Design, Fabrication, and Characterization of a Free Spectral Range Doubled Ring-Resonator Filter

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Abstract: Two-point coupling is used to double the free-spectral-range (FSR) of a ring-resonator filter. The filter, designed using rigorous electromagnetic simulations and fabricated using direct e-beam write, demonstrates 22 dB unwanted resonance suppression yielding an effective 40.8 nm FSR.

OCIS codes: **(130.3120) Integrated optics devices; (230.5750) Resonators; (230.7370) Waveguides. 1.**

Introduction

Coupled-microring filters are a promising approach to planar integrated-optical add/drop filters for wavelength-division multiplexed (WDM) networks [1-6]. Coupled cavities enable narrow, frequency-selective line-shapes with flat pass-bands while traveling-wave-cavity operation facilitates a natural separation of ports. Using very high index contrasts to enhance confinement, microring resonator *add-drop* filters have been demonstrated with free spectral ranges (FSR) exceeding 20 nm [6]. Still, these FSRs fall short of the minimum ~ 30 nm required to cover an optical band. Several Vernier schemes [] have been proposed to overcome this challenge. However, most of these schemes produce intolerable dispersion into the thru port, or alternatively, make the thru port inaccessible. Two-point ring-bus coupling [7] may be used to double the FSR of a ring-resonator filter while contributing only a minute amount of dispersion to the thru port at the suppressed resonance.

Here we implement two-point ring-bus coupling in a second order silicon nitride ring-resonator filter. The design of the filter was done using rigorous three-dimensional, finite-difference cylindrical mode-solver and time-domain codes. The theoretical results indicate 50dB extinction of the unwanted resonance is achievable in the through port. The structure was fabricated using direct e-beam write and the measured results indicate that 22 dB extinction of the suppressed resonance was achieved.

2. Design, Fabrication, and Experimental Results

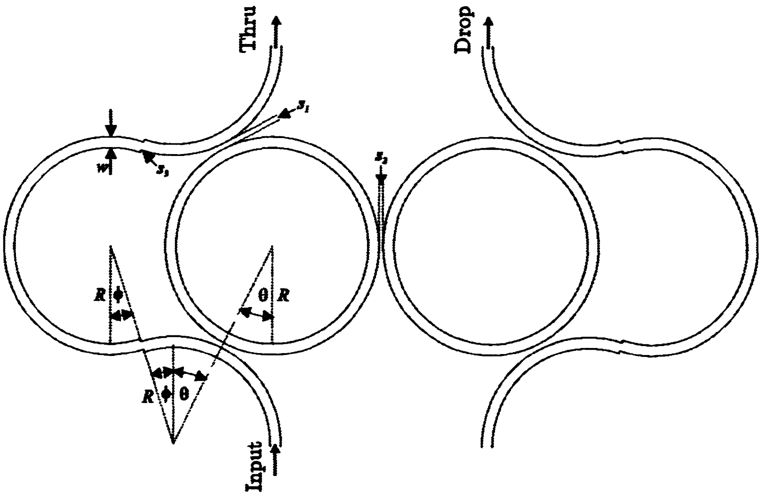


Fig. 1. (a) Diagram of waveguide cross-section and (b) diagram of a 2nd order FSR doubled ring-resonator filter

The design of the ring-resonator filter itself follows that described in [] except the ring-bus coupling is achieved through a two-point coupling approach. In order to suppress every other resonance, the frequency dependent coupling introduced by the Mach-Zehnder interferometer formed by the ring-bus coupling must have a FSR that corresponds to twice that of the ring. To do so, the path length difference between the two arms of the interferometer must be equal to half way around the ring (i.e. $\Delta L = \pi R$). We implement the appropriate path length difference with a series of arcs as depicted in Fig. 1. Simple geometric considerations indicate that the correct path length is arrived at from the following constraints.

$$\theta + \phi = \frac{\pi}{4} \tag{1}$$

and

$$\frac{\cos(\theta)}{\cos(\phi)} = \frac{2R + w + s_3}{2(R + w) + s_1} \tag{2}$$

where θ and ϕ are the arcs depicted in Fig 1, R is the ring radius, w is the waveguide width, s_1 is the separation between the rings and s_3 is a jog placed between the arcs to improve mode-matching. Combining (1) and (2) we arrive at the following solution for the angle ϕ.

