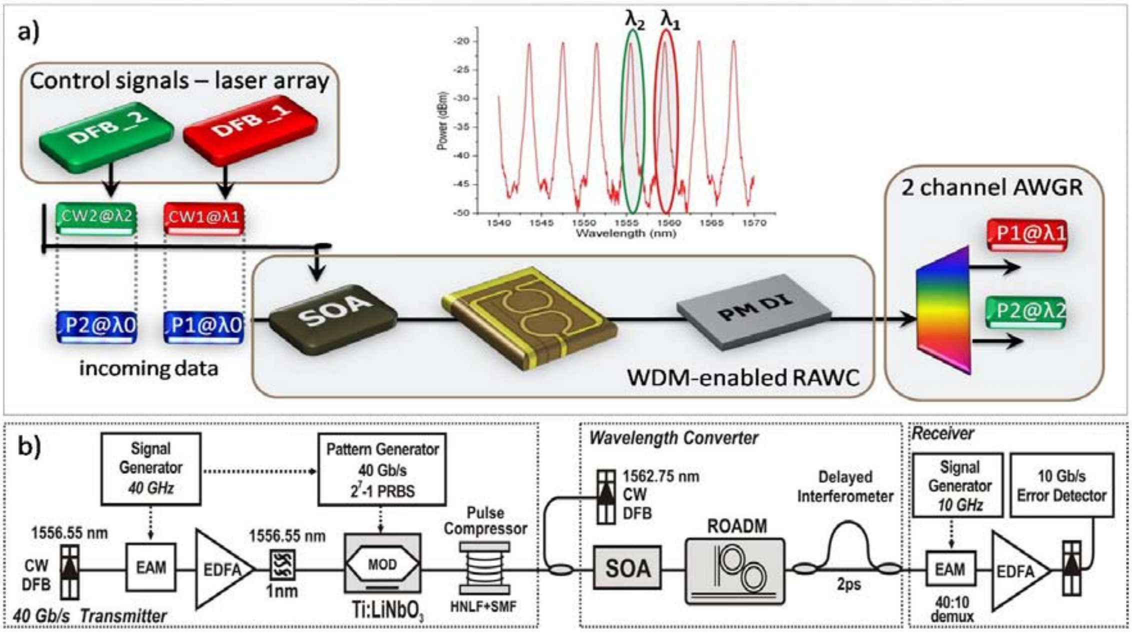

Figure 5 (a) Concept: all-optical wavelength conversion assisted by TriPleX micro-ring resonators, (b) experimental setup for 40 Gb/s continuous-mode wavelength conversion

- All-optical wavelength converter (AOWC) arrays. Each AOWC should be able to convert an optical packet to any of the different wavelengths supported locally by the router. Here we propose AOWCs implemented by cascading a single SOA and a periodic optical filter. Since SOAs and micro-ring resonators can be densely integrated in arrays, the SOA - TriPleX^{TM} ROADM scheme can provide scalable and power efficient AOWCs.
- Wavelength selective optical cross-connect (λ-OXC). The λ-OXC is responsible for switching optical packets from any input to any output depending on the wavelength assigned by the AOWCs. The λ-OXC can be implemented using cascaded TriPleX^{TM} ROADMs that will “drop” each packet to a specific output. By tuning the ROADMs the λ-OXC can be fully reconfigured supporting dynamic changes in the network topology.

The SOA - TriPleX^{TM} ROADM concept and its experimental demonstration are presented in the next sub-sections.

B. All-optical wavelength conversion using Si3N4-SiO2 micro-ring resonators

A key functionality for realizing high-speed photonic routing is the capability to wavelength convert packet-based traffic using high-speed, small footprint and energy efficient integrated components. A promising approach for implementing such wavelength converters is by exploiting the chirp induced through cross gain modulation of interacting pulsed and CW signals within a SOA [5]. By filtering specific spectral components of the wavelength-converted signal, slow SOA recovery temporal components are filtered, effectively speeding-up the impulse response of the wavelength converter system.

