A tunable 1x4 silicon CMOS photonic wavelength multiplexer/demultiplexer for dense optical interconnects

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Abstract: We report the first compact silicon CMOS 1x4 tunable multiplexer/ demultiplexer using cascaded silicon photonic ring-resonator based add/drop filters with a radius of 12µm, and integrated doped-resistor thermal tuners. We measured an insertion loss of less than 1dB, a channel isolation of better than 16dB for a channel spacing of 200GHz, and a uniform 3dB pass band larger than 0.4nm across all four channels. We demonstrated accurate channel alignment to WDM ITU grid wavelengths using integrated silicon heaters with a tuning efficiency of 90pm/mW. Using this device in a 10Gbps data link, we observed a low power penalty of 0.6dB.

OCIS codes: (250.0250) Optoelectronics; (130.0130) Integrated optics devices; (130.7408) Wavelength filtering devices (200.4650) Optical interconnects; (060.4510) Optical communications

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1. Introduction

Si photonics offers unique opportunity for implementing high performance chip scale interconnection networks with low cost [1–4]. Unlike on-chip electrical interconnects where multiple metal layers can be used readily for signal transport, Si photonic interconnects require silicon real estate for its signal routing using silicon waveguides. Although special design enables off-chip network routing [1], most of the networks require significant on-chip routing [2–4]. To minimize its impact to electronics, high density integration is required for the photonic links used to build the communication networks in addition to requirements on energy efficiency, latency, and bandwidth. Wavelength division multiplexing (WDM) is a natural solution to effectively reduce the number of interconnect waveguides, and consequently improve the integration density.

Several different approaches have been reported for wavelength channel multiplexing and de-multiplexing on silicon platform, including array waveguide grating (AWG) [5], echelle grating [6], MZI based interleaver [7], as well as cascaded ring add/drop filters [8,9]. Multiplexers based on AWG, echelle grating devices and interleavers are typically large in size, not desirable for area sensitive intra-chip applications. Ring resonator based add/drop filters using high index contrast Si waveguide, on the other hand, have the potential to make very compact multiplexer/demultiplexers with desirable optical performance. Ultra-compact single ring add/drop filter has been demonstrated using 3um radius ring resonator [10, 11]. High order ring resonators with multiple coupled rings were used to improve the pass band and channel isolation [12, 13]. To make multi-channel multiplexers, multiple add/drop filters were cascaded using rings slightly different in size [14].

One critical hurdle for ring resonator based WDM filters to overcome before practical application is its center wavelength accuracy, as well as the accurate channel spacing for multi-channel multiplexers or demultiplexers. Due to manufacturing tolerances, the effective index of the Si waveguide varies due to silicon layer thickness variation on SOI substrate, waveguide width variation, etch depth variation for ridge waveguide structure, as well as the residual stress on substrate. Each factor increases the required tuning range [1]. In addition, ambient temperature change also affects the waveguide effective index. All these variations cause significant wavelength shift for ring resonator based WDM filters. Although special fabrication techniques have been reported effective in achieving accurate channel spacing for multi-channel devices [15], tuning would still be required to align the filter center wavelengths with the pre-selected wavelength channels. In this paper, we demonstrate a 4-channel CMOS WDM multiplexer/demultiplexer using cascaded identical single ring resonators with integrated thermal tuner. The filters were tuned to align with WDM ITU grid wavelength channels with 200GHz spacing. Less than 1dB insertion loss (excluding the

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grating coupler IO loss), and better than 16dB channel isolation were achieved. In the following sections, the design of the device will be discussed. Optical performance characterization results, as well as high speed optical transmission testing results will be presented.

2. CMOS photonic 1x4 Si ring multiplexer

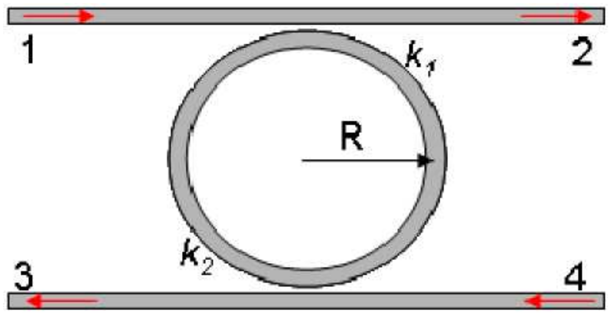

Fig. 1. Add/drop filter using ring resonator coupling with two bus waveguides.

