Asymmetric, pole-zero microring-resonator filters for efficient on-chip dense WDM multiplexers

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Abstract: Channel add-drop filters with asymmetric responses based on transmission zero engineering are proposed and demonstrated in a zero-change 45nm SOI CMOS process. They enable multiplexers with 2.4× higher channel density using the same order filter.

OCIS codes: (130.3120) Integrated optics devices; (130.7408) Wavelength filtering devices; (250.5300) Photonic integrated circuits

1. Introduction

Demand for high-bandwidth-density and energy efficient on-chip optical communication systems has motivated substantial photonics integration research in recent years [1,2]. Microring resonator filters have become a staple building block for on-chip wavelength division multiplexing (WDM) due to their simplicity and versatility [3,4]. Microring filters are typically designed as serially-coupled all-pole filters [5] (with no transmission zeros to the drop port). Various geometries have been studied that enable a pole-zero response [6,7].

In this paper, we propose and demonstrate a simple 2^{nd}-order microring based filter with a controllable drop-port transmission zero. The device is demonstrated in a 45 nm SOI CMOS process relevant to monolithic photonic interconnects. We also show that this zero control enables serially cascaded WDM filter banks with a decrease in channel spacing (increase in bandwidth density) of up to a factor of 2.4 compared to an all-pole filter of the same order.

2. Achieving one finite detuning transmission zero

All-pole (serially coupled) microring filters have no transmission zeros (i.e. they're at infinite detuning). We seek a photonic filter with 2 poles and 2 zeros in the through port, and 2 poles and 1 zero in the drop port. An abstract representation of this filter is shown in Fig. 1(a). A simple guideline can be used to quickly determine a physical implementation that achieves the desired response. In general, the number of zeros in transmission to a given port is equal to the resonant order, N, minus the *minimum* number of resonators traversed from input to output [8]. Using this rule, the structure shown in Fig. 1(b) realizes the desired response.

Fig. 1(c) shows the response derived from a coupling of modes in time (CMT) model [9]. The pole-zero response was derived from a Butterworth response (i.e. $r_i = \mu$) and, as an example, was chosen such that the rise in transmission

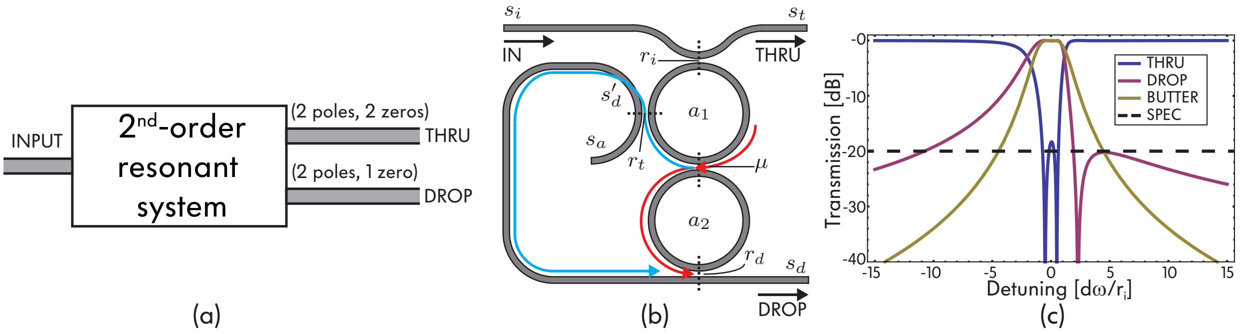

Fig. 1. (a) Abstract representation of 2-pole, 1-zero resonant system; (b) physical implementation that uses a weak tap coupler to produce feed-forward interference enabling a transmission zero; (c) representative transmission response of the pole-zero filter. Also plotted is the response of a Butterworth filter for comparison.

