Advances in silicon photonics WDM devices

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System performance scaling imposes an increase of package-to-package aggregate bandwidths to interface chips in high performance computing. This scaling is expected to encounter several I/O bottlenecks (pin count, speed, power consumption) when implemented in the electrical domain. Several optical interface technologies are being proposed among which silicon photonics, considered as a promising candidate. In this paper we will review the recent progress made in this technology that may enable multi-channel WDM links for package-to-package interconnects: 1.0V drivers with microring modulators and compact manufacturable microring filters with efficient thermal tuning.

Keywords: Optical interconnects, photonics, silicon photonics, microring, WDM.

1. INTRODUCTION

System performance scaling imposes an increase of package-to-package aggregate bandwidths to interface chips in high performance computing up to several TB/s in the near future [1], [2] as predicted by the International Technology Roadmap for Semiconductors (ITRS). This scaling is expected to encounter several I/Os bottleneck (pin count, speed, power consumption) when implemented in the electrical domain. Several optical interface technologies are being proposed among which silicon photonics, considered as a promising candidate [3] for its compatibility with CMOS manufacturing and its ability to realize a high level of photonics integration with sufficiently good electro-optical performance.

1.1 Proposed WDM architecture in silicon photonics

Wavelength Division Multiplexing (WDM) is a common technique used in optical communication networks to minimize the number of fibers necessary to carry a given bandwidth. Such approach is also considered for short distance optical links to increase the bandwidth density through packages. An important challenge faced by this approach is to guarantee its operation over a wide range of operating temperature since these systems usually make use of components exhibiting a spectral response that varies with temperature. The impact of the operating temperature change can be reduced either by using thermally insensitive components or by maintaining the components at a given temperature by heating or cooling. Silicon photonics waveguide based components are typically very thermally dependent due to the large variation of the silicon refractive index with temperature. Designs have been proposed to realize thermally insensitive filters in silicon photonics but they remain large in dimensions and limited in bandwidth scalability. Alternatively filters must be thermally tuned to guarantee the system's operation. In order to minimize the energy used for thermal tuning and meet the energy per bit target, the use of microring resonator devices has been proposed for their small footprint and expected low insertion loss. A WDM architecture using microring devices is proposed in Figure 1. The WDM laser continuous wave (cw) laser source is coupled onto a silicon photonics circuit using a single polarization grating coupler. The unmodulated WDM light can be split through a broadband splitter to "power" multiple parallel links. Each link will be implemented as detailed in the schematic. Each wavelength

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along the common bus is modulated by a separate all-pass microring resonators that changes its absorption based on the associated driver voltage. The microring is tuned-in to match the desired wavelength using an integrated heater. The tuning is controlled actively using a monitoring photodiode that feeds an electronic circuit to adjusts the heater current. The WDM signal couples out through a single polarization coupler into a fiber array. At the receiver the signal is coupled onto the silicon photonics circuit through a polarization splitting coupler that sends each polarization to a different waveguide. For each polarization, each wavelength is then filtered out a coupled to a single photo-detector per wavelength followed by a Trans-Impedance Amplifier (TIA). The filters are made with microrings filters and are tuned to the desired wavelength using integrated heaters controlled by collective tuning.