Ring resonator coupled with two bus waveguides forms a 4-port add/drop filter device, as shown in Fig. 1. For unit optical input at port 1, its through output at port 2 and drop output at port 3 can be expressed as Eq. (1) and (2), respectively [16–19]

$$S_{21} = a\frac{\sqrt{1-K_1} - \sigma\sqrt{1-K_2}e^{-j\beta 2\pi R}}{1-Ge^{-j\beta 2\pi R}}, \quad K_i << 1 \tag{1}$$

and

$$S_{31} = -\frac{a^2\sqrt{K_1K_2e^{-\alpha 2\pi R}e^{-j\beta 2\pi R}}}{1-Ge^{-j\beta 2\pi R}}, \quad K_i << 1 \tag{2}$$

Where R is the radius of the ring, K_1 and K_2 are the bus waveguides to ring waveguide coupling coefficients, a is the amplitude loss per pass at the ring coupling, $\beta=kn_{eff}$ is the propagation constant, $k=2\pi/\lambda$ is the vacuum wave number, n_{eff} is the effective refractive index of the waveguide, α is the amplitude attenuation coefficient of the waveguide loss, $\sigma=a^2e^{-\alpha 2\pi R}$ is the round trip loss assuming the couplers have the same loss coefficients: a, and $G=\sigma\sqrt{1-K_1}\sqrt{1-K_2}$ is used to simplified the expressions.

For high speed data transmission, it is desirable for the add/drop filter to have low loss and wide pass band. Given ring waveguide loss and negligible coupler loss, the bus-waveguides-to-ring coupling coefficients control the single ring add/drop filter loss and bandwidth. Assuming identical coupling at both couplers with small loss (a=0.999), and 10dB/cm ring waveguide loss, the filter transmission profiles with 12μm ring for various coupling coefficients are shown in Fig. 2. Higher coupling ratio leads to lower loss and wider pass band for the drop filter. At the same time, unfortunately, it also results in lower channel isolation. Higher ring waveguide loss increases the drop filter loss, but doesn't affect the pass band much because the loaded Q of the device is dominated by the coupling ratio. One nice feature to mention is that even significant change in coupling ratio has little impact to the through port output for neighboring wavelength channels.

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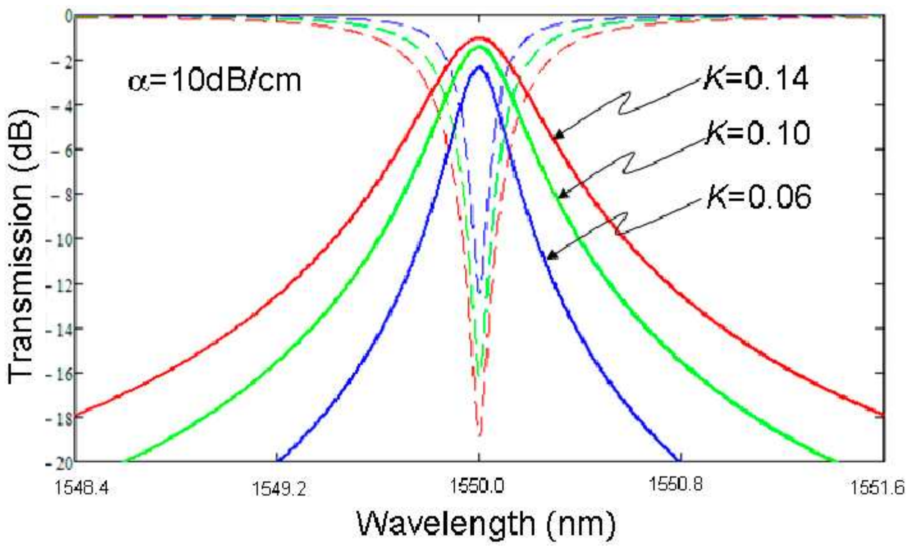

Fig. 2. Ring add/drop filter profile versus different bus waveguide to ring coupling ratio for given ring waveguide loss (α=10dB/cm) and coupler amplitude loss (*a*=0.999).