Figure 5 shows the ring-assisted AOWC (RAWC) concept. The data packets P1 and P2 enter the SOA serially as pump signals. After reading the header of P1 the router controller drives DFB_1 that generates a packet-length CW signal at wavelength λ1. This signal is launched in the SOA as probe signal, synchronized with P1. Similarly, the subsequent data packet P2 is temporally aligned with a packet CW at wavelength λ2. The pump signal modulates the SOA gain and via Cross-gain modulation (XGM), this modulation is transferred to the probe signal. As such, an inverted (wavelength-converted) copy of the pump signal appears at the output of the SOA, The temporal profile of the converted signal shows chirping due to the refractive index modulation in the SOA with the leading edge of the probe signal being red-shifted and the trailing edge being blue-shifted. A micro-ring resonator ROADM is cascaded after the SOA with the drop-port spectrum depicted in figure 2. The probe signals are selected to coincide with the transmission peaks of the ROADM and by detuning the micro-ring resonators with respect to the CW wavelengths either blue or red shift chirp filtering may occur, leading to the acceleration of the effective operational speed of the AOWC. Depending on the ROADM detuning, the signal at the output can be either inverted or non-inverted [6]. In the case of inverted AOWC, a cascaded Delayed Interferometer (DI) is required to restore pulse polarity. The spectral response of the DI is detuned so that one of the spectral “dips” of the notch filter is superimposed with the optical carrier. As such, the excess CW signal which remains un-modulated by the XGM effect in the SOA is removed and the polarity of the signal is restored.

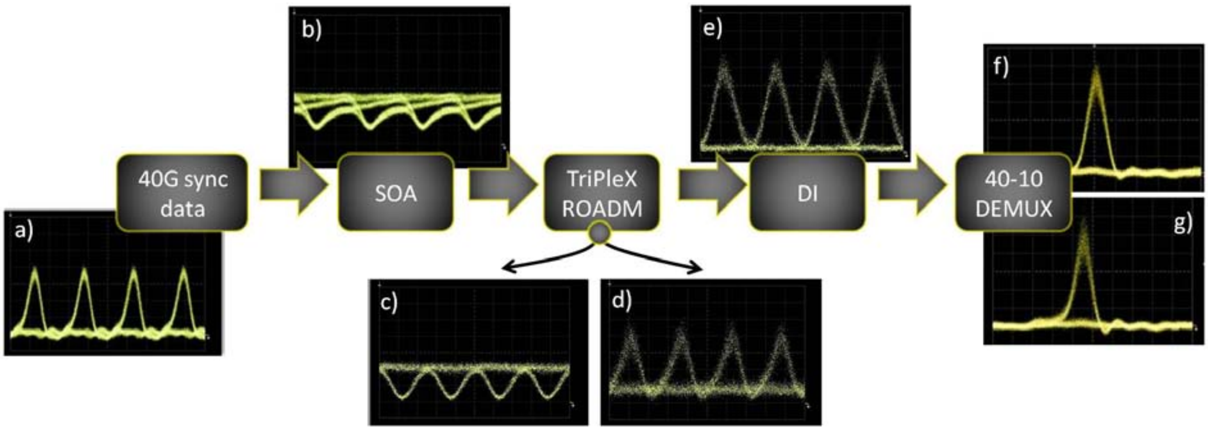

Figure 6. (a) Concept: all-optical wavelength conversion assisted by TriPleX micro-ring resonators, (b) experimental setup for 40 Gb/s continuous-mode wavelength conversion

C. Experimental evaluation

Initially we evaluated the performance of the RAWC by converting a continuous data stream on a single CW wavelength. Figure 5(b) shows the experimental setup. The 40 Gb/s transmitter consists of a CW DFB laser at 1556.55 nm, an Elecroabsorption Modulator (EAM) driven at 40GHz for pulse carving and a Ti:$LiNbO_3$ modulator to modulate the 40GHz clock and provide a 2^7-1 PRBS. The 40 Gb/s data stream pulses were compressed to 3ps using a non-linear fiber compressor.