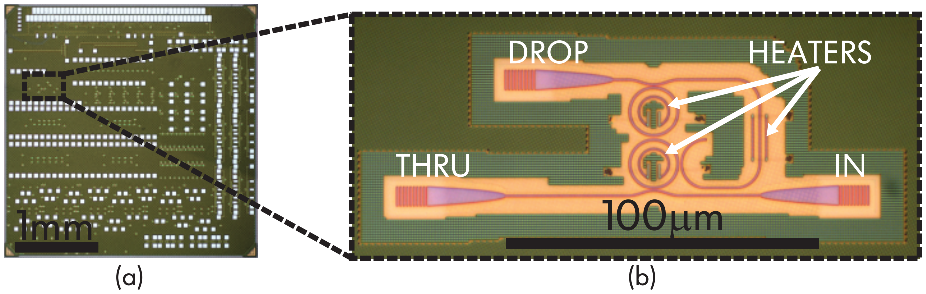

Fig. 2. Optical micrographs of the fabricated devices. (a) Full chip made in 45nm SOI CMOS; (b) magnified image showing single device.

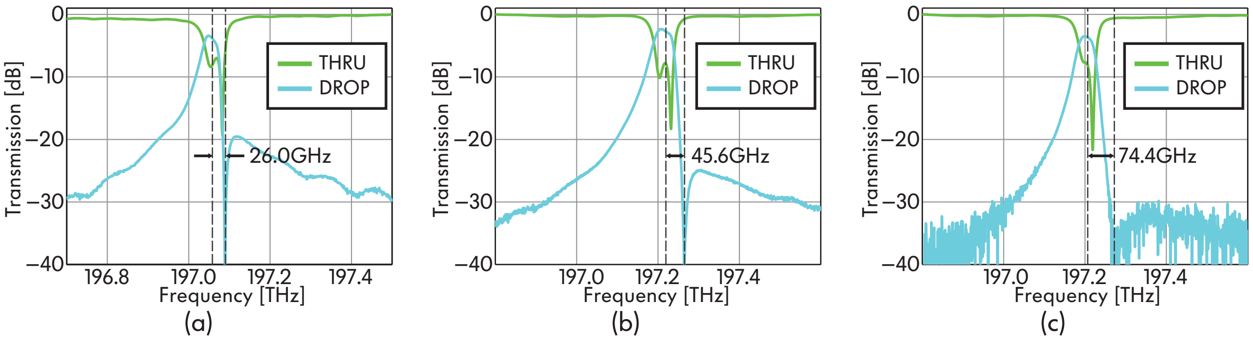

Fig. 3. Measured transmission spectra of pole-zero devices. (a) Response with zero detuning at 26GHz; (b) response with zero detuning at 45.6GHz; (c) response with zero detuning at 74.4GHz.

after the zero location does not rise above -20dB. The CMT model results in three design equations:

$$r_d - r_i + r_t = 0, \qquad \delta\omega' = -\frac{2\sqrt{r_d r_t}\,\mu\cos\phi}{r_d + r_i - r_t}, \qquad r_t = \frac{\mu^2 r_d}{(\delta\omega' + \delta\omega_{zd})^2 + r_d^2} \tag{1}$$

where $\cos\phi$ is given by

$$\cos\phi = \frac{\delta\omega' + \delta\omega_{zd}}{\sqrt{(\delta\omega' + \delta\omega_{zd})^2 + r_d^2}} \tag{2}$$

and $\delta\omega'$ is the relative detuning of the two rings such that their uncoupled resonances are at $\omega_1 = \omega_0 + \delta\omega'$ and $\omega_2 = \omega_0 - \delta\omega'$, $\delta\omega \equiv \omega - \omega_0$, and $\delta\omega_{zd}$ is the frequency detuning of the transmission zero.