We used a Luxtera-Freescale 130nm SOI CMOS platform for device development. Ridge waveguides were optimized for both low loss and to enable tight bending for compact devices with waveguide thickness of 300nm, width of 360nm, and slab height of 150nm. This waveguide structure only support TE mode. To design the drop filter correctly, we first characterized the coupling from bus waveguide to different size rings. The measurement results are shown in Fig. 3, indicating that even for small ring with 10μm in radius, coupling ratio could be adjusted from very little to reasonably big by varying the gap to achieve desirable pass band, loss and channel isolation.

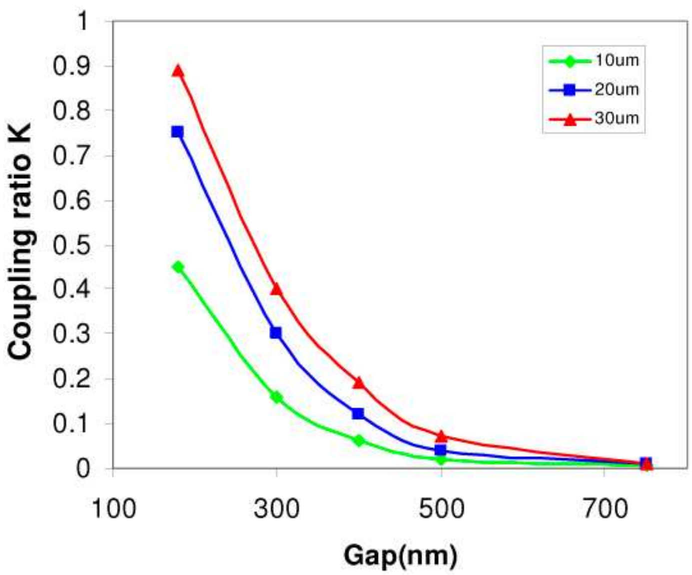

Fig. 3. Measured bus waveguide to ring coupling ratio for different gaps and different ring radius of 10μm,20μm, and 20μm.

To have good channel isolation, we chose channel spacing of 200GHz (or 1.6nm) for the 1x4 multiplexer/demultiplexer. We chose this relatively wide channel spacing also because

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our focus with this work was not to maximize spectral density but rather to minimize power density [1]. Using widely spaced WDM channels allows us to use single-ring filters instead of high order ring filters to achieve desirable optical performance, and hence less tuning power. But we are really not able to use coarse WDM because of the limited optical bandwidth of silicon optical modulators and other components. So instead we use neither very dense WDM nor coarse WDM, but rather an "intermediate-density" WDM grid.

We chose ring radius of 12µm to have big enough free spectral range (FSR) to accommodate 4 channels at 1.6nm spacing. Expecting low penalty for 10Gbps data transmission, we aim for drop filter with larger than 0.4nm 3dB bandwidth. The pass band is determined by the loaded Q of the device, which is dominated by the coupling coefficient K as we discussed above. Using Eq. (2), we estimated K of about 0.15 is needed. Based on the measured coupling, we selected gap of 325nm from the bus waveguide to the ring. We cascaded four add/drop filters on the same bus waveguide to form a 4 channel multiplexer/demultiplexer. Instead of using rings slightly different in size to achieve filters with different center wavelengths, we used identical rings with integrated thermal tuning. For better efficiency, we integrated the heater directly to the ring waveguide by doping part of the ring slab as doped resistor, as inset SEM picture shown in Fig. 4.

The fabricated 1x4 WDM multiplexer/demultiplexer with integrated thermal tuning is shown in Fig. 4. The total area of a single ring resonator including the tuning resistors was 26x40 microns. The pitch for the ring devices was 500µm. As shown below, we observed no thermal crosstalk between devices at this pitch. Grating couplers at 250µm pitch were used for optical I/O, coupling to fiber array. Injecting current to the doped resistors though the tuning pads, we can heat up the ring waveguide, and in turn change the index of the waveguides to shift the filter center wavelength until it's aligned with the target wavelength channel.