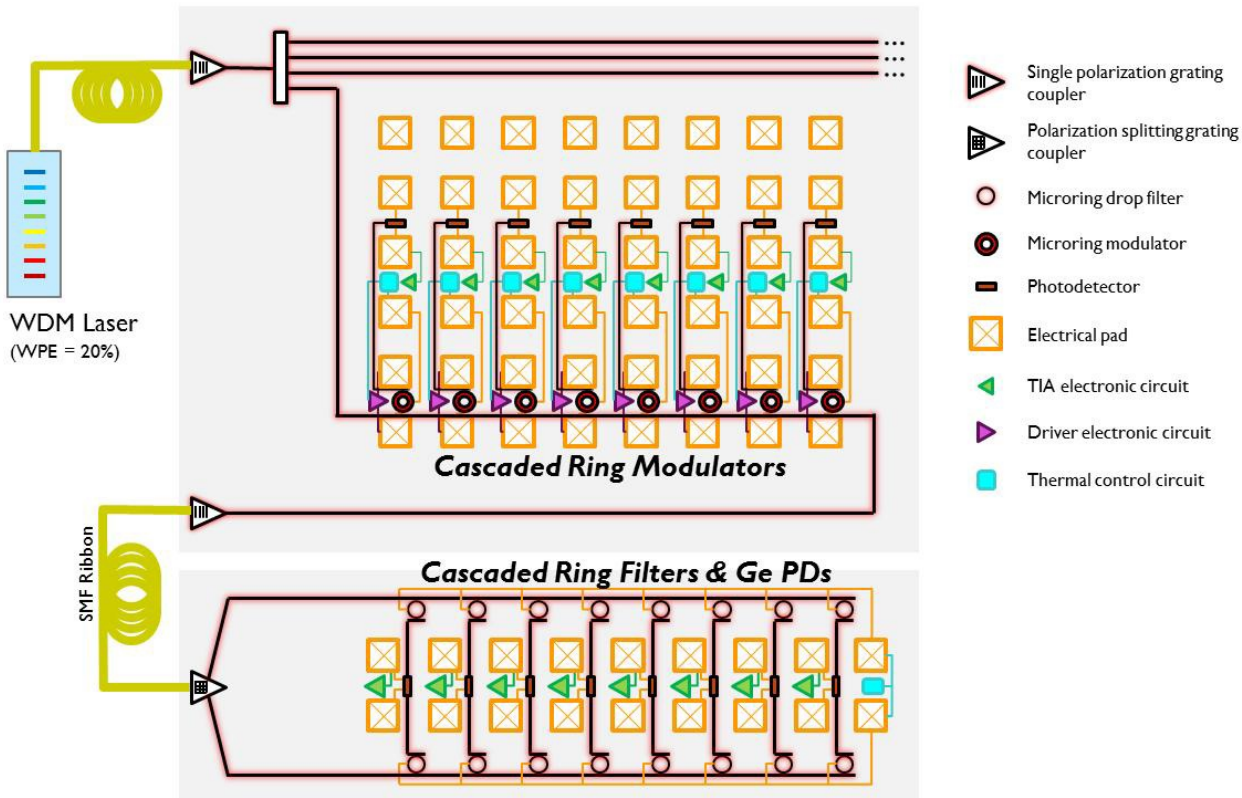

Figure 1. Schematic of a WDM architecture schematic based on micro-ring resonators and grating couplers.

1.2 Silicon photonics integration platform

Figure 2 provides a cross-section schematic of the silicon photonics technology used to implement the architecture proposed in 1.1. It is based on 200mm SOI substrates with a 220nm Si layer above a 2000nm buried oxide. The fabrication process uses a modified 130nm CMOS flow augmented with 193nm lithography for all the waveguide patterning layers and with low defect Ge-on-Si RPCVD epitaxy. The platform is flexible to allow silicon modulators made with p-n diodes or with MOS capacitors. High efficiency grating couplers are made using a poly-Si overlay. The integrated heaters are made using either doped silicon in the waveguide plane or with tungsten in the back-end-of-line layers.

The electronics circuits are fabricated on a separate die and assembled with the silicon photonics circuits using flip-chip assembly methods.

1.3 WDM challenges in silicon photonics

The proposed architecture faces many challenges, some of them are explained hereafter. First of all the microring modulator must produce a high extinction ratio at high bandwidth and low insertion loss while being driven by CMOS drivers operating at 1.0V supply. At the same time the modulators must be thermally tuned to operate at the desired wavelength. The thermal power as well as the power dissipated in the thermal control circuits must be reduced to minimize the impact on the total energy per bit spent for transmission. The transmitter challenges will be addressed in 2. On the receiver side it is critical to realize an efficient de-multiplexing of the incoming WDM signal using a simplified control and efficient heaters integrated. This will be addressed in 3.