The RAWC comprises the SOA, the 2nd order TripleX™ ROADM and a DI used only in the case of inverted operation. The ROADM consists of the two coupled Si_3N_4–SiO_2 TriPleX™ microring resonators that can be tuned independently by on-chip heaters. The Free Specrtal Range (FSR) of the device is 4 nm and the FWHM bandwidth is 0.6 nm. The DI is implemented using two polarization beam splitters (PBS) and standard polarization maintaining (PM) fiber. The DI provided a differential delay of 2 ps between TE and TM polarization components. The 2ps delay corresponds to 500 GHz FSR and is chosen to match the FSR of the ROADM and ensure that the DI spectral "dips" will attenuate only the optical carrier of the wavelength converted signal whereas the rest of the spectrum will remain unaffected. The local probe wavelength is provided by a CW DFB at 1562.75 nm. Finally the receiver part consisted of a 40-to-10 Gb/s EAM-based demultiplexer and a 10 Gb/s error detector.

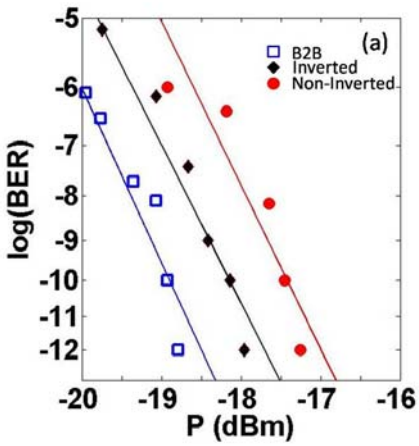

Figure 7. BER curves for RAWC of continuous data

Figure 6 illustrates the experimental results recorded with a 80 GHz digital communication analyzer. The eye diagram of the incoming data is depicted in figure 6a). Figure 6b) shows the signal directly at the output of the SOA indicating the device slow recovery time. Firstly, the ROADM is detuned by 0.1 nm selecting the lower signal wavelength (blue-shift chirp) and the inverted signal of figure 6c) is obtained. The eye diagram reveals

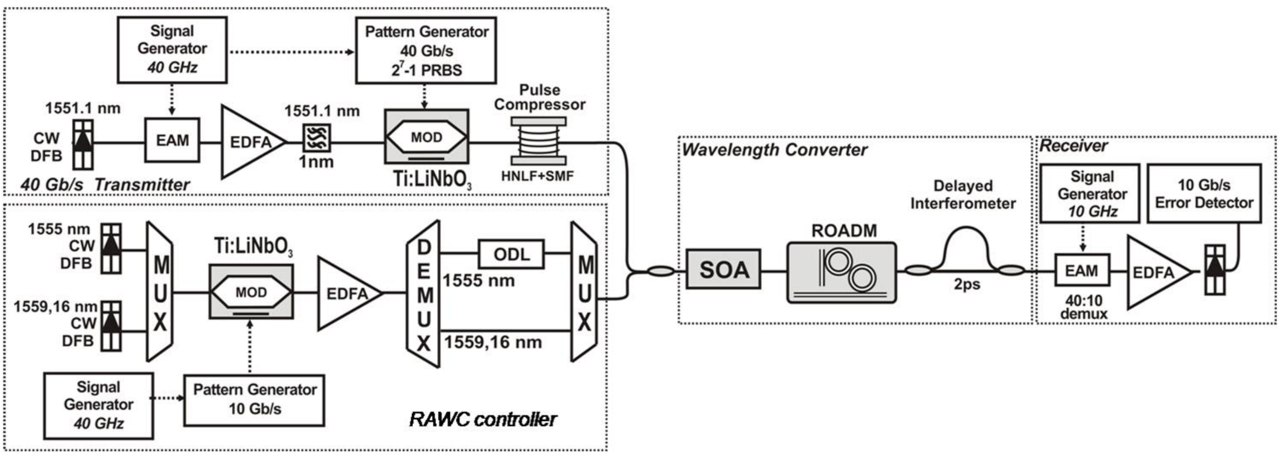

Figure 8. Experimental setup for the packet-mode, WDM-enabled RAWC.

that the ROADM filtering accelerates the operational speed of the system within the 40 Gb/s bit slot. The inverted signal at the output of the ROADM is launched in the PM DI and the pulse polarity is restored (figure 6e). Identical experimental setup was used for non-inverted wavelength conversion with the exception of the DI. By detuning the ROADM 0.3 nm with respect to the probe signal, the non-inverted eye diagram of figure 6d) was obtained. Figure Ff) and g) show the eye diagrams of the 10 Gb/s demultiplexed signals. Figure 7 shows the BER measurements. The inverted wavelength converted signal exhibits a power penalty of 0.84 dB whereas a power penalty of 1.5 dB is measured for the non-inverted signal. The higher penalty for the non-inverted operation is mainly due to the higher detuning required, which leads to higher loss and higher OSNR degradation.