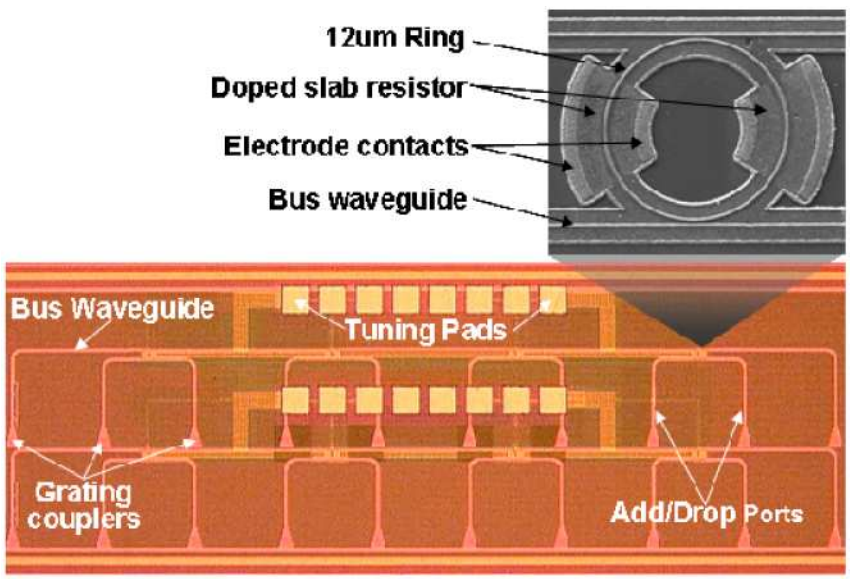

Fig. 4. Fabricated 1x4 multiplexer/demultiplexer by cascading 4 ring add/drop filters with integrated doped resistor thermal tuner (shown in the inset SEM picture) using FreeScale 130nm SOI CMOS process. Grating couplers are used for optical I/Os.

3. Performance testing and results

We tested the fabricated device for both optical performance parameters and high speed data transmission performance. Details are discussed in the following context.

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3.1 Optical characterization

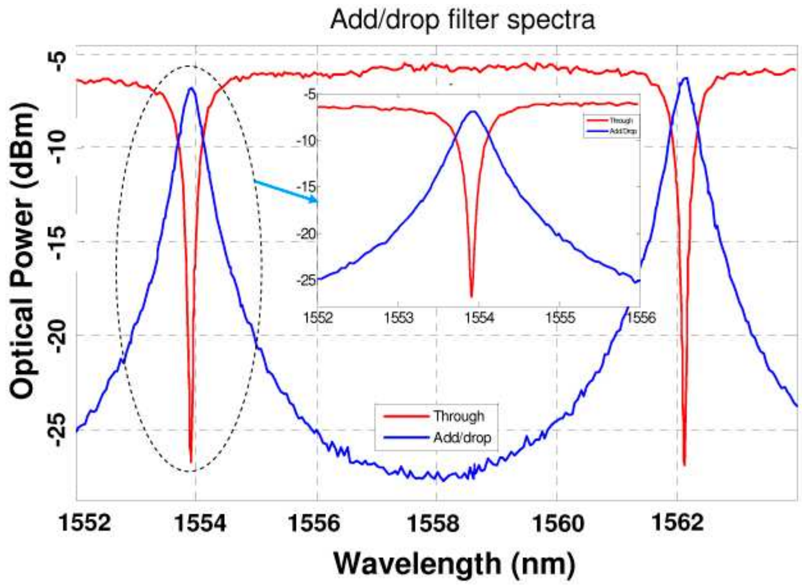

Fig. 5. The through port (red) and add/drop port (blue) spectra of the fabricated CMOS ring add/drop filter. The inset blow-up plot shows the details of one of its resonances, indicating 0.4nm 3dB pass band, and better than 16dB channel isolation for 1.6nm channel spacing.

