Wavelength Routing and Multicasting Network in Ring-Based Integrated Photonics

Zhan Su,[1] Erman Timurdogan,[1] Michele Moresco,[1] Gerald Leake,[2] Douglas D. Coolbaugh,[2] and Michael R. Watts[1,*]

[1]Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[2]College of Nanoscale Science and Engineering, University at Albany, Albany, New York 12203, USA
**Corresponding author: mwatts@mit.edu*

Abstract: Wavelength routing and multicasting network is demonstrated in cross-grid waveguide structure. High channel efficiency and extensibility to a large-scale system are achieved with 0.5mW tuning power and 0.8dB power penalty among all casting functions.
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1. Introduction

Silicon photonics [1] has attracted attentions in both academia and industry with its promising applications in large-scale, high-bandwidth, ultralow-power [2] optical interconnects. Electronic switches are currently dominating the market while struggling to scale without significant cost penalty. Silicon photonics can be fabricated and integrated within current CMOS fabrication foundries and adds insignificant cost penalty due to its large feature size (>100nm). In addition, switching from electrical to optical domain enables multiplexing in wavelength and polarization, increasing bandwidth density within a single fiber, leading to a scalable solution. However, this requires functional silicon photonic systems to be realized. There are two types of routing – from a port to a designated port (unicast) or to multiple designated ports with equal power splits (multicast). Up to date, silicon photonic systems were only able to realize these functions separately. Using conventional tunable silicon photonic add-drop filters, high radix unicast network was demonstrated in ref. [3]. However, multicasting was not possible since the power in one wavelength could not be split into multiple ports. A photonic multicast network was realized using Four-Wave-Mixing (FWM), where a modulated pump wavelength is converted to multiple optical wavelengths (i.e. frequency channels) [4]. The nonlinear nature and high optical intensity constraint of FWM limited the implementation of this technique in large-scale networks. Therefore, a linear filter that drops partial power of the channel and splits the power into multiple ports is desired. The partial-drop filters [5] were introduced recently for this exact solution, making it possible to have both unicasting and multicasting functions in a standalone integrated system.

Here, we demonstrate for the first time a combination of unicast and multicast silicon photonic network (each with 2λ routing). A cross-grid architecture [6] is selected and the partial and full add-drop filters were used for multi- and uni-cast functionalities. All filters have integrated silicon tuners (~8.25uW/GHz tuning efficiency) for wavelength alignment to the designated wavelength-division-multiplexed (WDM) channels. The total tuning power for alignment was only 0.5mW. When a data stream is injected to these channels and routed throughout the network, "error-free" (bit-error-rate < 10^{-12}) routing were realized and power penalty variations were only 0.8dB among all casting functions. The demonstrated network building blocks combined with the flexibility of cross-grid architecture can enable a massively scaled network.

2. Device Characterization and Experimental Results

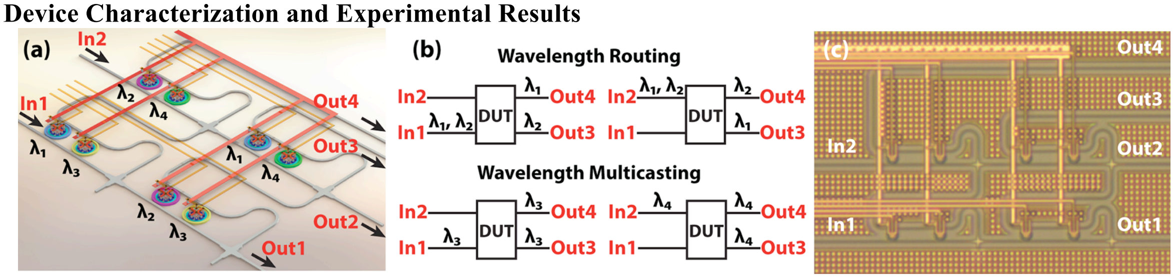

Fig. 1. (a) Schematic of the wavelength routing and multicasting network. Each wavelength denotes the resonance of the microring resonator. (b) Illustration of the functions of the network. (c) Optical image of the fabricated device. Each ring can be thermal tuned by an integrated thermal tuner.