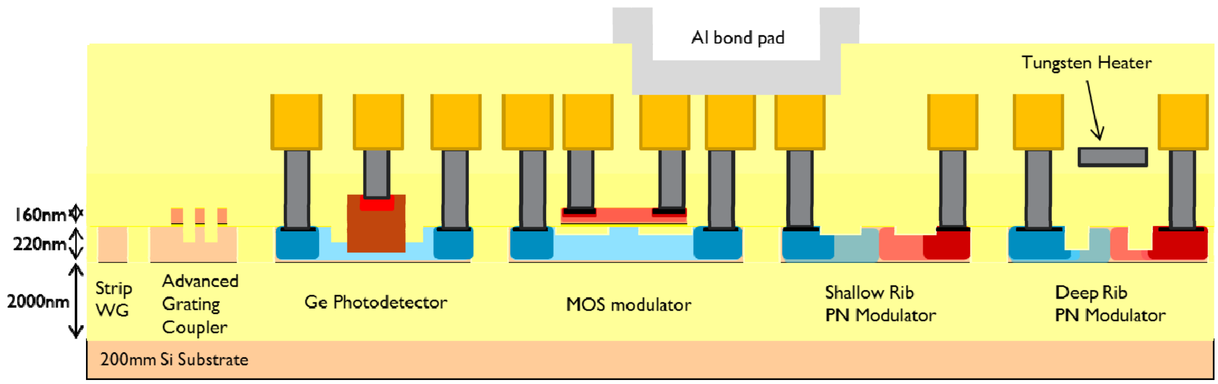

Figure 2. Cross section schematic of the silicon photonics integrated platform combining high quality passives, silicon modulators, integrated heaters and Ge-on-Si photo-detectors.

2. MICRORING-BASED WDM TRANSMITTER

The proposed architecture relies on silicon microring modulators for their compactness that limits the drivers complexity and power consumption and their ability to have low transmitter penalty (defined in [4]) at low peak-to-peak voltages. The first demonstration of silicon microring resonator modulators dates from 2005 [5] and continuous progress has been made since then to increase their operating speed [6], [7] and efficiency [8]. For instance we have demonstrated that the implementation of interdigitated PN junctions as proposed in [9] improves significantly the microring modulator performance with a modest bandwidth penalty [10]. As shown in Figure 3 the insertion loss is reduced and the extinction ratio is increased for a 1V peak-to-peak voltage swing. This results in a reduction of the transmitter penalty by about 2.5dB down to only 4.3dB for a modulation near 10Gb/s. A complete assessment of a transmitter performance must include the driver electronic circuit. As discussed above we have fabricated separately the electronics and the photonics dies and used flip-chip assembly to realize the electrical interconnection (**Figure 4**, left), similarly to the approach followed in [11]. We have realized a 1.5Vpp swing driver using a 40nm CMOS foundry technology that reduces significantly the transmitter penalty compared to a 1.0Vpp swing (**Figure 4**, middle) [12]. The driver and microring modulator operated at 10Gb/s ((**Figure 4**, right) at an energy of 380fJ per bit.