The performance of the RAWC was also evaluated by wavelength converting a sequence of two 40 Gb/s time-domain multiplexed (TDM) optical packets. Each packet is converted onto a new wavelength, verifying the system capability to operate in a WDM environment. Figure 8 illustrates the experimental setup of the packet-mode RAWC. The two 40 Gb/s, TDM data packets of the same wavelength (1551.1 nm) enter the RAWC, temporally synchronized with two different CW packets. The CW packets are generated using two DFB lasers (1555 nm and 1559.16 nm), modulated at the packet rate in a Ti:$LiNbO_3$ modulator. A mux-demux stage and an optical delay line are used to provide the 2-wavelength TDM CW packet stream. Due to the temporal synchronization of the packet stream, the first data packet is converted to 1555 nm and the second packet to 1559.1 nm. In the RAWC, the multi-wavelength operation is enabled by the periodic response of the integrated ROADM.

Figure 9 illustrates the experimental results for the WDM-enabled operation. Figures 9a) and (b) show the pulse trace and the eye diagram of the inverted wavelength converted packets at 1555 nm. The same results for the wavelength converted packet at 1559.16 nm are depicted in figures 9c) and d). The eye diagrams reveal identical wavelength conversion for the two consecutive packets at the two different wavelengths. Figure 9e) shows the corresponding BER curves. Error free operation was obtained with a 0.8 dB power penalty for the data packets at 1559.1 nm and 1 dB power penalty for the data packets at 1555 nm. The optical power requirements were 7 dBm for the CW and 3 dBm for the data packets. The RAWC requires approximately 1.5 W of electrical power to operate, which includes the SOA bias and TEC currents as well as driving requirements for the micro-ring resonator heaters

IV. CONCLUSION

Realization of photonic integrated systems-on-chip using micro-photonic integration technologies is a promising path for developing transmission and switching hardware of next generation optical networks. Planar lightwave circuits, acting as photonic printed circuit boards can increase the integration scale and the aggregate throughput of photonic devices. The silica-on-silicon low index contrast material is capable for hybrid integration of III-V active elements such as lasers and modulators enabling high-capacity transmission and

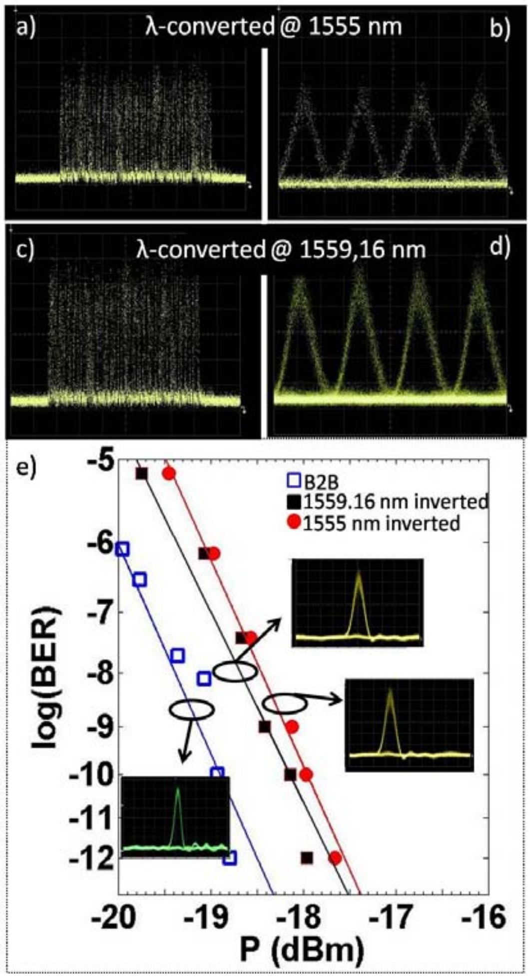

Figure 9. BER curves for RAWC of continuous data

regeneration systems. The TriPleX[TM] high-index contrast material is capable for ultra-small and power efficient components suitable for photonic routing platforms. Here we have reviewed the recent advances in component fabrication and system demonstration using these two promising material systems.

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