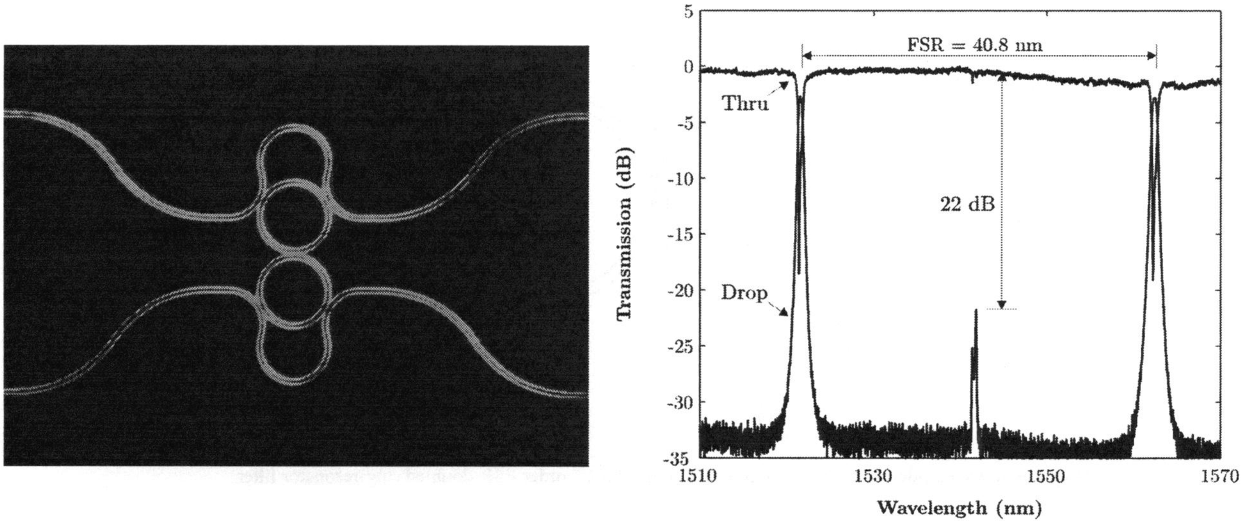
$$\phi = \tan^{-1}\left[\sqrt{2}\left(\frac{2R + w + s_3}{2(R + w) + s_1} \right) - 1 \right] \tag{3}$$

Second order filters do not provide a sufficiently fast roll-off for DWDM applications. To achieve the required response pairs of filters may be cascaded in series. When pairs of filters are cascaded in series the filter was designed to achieve 27 dB extinction 80 GHz from the channel center, a flat drop response with a 1 dB 40 GHz bandwidth, and > 35 dB extinction in the thru port in the presence of 10 dB/cm loss. To achieve the desired response with rings depicted in Fig. 1a, ring-bus and ring-ring couplings of 10.7 % and 0.4 % are needed. Since two coupling points were used, the maximum coupling into the ring C_{max} is

$$C_{\max} = \left| t\sqrt{1 - |t|^2} + t \right|^2 \tag{4}$$

where t is the field amplitude transmission coefficient into the ring from a single coupling point. Rigorous three-dimensional finite-difference time-domain (FDTD) simulations of the coupler regions were used to determine the complex ring-bus and ring-ring coupling coefficients at the resonant wavelength ($\lambda = 1545$ nm). Rounded to a 6 nm scanning-electron-beam lithography (SEBL) system pixel size, the FDTD simulations indicate that this corresponds to ring-bus and ring-ring separations of $s_1 = 144$ nm and $s_2 = 312$ nm.