3. Experimental results

The proposed device was realized in the IBM 45 nm 12SOI CMOS process [10] with no process changes in foundry. Fig. 2(a) shows an optical micrograph of the fabricated chip (top metal side). Fig. 2(b) shows an optical micrograph of one of the fabricated devices. Each ring has a circular doped-silicon heater in the center to control the resonant frequencies, and the coupling arm has a heater to control the phase shift. Three devices were designed with different target offset frequencies from the passband center for the transmission zero. Fig. 3 shows measured through- and drop-port responses for the three devices. Measured values are summarized in Table 1, showing close agreement of design to measured data.

4. Serially cascaded banks of pole-zero filters as demultiplexers

The pole-zero filters enable an efficient design for a serially cascaded WDM (de)multiplexer. If adjacent channel center wavelengths are spaced by the detuning of the zero relative to the passband of the filter, then the channels can be very densely packed. This is because, on one side of the passband, the channel rejection is aided by the transmission zero, and the other side is aided by the previous channel's through port. In comparison to all-pole filters of the same order, the pole-zero filters support a channel spacing that is up to 2.4 times smaller, effectively increasing the accessible bandwidth density by the same factor.

Table 1. Comparison of filter design specifications with measured results

Device	BW, design (GHz)	BW, meas. (GHz)	Zero location, design (GHz)	Zero location, meas. (GHz)	IL (dB)
1	40	41.7	24	26	2.38
2	40	49.5	40	45.6	1.88
3	40	44.3	83.7	74.4	2.87

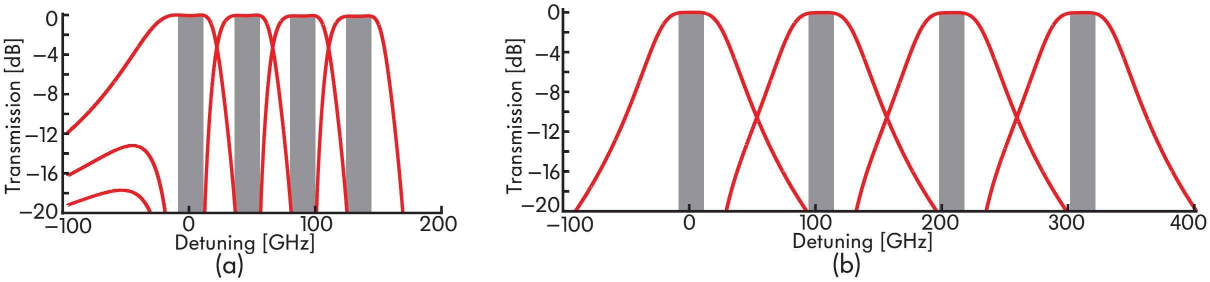

Fig. 4. Example designs showing densely packed channels using a pole-zero filter bank. (a) Pole-zero demultiplexer with 20GHz passband and 44GHz channel spacing; (b) Butterworth demultiplexer with 20GHz passband and 106GHz channel spacing.

Fig. 4 shows an example demultiplexer design using a pole-zero filter and a Butterworth filter. The example design specifications are a 20 GHz passband and 20 dB adjacent channel rejection. The pole-zero filter enables a channel spacing of 44 GHz, while a Butterworth filter is limited to 106 GHz channel spacing. Note that, although the pole-zero response was derived from the Butterworth response, a ripple is introduced in the passband. If instead compared to a Chebyshev filter with the same ripple, the channel spacing advantage decreases slightly to a factor ≈ 1.8 improvement.

5. Conclusion

A microring filter geometry that is a perturbative extension of serially-coupled resonant filters was proposed and demonstrated to support asymmetric responses with a transmission zero. In such "pole-zero" filters, it was shown that the zero location can be controlled by designing the appropriate couplings and phase in the extra coupling arm. Although the filter bandwidth and zero location matched design fairly closely, the filter performance can still be improved in terms of insertion loss and passband shape. We also proposed using the asymmetric filters in serially cascaded (de)multiplexers to achieve densely packed WDM channels suitable for on-chip interconnects.

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