Second-Order Wavelength-Selective Partial-Drop Multicast Filter Bank

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Abstract: A wavelength-selective 2nd-order 1-by-8-port optical multicast filter bank is demonstrated utilizing microring resonators, achieving ~2.6× faster roll-off than 1st-order design while maintaining highly uniform responses among all eight drop ports.

OCIS codes: (130.3120) Integrated optics devices; (230.5750) Resonators; (230.0250) Optoelectronics.

1. Introduction

Optical interconnects have gained wide research interests over past few years as a promising solution for reducing bandwidth limitations and scaling multicore microprocessor architectures. Thus far, intra-chip [1] and inter-chip links [2] have been demonstrated with the progressive advancement of state-of-art CMOS foundries. To further unleash the potential of on-chip optical communications, a high-performance, wavelength division multiplexing (WDM) compatible multicast system is desired. Previously, a silicon wavelength-selective partial-drop broadcast filter bank was proposed and demonstrated utilizing 1st-order microring resonators [3,4]. However, 1st-order Lorentzian filters suffer significant channel crosstalk at tight channel spacings. As a result, their applications in data- and telecom communications are substantially limited. In order to overcome this disadvantage and enable high-density WDM systems, a high-order filter-based multicast system design is desired.

Here, we design and demonstrate a 2nd-order wavelength-selective 1-by-8-port partial-drop multicast filter bank utilizing adiabatic microring tunable filters. The 8-channel device has an average full-width-half-maximum (FWHM) bandwidth of 80.2 GHz with a standard deviation of only 5.4 GHz. In addition, the filter bank maintains almost identical responses over the 8 drop ports with a power variation of only ¼ dB. The sharp roll-off of the 2nd-order filter design reduces channel spacing from 648 GHz to 250 GHz compared to 1st-order designs, providing better than -25 dB channel-to-nearest-channel crosstalk level while improving channel density by 259%. Despite the large number of tuning elements and ring resonators involved, the total insertion loss of the system is only 1.7dB. The combination of high uniformity, sharp roll-off, and low insertion loss make this design attractive for applications such as on-chip multicast systems as well as high-sensitivity transceiver designs [5].

2. Designs and Experimental Results

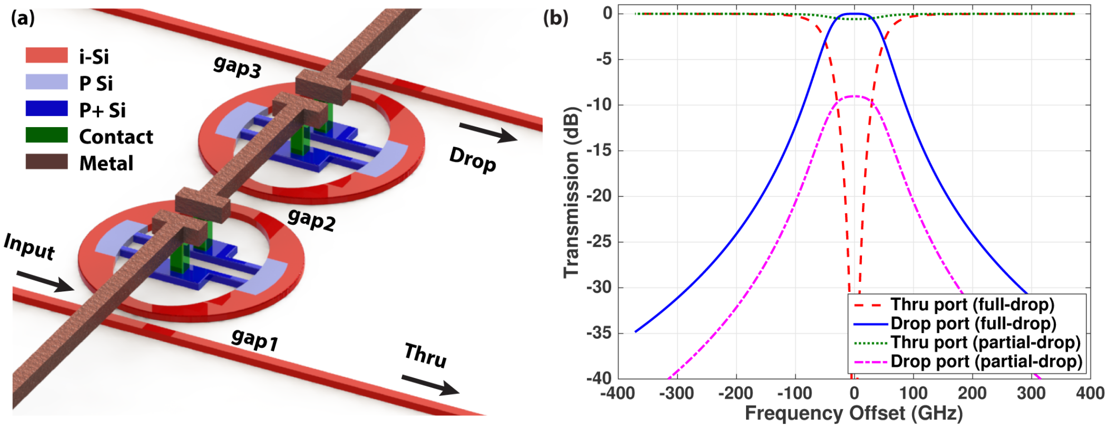

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Fig. 1 – (a) Schematic of 2nd-order filter using adiabatic microring resonators. (b) Simulated transmission spectra of thru ports and drop ports for both lossless full-drop filter and partial-drop filter with same FWHM bandwidth and 1/8 power splitting ratio on resonance.

A typical schematic of 2nd-order filter using adiabatic microring resonators is shown in Fig. 1(a). Though adiabatic ring resonators have been shown to have a better tolerance to wafer-scale thickness and fabrication variations [6], integrated heaters are introduced to the structure for fine tuning of resonant wavelengths.

There are three gap sizes (gap1, gap2, and gap3) that are crucial to 2nd-order filter responses. For normal 2nd-order filters where all of the power of the resonant wavelength is directed to the drop port (shown as full-drop spectra in Fig. 1(b)), gap1 and gap3 are chosen to be the same. As a comparison, to achieve power splitting while maintaining wavelength selectivity (shown as partial-drop spectra in Fig. 1(b)), gap1 and gap3 need to be different. By adjusting gap2 with respect to gap1 and gap3, a single 2nd-order partial-drop filter can be achieved. However, when multiple stages are involved, achieving equal power distributions among all drop ports while maintaining the same 2nd-order filtering response becomes difficult.