A well-known limitation of the microring-based modulator is its very limited operating bandwidth range as illustrated in **Figure 3** (c) and (d) with the grey bands, that is only a few tens of pm. Therefore a mismatch larger than this range between the incoming laser wavelength and the ring resonance results in a severely degraded modulation as discussed in [13]. It is therefore important to control the operating point of the modulator by controlling its temperature to a few tenths of a degree. This can be done by implementing a heater around or above the modulator coupled with a dynamic feedback loop as proposed in [14] and [15]. This poses two problems. First, the heater element should be as efficient as possible to minimize the power required for operation. This can be realized using local substrate removal that can significantly reduce the tuning power by isolating the heated waveguide as demonstrated by P. Dong in [16] with a ~150K temperature change with a power of 2.5mW. Second, the feedback loop must be driven by a signal monitoring the power in the modulator to operate the device a minimum transmitter penalty. The signal can be taped from the modulated output or taped directly from the microring by adding a drop port and then detected in a Ge-on-Si photodetector as proposed in [13]. For a 0.25mW of optical power at the modulator input the generated photo-current from the monitor diode is on the order of ~10μA while the dark current is below 30nA. Such signal is expected to be sufficient to feed the control loop.

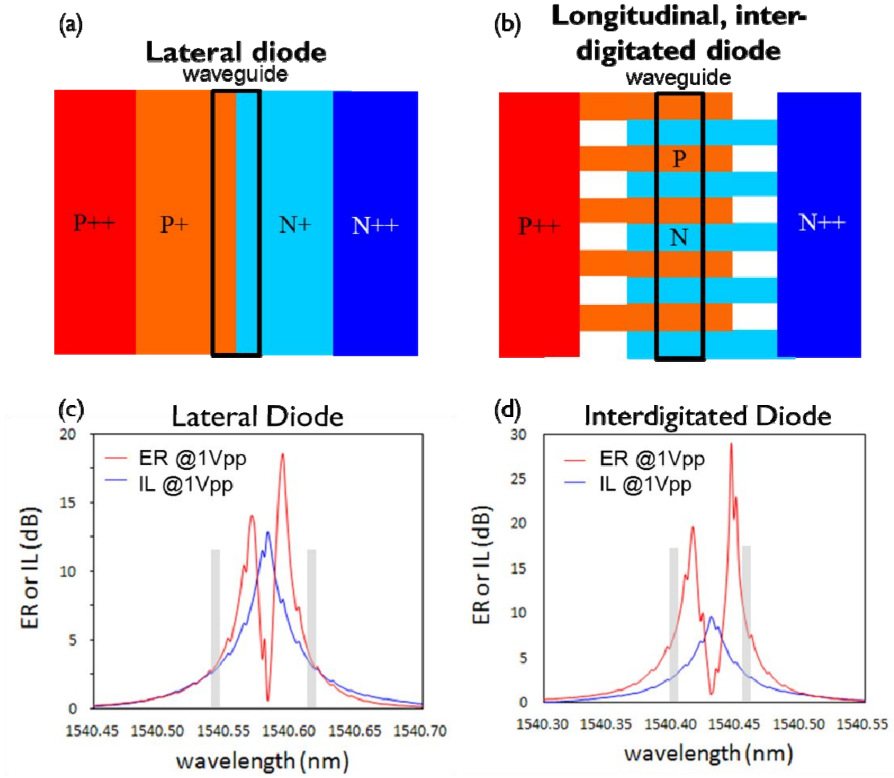

Figure 3. Top-down waveguide schematic of (a) a lateral p-n diode and (b) a interdigitated diode. The extinction ratio and insertion loss for a 1.0V peak-to-peak are shown for lateral (c) and longitudinal (d) diode configuration. In (c) and (d) the grey band illustrates the operating range with minimum transmitter penalty.