Single add/drop filter performance was first characterized by injecting light to port 2, and measuring the through output at port 3 and drop output at port 1 using fiber array and tunable laser source. The result spectra are shown in Fig. 5. The free spectral range of the ring is about 8.2nm. The 3dB pass band, $\delta\lambda_{FWHM}$, is measured to be about 0.4nm. The peak insertion loss, however, cannot be obtained from the measurement directly because the fiber to grating coupling loss is unknown. Assuming the grating coupler loss is the same for all three ports, the filter insertion loss can be calculated from the following mathematics. The 3dB pass band, $\delta\lambda_{FWHM}$, can be expressed as [17]:

$$\delta\lambda_{FWHM} = \frac{\lambda^2}{\pi n_g 2\pi R} \cdot \frac{1-G}{\sqrt{G}} \tag{3}$$

The coupling ratio at both bus waveguides are the same,

$$K_1 = K_2 = K \tag{4}$$

The measured through port loss, and drop port loss at the center wavelength are,

$$Loss_{Through} = -\left[10\log_{10}(|S_{21}|^2_{\lambda c}) + Loss_{GC}\right] \tag{5}$$

$$Loss_{Drop} = -\left[10\log_{10}(|S_{31}|^2_{\lambda c}) + Loss_{GC}\right] \tag{6}$$

where $Loss_{GC}$ is the fiber to grating coupler coupling loss, and λc is the filter center wavelength. From Eq. (3)~(6), we obtained K=0.128, and $|S_{31}|^2_{\lambda c}$ =0.824, or in other words, 0.84dB insertion loss for the drop filter.

Next, we tested the performance of the cascaded filters. The through port spectrum (port 1 to port 10), as plotted in Fig. 6, shows that the four devices have similar FSR of about 8nm, and their resonances are slightly different from each other. It is expected for 4 rings designed

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to be identical. Due to epi-thickness variation and manufacturing tolerances, the effective index of the rings will be slightly different from each other. Obviously, we need to tune the filters to align with the selected wavelength channels.

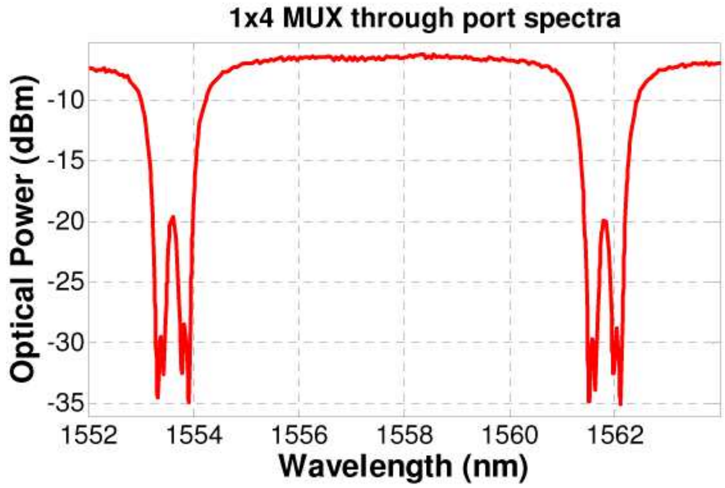

Fig. 6. The measured through port spectra of the 4-channel CMOS ring multiplexer/demultiplexer.

The integrated thermal tuning resistor showed resistance about 200Ω. Injecting current through the resistor, we were able to heat up the ring and move the filter anywhere within the FSR. Figure 7 shows the filter center wavelength shift vs. tuning power for all four channels. Fairly uniform and linear tuning response was obtained with efficiency of about 90pm/mW.

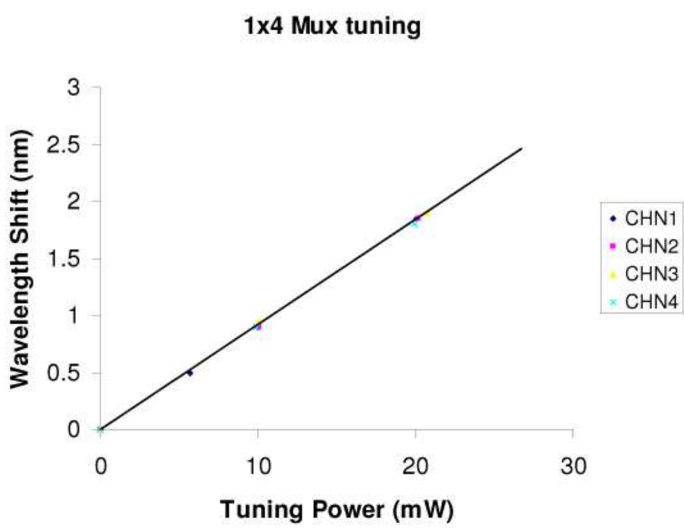

Fig. 7. Measured thermal tuning performance with the integrated doped resistor heater. Uniform performance obtained across 4 channels with tuning efficiency of about 90pm/mW.