3. Fabrication and experimental results

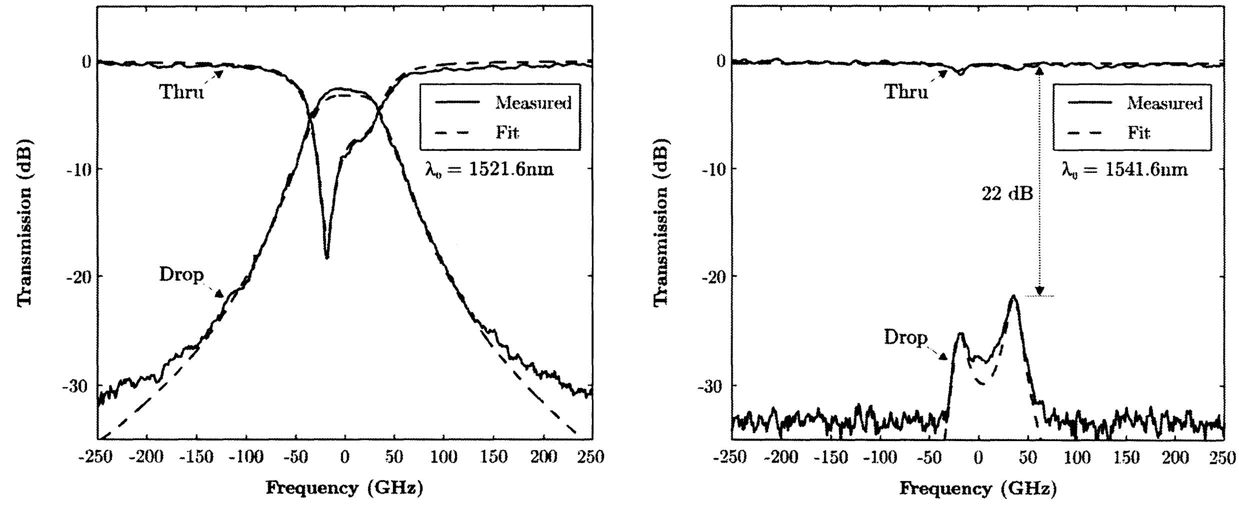


(a) (b)

Fig. 2. (a) Optical micrograph of FSR doubled filter and (b) measured filter response

The devices were fabricated using direct write SEBL. The fabrication process is similar to the one described in [7]. The pattern was defined in 200 nm of poly-methyl-methacrylate (PMMA) using a Raith 150 SEBL system at 30 keV. A hardmask was formed by evaporating and lifting off a thin film of Ni. The waveguides were created by a 500-nm-deep conventional reactive-ion etching step using a gas mixture of CHF_3 and O_2. Finally, the Ni hardmask was removed. The e-beam dose to the center ring of several identical filters was varied to slightly enlarge the center ring to tune it into resonance with the other rings in the filter. Fig. 2a is an optical micrograph of a fabricated filter.

The measured filter response (Fig. 2b) demonstrates an effective 40.8nm FSR. Close-ups of the measured desired and suppressed resonances along with fits to the responses are depicted in Fig. 3a and 3b. The desired drop response is quite similar to the design response with the bandwidth and shape of the responses being nearly identical. The curves only differ by some excess loss found in the measured drop response. The thru response exhibits an asymmetry found on all second order filters fabricated on the chip. Curve fitting indicates that the asymmetry is due to a frequency shift of 23 GHz between the rings in the filter. The asymmetry is likely the result of an e-beam discretization error. The suppressed drop response exhibits ~22 dB of extinction. Imperfect extinction of the suppressed resonance is likely the result of an imbalance in the Mach-Zehnder path length.



(a) (b)

Fig. 3. (a) Close-up of desired and (b) suppressed resonances with fitted data superimposed.

4. Conclusions

The free spectral range of 2nd order ring resonator filters were effectively doubled by using two-point coupling to induce a frequency dependence on the filter coupling mechanism. The fabricated devices exhibit a measured extinction in the suppressed resonance of ~ 22 dB. Although short of the anticipated 50 dB extinction, the measured extinction 22 dB is close to the 30 dB typically required for the OADM application and represents a major step towards achieving wide FSR ring-resonator-based filters.

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