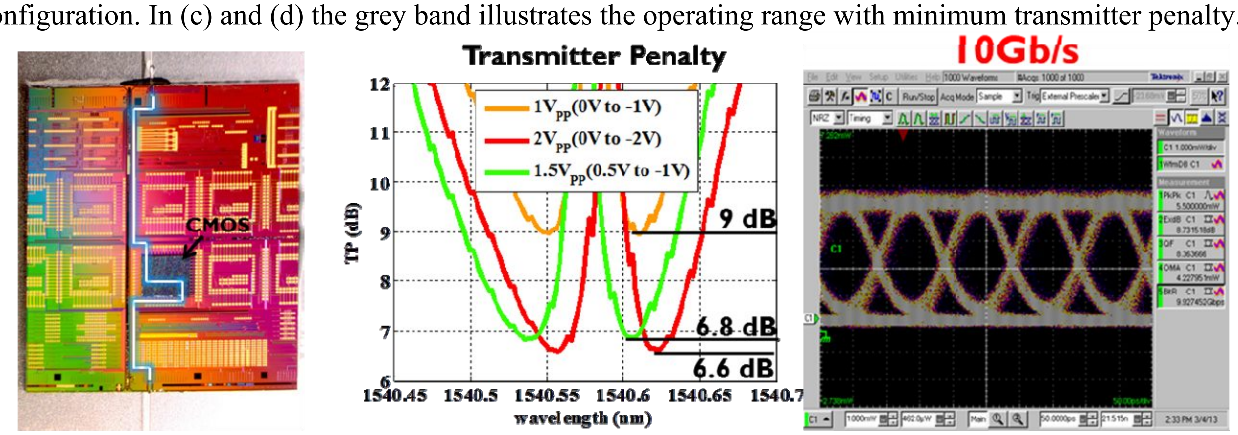

Figure 4. Left: Flip-chip 40nm CMOS driver circuit on top of a silicon photonics transmitter circuit with microring modulators. Middle: Transmitter penalty as function of wavelength for various voltage swing. Right: 10dB extinction ratio at 10Gb/s modulation realized with a 40nm driver operating at V_{DD}=1.1V.

3. MICRORING-BASED WDM RECEIVER

The WDM receiver proposed in **Figure 1** is based on the de-multiplexing of the WDM signal using microring based filters that are compact hence more suited for an efficient thermal control than other WDM filters. This approach has been proposed by Zheng et al in [17] and the concept is illustrated in **Figure 5**.

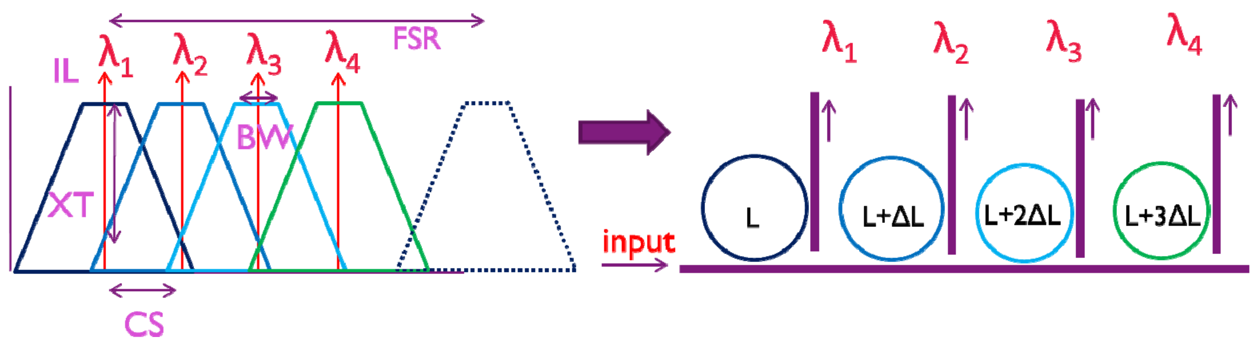

Figure 5. Demultiplexer spectrurm design and implementation in microring resonators.