We tuned the four filters with different power to align them with ITU WDM grids at 200GHz spacing. Figure 8 shows the measured spectrum of the 4-channel multiplexer/ demultiplexer. The center wavelengths of the four channels are 1554.13nm, 1555.75nm, 1557.36nm, and 1558.98nm respectively. Uniform performances, larger than 0.4nm 3dB passband, less than 1dB insertion loss, and better than 16dB channel isolation, were achieved across all four channels.

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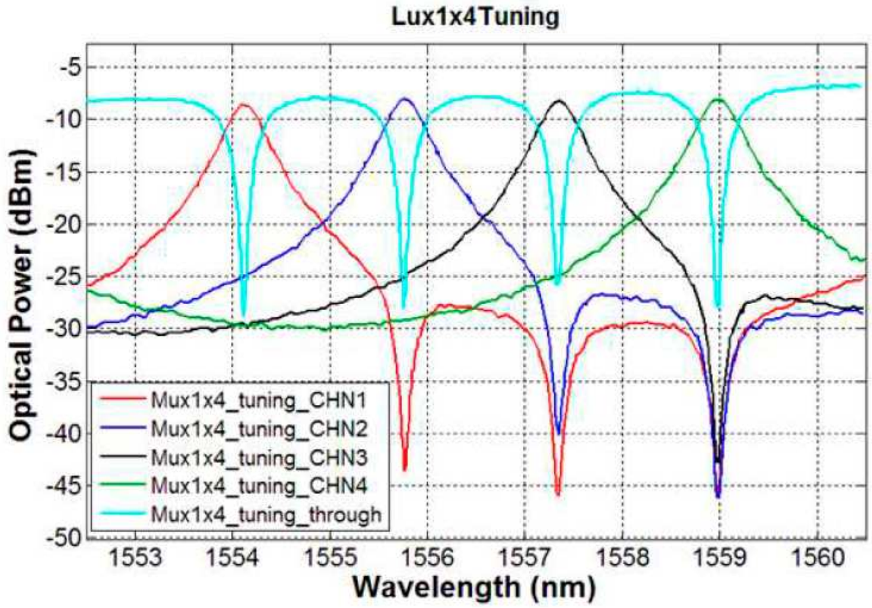

Fig. 8. The through spectra (light blue) and drop spectrums (red, blue, black, and green) of the CMOS 4-channel WDM multiplexer/demultiplexer thermally tuned to WDM ITU wavelength channels 1554.13nm, 1555.75nm, 1557.36nm, and 1558.98nm.

3.2 High speed data transmission performance

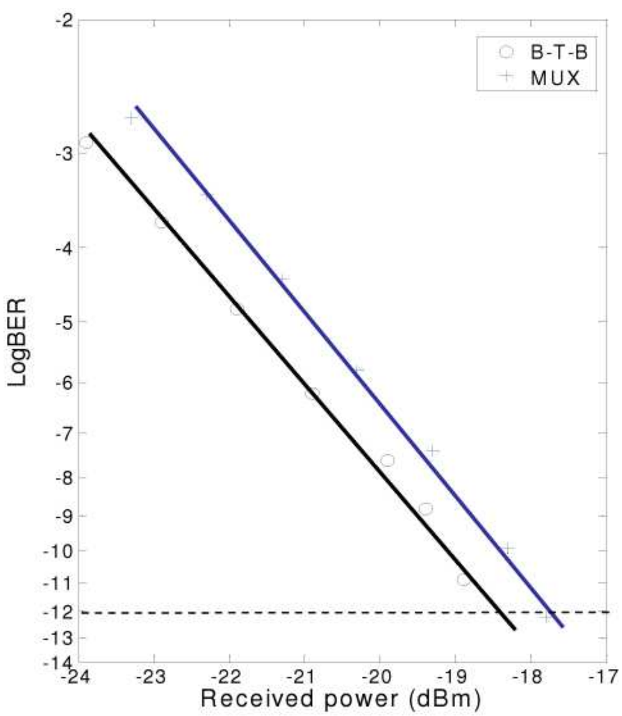

Fig. 9. BER versus receiver power for transmitter/receiver back-to-back (black) and through the CMOS ring add/drop filter (blue). About 0.6dB power penalty at receiver is observed.