The schematic of the wavelength routing and multicasting network is shown in Fig. 1 (a) and its functions are illustrated in Fig. 1 (b). It consists of two input ports and four output ports (2 thru ports, 2 drop ports). In the schematic, λ_1 and λ_2 denote normal ring filters with equal gaps to bus and drop waveguide where channel-dropping function (uni-casting) is performed. Thus, information encoded in different wavelength to the same input ports will be routed to different output ports (Out3 and Out4 ports). Different from full-dropping functions of λ_1 and λ_2 filters, partial-drop function is utilized in λ_3 and λ_4 filters. This way, information carried by λ_3 from input 1 and λ_4 from input 2 will be multicasted to both drop ports. In total, only one wavelength channel is occupied for multicasting purpose for each input.

The proposed structure was fabricated on a 300mm SOI wafer with a 200nm device layer using optical immersion lithography. The integrated heaters are introduced by p and n type doping concentrations of $\sim 1\times10^{18}$ cm^{-3} and interior p+ and n+ contacts with doping concentrations at a level of $\sim 1\times10^{20}$ cm^{-3}. The interior ridge microring combined with 400nm wide bus waveguide, ensures single-mode coupling into the microring resonators [7]. The optical image of the fabricated device is shown in Fig. 1 (c). In total, eight tunable ring filters are utilized in this network. Each ring has a tuning efficiency of ~8.25 μW/GHz. The transmission spectra of the network after thermal tuning are shown in Fig. 2 (a) and (b). Large and clean FSR of 4.22THz and four well-separated wavelength channels (marked in Fig. 2) are demonstrated. It is easy to see that the received powers of the multicasting wavelengths channels (λ_3 and λ_4) are ~3dB less than the routing wavelengths channels (λ_1 and λ_2). This is related to the multicasting function where total input power is evenly divided among all the output ports. The full-width-half-maximum (FWHM) of tunable partial- and full-drop filters were 54GHz and 62GHz, respectively. The FWHM is targeted to achieve almost no insertion loss (<0.1dB) per tunable filter [7]. The total tuning power for compensating for wafer scale variations and aligning the resonant wavelength of eight microring filters is aggregated to be 0.5mW, which can be further reduced by [8]. The wavelength crossings, demonstrated in [9], are utilized in the network. Less than 1dB power difference is observed due to different aggregated loss of waveguide crossings along each path.

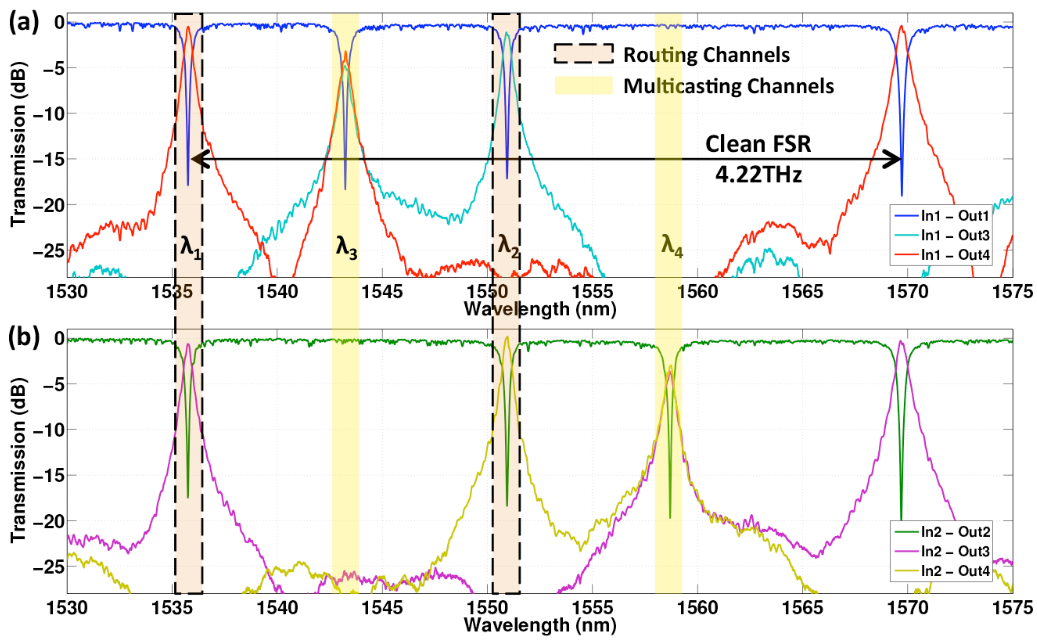

Fig. 2. (a) Transmission spectra of In1 to output ports 1, 3 and 4. (b) Transmission spectra of In2 to output ports 2, 3 and 4.