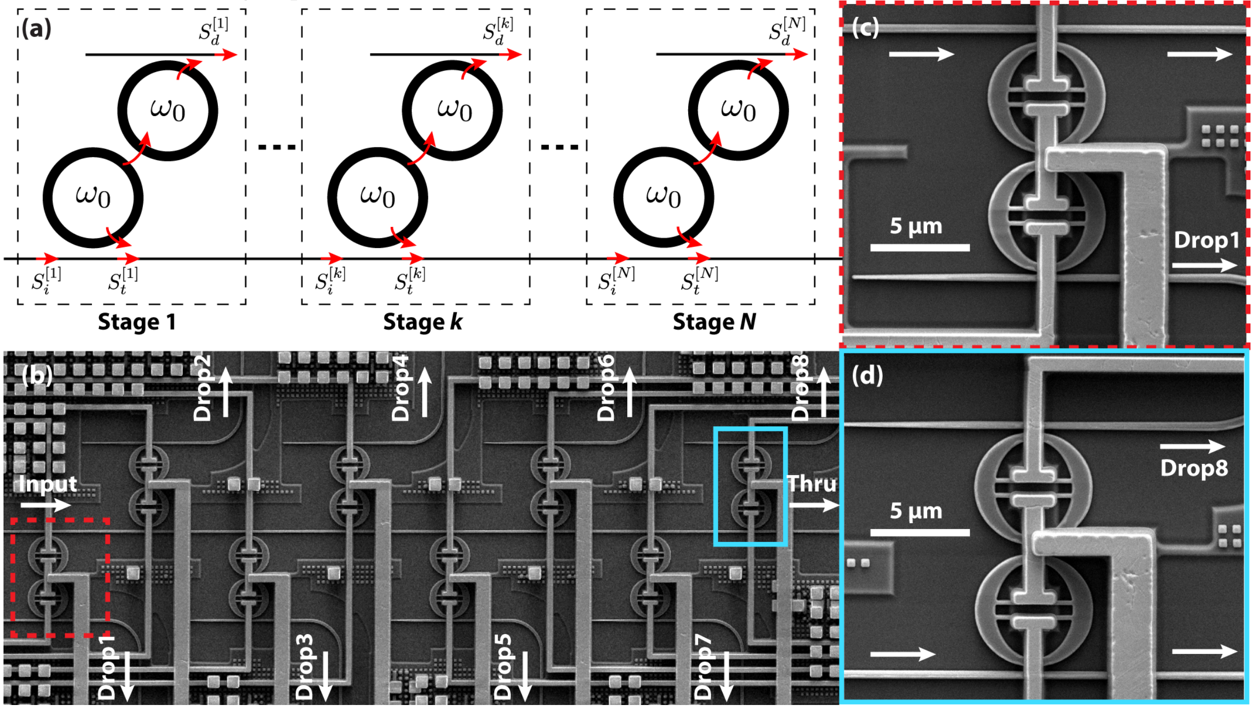

Fig. 2 – (a) Schematic of an *N*-stage 2nd-order ring-based multicast filter bank**.** (b) Scanning electron micrograph (SEM) of the fabricated device after dry etching to remove the top SiO$_2$ cladding. (c) Zoom-in of the first stage (red dashed box in Fig. 2(b)). (d) Zoom-in of the last stage (cyan solid box in Fig. 2(b)).

The schematic of an *N*-stage 2nd-order multicast system is shown in Fig. 2(a). *S* represents the wave amplitude, which is normalized so that $|S|^2$ represents the power (i, t and d stand for input, thru and drop respectively). The superscript k represents the kth stage. All the ring resonators share the same resonant frequency ω_0. Here we define the transfer functions for thru and drop ports of each stage as

$$\text{thru port: } t^{[k]} = \frac{S_t^{[k]}}{S_i^{[k]}} \text{ and drop port: } d^{[k]} = \frac{S_d^{[k]}}{S_i^{[k]}} \text{ for } k = 1 \text{ to } N.$$

With input power entering the bus waveguide from the left side in Fig. 2(a), due to the cascading nature of the device, the k^{th} stage drop port output is dependent on the thru port power of the k-1 stage. Therefore, the following condition needs to be satisfied for all stages (k =1 to N-1) to achieve equal power distributions:

$$\left|t^{[k]} \cdot d^{[k+1]}\right|^2 = \left|d^{[k]}\right|^2 \qquad (1)$$

The final response of each drop port can be computed by incorporating 2nd-order filter transfer function [7] into Eqn. 1. As a result, a recursive relation can be derived to connect the filter design parameters of sequential stages. Through designing a 2nd-order partial-drop filter with 1/*N* peak power on resonance and desired FWHM bandwidth for the first stage, design parameters for the whole partial-drop filter bank system can be readily achieved.