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High speed data transmission through the multiplexer was performed using off-the-shelf 10G lightwave transmitter and receiver. Compared to transmitter/receiver back-to-back measurement, we observed about 0.6dB power penalty at receiver for bit error rate of 10^{-12}, as depicted in Fig. 9. We further detune the filter to characterize impact of center wavelength misalignment. Figure 10 plots the BER versus received optical power for filter center wavelength shift of 0nm, 0.04nm, 0.08nm, 0.125nm and 0.266nm respectively. In addition to the measured signal attenuation of 0dB, 0.1dB, 0.8dB, 1.4dB, and 4dB respectively due to the center wavelength offset, we observed negligible power penalty at the receiver. It indicates that for small filter center wavelength offset, the power penalty to high speed signals can simply be approximated by the signal attenuation to the signal carrier wavelength from the shifted filter. Given the Lorentzian filter shape, the center wavelengths of the add/drop filters have to be maintained fairly accurately (<0.1nm) to have little impact to high speed data transmission, *i.e.* less than 0.5dB power penalty at the receiver, which would require ring temperature stability of better than 1°C when thermal tuning is used.

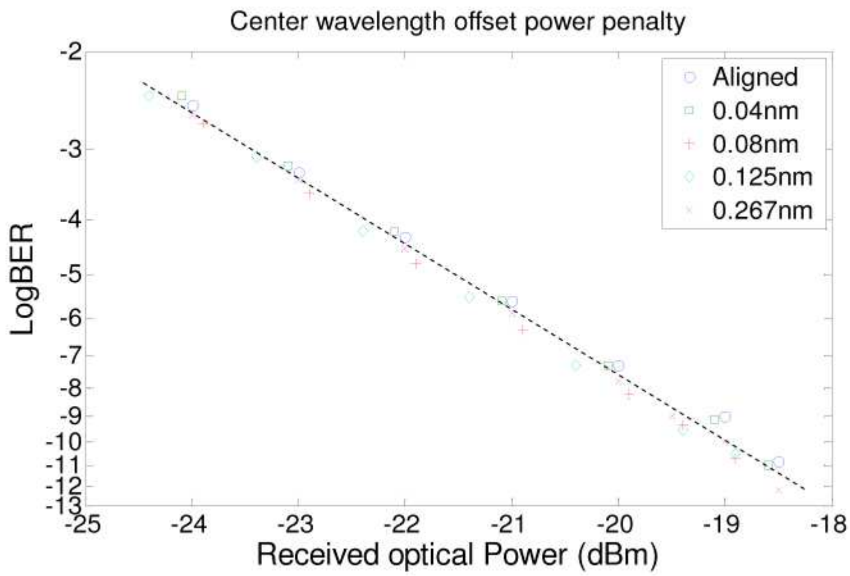

Fig. 10. BER versus received power for 10Gbps data transmission through the CMOS ring add/drop filter with center wavelength offset of 0nm, 0.04nm, 0.08nm, 0.125nm, and 0.267nm respectively. Power penalty due to the wavelength offset from the filter resonance peak was observed to be negligible.

4. Conclusions

We demonstrated a tunable CMOS 1x4 multiplexer/demultiplexer using cascaded ring resonator based add/drop filters with integrated doped-resistor thermal tuner. This compact WDM device achieved low insertion loss, good channel isolation and wide enough pass band for high speed data transmission. These promising performance results match well with the design expectations. Using thermal tuning, add/drop filters made of identical rings were aligned with WDM ITU grid wavelengths accurately with 200GHz spacing. At a relatively large ring pitch of 500microns, no observable thermal crosstalk was measured. Future work will include devices placed at a smaller pitch. Due to a non-ideal filter passband, we observed a 0.6dB power penalty for 10Gbps data transmission. This can be reduced further when higher order flat-top filters are used. In addition, it is found that the filter center wavelength offset relative to the signal carrier wavelength simply attenuates the high speed optical data signal with negligible additional power penalty. Using smaller rings and cascading more rings together, WDM multiplexer/demultiplexer with more channels can be built seamlessly. With

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proper ring tuning control, we believe cascaded ring multiplexer/demultiplexers can and will play an important role in dense chip scale interconnects.

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