It is well-known that these resonator devices are very sensitive to fabrication variation when implemented in highly confined photonics technology: a 1-nm waveguide thickness or width variation can lead to a 1-nm microring spectral response shift. Because of the Lorentzian response of a single ring resonator filter, any small process variation will lead to an excessive insertion loss as shown in **Figure 6** (left): a 4-channel single ring de-mux filter shows a resonance wavelength range of 0.75nm resulting from the local linewidth variation from one device to the next. This resonance wavelength variability sets the minimum insertion loss for the 1x4 de-multiplexer to -6dB if the rings are not tuned individually to their operating wavelength. In [18] we proposed a 4-channel filter based on flat-top double-ring resonators. This type of filter allows to mitigate the impact of the local process variability on insertion loss and crosstalk. We have demonstrated this using 130nm CMOS fabrication process combined with 193nm lithography. The "as fabricated" 4-channel 300GHz channel spacing de-multiplexer exhibits a worst-channel insertion loss of -1.4dB and crosstalk of -18dB (wafer average).

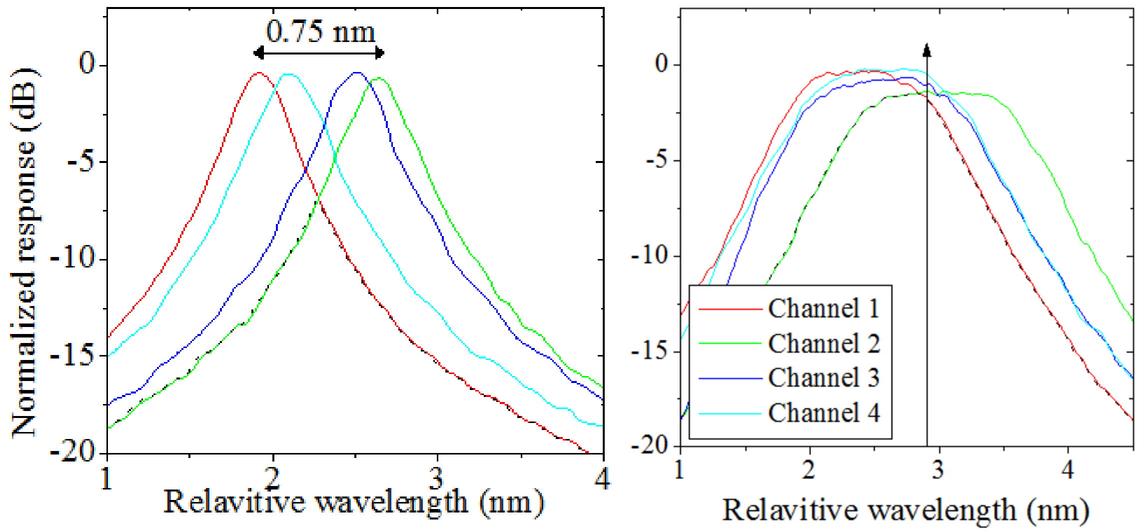

Figure 6. A four channel demultiplexer spectral response for (left) single ring and (right) double ring filters. The responses wavelength is normalized to the designed channel center wavelength.

This filter performance makes possible the implementation of a simplified filter thermal control loop that requires only one photo-detector and one heater current by monitoring only the through signal that is not dropped by the filters and tuning the ring filters collectively.

4. CONCLUSION AND OUTLOOK

The silicon microring-based devices performance has significantly improved in the past years with improved fabrication processes and improved designs. Modulators can operate at high speed up to 60Gb/s and designs can be tailored to have low transmitter penalty using CMOS compatible drivers operating with ~1.0V power supply. Work is on-going to further improve the operating speed – transmitter penalty trade-offs. Options have been proposed and demonstrated for realizing efficient thermal control and locking the modulator operating wavelength with the incoming cw laser wavelength. This topic must remain a development focus to enable commercial deployment of such technology. On the receiver side the recent demonstration of microring-based 4-channel 300GHz channel spacing filter with a simplified thermal control makes now such approach practical. Our on-going work aims at demonstrating that such concept can be extended to a polarization diverse circuit including 2D grating couplers. We are also exploring the limits of this approach to realize denser and coarser WDM architectures. Although it was not addressed in this paper, the fiber-to-chip coupling must be also improved to be wider bandwidth and more efficient to meet coarse WDM requirements.

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