With microring technologies, high-speed data can be easily transmitted throughout the device. Setup shown in Fig. 3 (a) is used to test the wavelength routing and multicasting functions of the device. A continuous-wave tunable laser (TL) source was first coupled into a single-mode-fiber. The light was then transmitted through a commercial lithium niobate ($LiNbO_3$) modulator with polarization controllers (PCs) before and after the modulator to align the polarization to the on-chip transverse-electric (TE) waveguide mode. The modulator was encoded with non-return-to-zero (NRZ) on-off keying (OOK) pseudo-random bit sequence (PRBS) using a pulse pattern generator (PPG) with a pattern length of 2^{31}-1. The output from the chip was then transmitted to a 5/95 power splitter and went through the variable optical attenuator before being received by the PIN-TIA (Trans-Impedance-Amplifier) detector with a limiting amplifier. The signal was evaluated using Bit-Error-Rate tester (BERT). Both the PPG and BERT were synchronized to the clock synthesizer.

Fig. 3 (b) shows the eye diagrams of 10Gbit/s data rate for both wavelength routing (λ_1 and λ_2) and multicasting (λ_3 and λ_4) functions. In both case, clean and open eye diagrams were observed and designed functionality were achieved. We then took the BER curves and measured the power penalty of individual function for 10Gbit/s data rate. The BER curves for the overall network performance are shown in Fig. 3 (c). The power penalty differences among all the functions are less than 0.8dB, indicating very little degradation of the signal integrity bypassing the whole network. Though the network shown here only shows two-wavelength routing and two-wavelength multicasting in a two-by-two cross-grid waveguide structure, with the increase of ring numbers and utilization of high-order filter designs, larger network with larger number of wavelength channels is readily achieved.

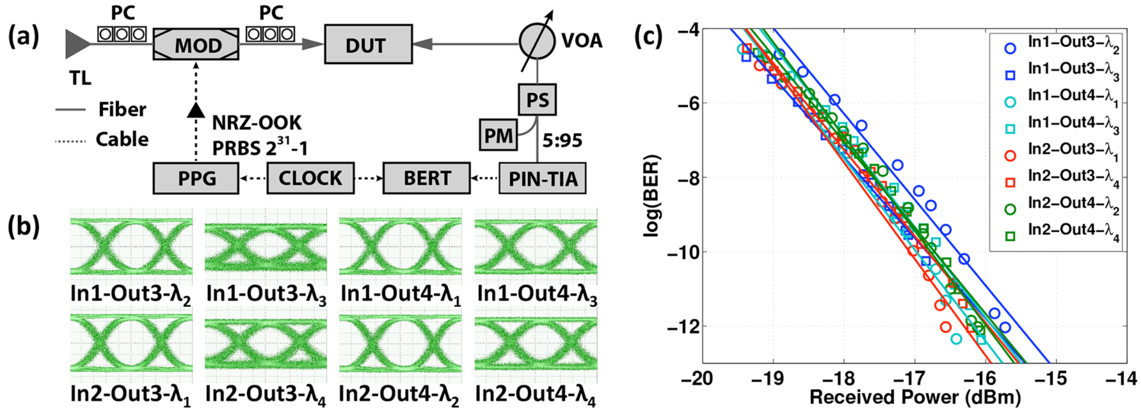

Fig. 3. (a) Schematic of the measurement system. (b) Eye diagrams of different routing/multicasting function of the designed network. (c) Experimentally measured bit-error-rate (BER) curves for all configurations of the designed network with 10Gbit/s data rates generated from an external commercial $LiNbO_3$ modulator.

3. Conclusion

To summarize, a two-wavelength routing and two-wavelength multicasting network is, for the first time, demonstrated in integrated photonics ring-based two-by-two cross-grid waveguide structures. The total thermal tuning power is 0.5mW and the network shows less than 0.8dB power penalty at a BER of $1e^{-9}$ among all the designed functions. The flexibility of cross-grid waveguide system and easy extension of ring-based resonator structure to large number of wavelength channels make it a viable solution for on-chip communication networks.

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4. References

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