Based on the theory mentioned above, we designed a 1-by-8-port 2nd-order partial-drop system. The proposed structure was fabricated in a state-of-art CMOS foundry on a 300-mm SOI wafer with a 220-nm device layer using 193-nm optical immersion lithography. A scanning electron micrograph (SEM) of the fabricated device after removing the top SiO_2 cladding is shown in Fig. 2(b). It consists of eight 2nd-order filters coupled to the same bus waveguide. Input laser power is coupled into the bus waveguide from the left side and filtered by each filter. Integrated heaters are introduced to each filter by p-type doping with concentrations of 1×10^{18}cm^{-3} (P Si) and 1×10^{20}cm^{-3} (P+ Si) (shown in Fig. 1(a)) to compensate wafer-scale thickness and fabrication variations. The fabricated adiabatic rings are 6-μm in diameter, ensuring single-mode operation and a large free-spectral-range (FSR) of 36.2nm for WDM applications. Zoom-ins of the 2nd-order filters of the first stage is shown in Fig. 2(c). The 2nd-order filter has different coupling gaps to bus and drop waveguide. This will allow the first stage to partially select the input power into the Drop1 port. In contrast, the last stage, as shown in Fig. 2(d), utilizes a symmetric coupling scheme, allowing full power collection on resonance so as to achieve same transmission spectrum as previous stages.

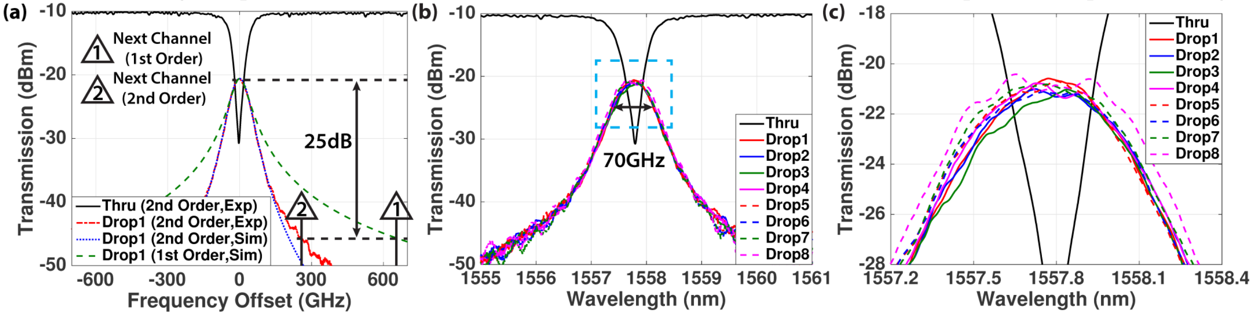

Fig. 3 – (a) Transmission spectra of port Thru and Drop1 of the designed 1-by-8-port 2nd-order multicast filter bank. Simulated port Drop1 response for both 1-by-8-port 1st-order and 2nd-order multicast filter bank with the same FWHM bandwidth are included for comparison. Nearby frequency channels with < -25dB crosstalk level are marked with 1 and 2 for 1st-order and 2nd-order system respectively. (b) Transmission spectra of the 2nd-order partial-drop filter bank after thermal tuning. (c) Zoom-in of the transmission spectra of the system (marked by a dashed box in Fig. 3(b)), showing a power variation of ¼ dB at the resonant wavelength.

The transmission spectra of port Thru and Drop1 of the designed 1-by-8-port 2nd-order multicast filter bank are shown in Fig. 3(a). The FWHM bandwidth of Drop1 is ~73 GHz and the experimental result matches well with the simulated one (blue dashed line). The simulated port Drop1 response of a 1-by-8-port 1st-order multicast filter bank is also plotted in Fig. 3(a) for comparison. Assuming a < -25dB channel-to-nearest-channel crosstalk, 1st-order system demands a 648 GHz channel spacing (marked by 1 in Fig. 3(a)), while the 2nd-order system only requires 250 GHz channel spacing (marked by 2 in Fig. 3(a)), enabling ~2.6× better channel density than the 1st-order design [3,4]. The overall transmission spectra of the designed system after thermal tuning are shown in Fig. 3(b), and a zoom-in of the top of the responses (marked by a dashed box in Fig. 3(b)) is shown in Fig. 3(c). The responses from Drop1 to Drop8 overlap well with each other, showing a power variation of ¼ dB on resonance and a FWHM bandwidth variation of 5.4 GHz, demonstrating both design and fabrication accuracy. In addition, it is worth noticing that the overall loss of the system is only 1.7 dB, despite a large number of heaters and ring resonators involved in the system.

3. Conclusion

We have proposed and demonstrated a 2nd-order wavelength-selective 1-by-8-port partial-drop multicast filter bank utilizing adiabatic microring tunable filters. The system provides an average 80.2 GHz channel bandwidth with only a 5.4 GHz standard deviation while maintaining a low ¼ dB resonant power variation across all 8 drop ports, demonstrating nearly identical responses. Compared with 1st-order designs, the sharp roll-off of 2nd-order filter reduces channel spacing from 648 GHz to 250 GHz, enabling ~2.6× higher channel density, making this attractive for applications such as on-chip multicast communications and integrated high-sensitivity transceiver designs.

4. References

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