Microring-resonator filter with doubled free-spectral-range by two-point coupling

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Abstract: Two-point coupling is used to double the free-spectral-range (FSR) of a microring-resonator filter. The filter, designed using rigorous electromagnetic simulations and fabricated using e-beam lithography, demonstrates 22 dB resonance suppression yielding a 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 [1-5]. 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 [4,5]. Still, these FSRs fall short of the minimum ~ 30 nm required to cover an optical band. Several Vernier schemes [6] 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 [7,8] 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 microring-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 > 55 dB extinction of the unwanted resonance is achievable in the through port. The structure was fabricated using direct-write scanning e-beam lithography (SEBL), and a 22 dB extinction of the suppressed resonance was achieved.

2. Design

The design of the ring-resonator filter follows that described in [5] 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 twice the FSR of the ring resonator. 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. Here, both bus waveguides were coupled to the rings with two-point coupling to maximize extinction of the suppressed resonance.

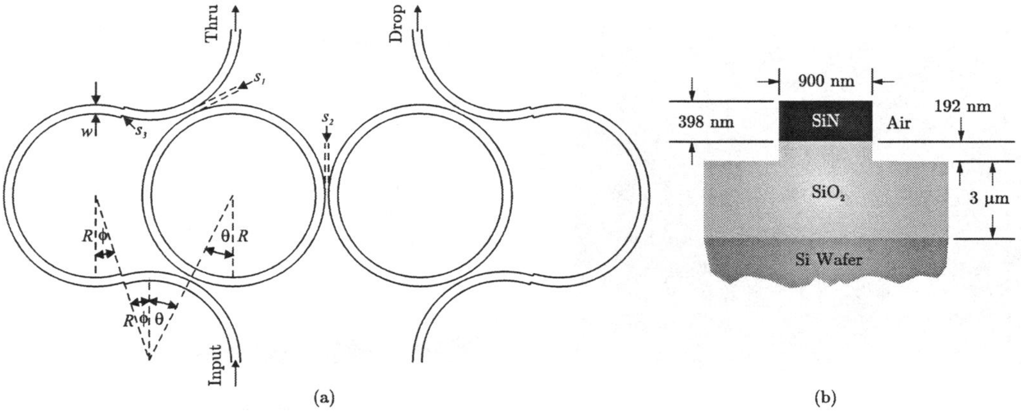


Fig. 1. (a) Diagram of a second order FSR doubled filter and (b) a diagram of the waveguide cross-section. The silicon-rich silicon nitride core has an index of 2.18 at 1.55 um while the silicon oxide cladding has an index of 1.45 at 1.55 um. The outer radius of the rings is 8 um.

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.

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

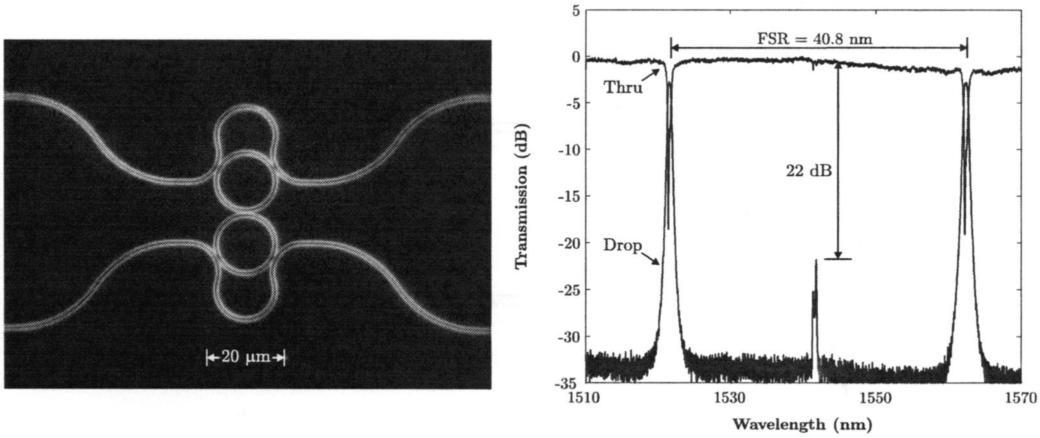
Second order filters do not provide a sufficiently fast roll-off for DWDM applications. However, this scheme can be applied directly to filters of any order. Alternatively, to achieve the desired roll-off, filters may be cascaded in series. When cascaded in series the filter was designed to achieve 27 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 from the ring resonator 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 (λ = 1530 nm). Rounded to fit on the 6 nm scanning-electron-beam lithography (SEBL) system x-y grid, the FDTD simulations indicate that this corresponds to ring-bus and ring-ring separations of s_1 = 146 nm and s_2 = 312 nm. Based on cylindrical waveguide mode overlaps s_3 was chosen to be 52 nm.

3. Fabrication and experimental results

The devices were fabricated using direct write SEBL The fabrication process is similar to the one described in [4]. 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 deep conventional reactive-ion etching step through 398 nm of silicon nitride and 192 nm of silica using a gas mixture of CHF_3 and O_2. Finally, the Ni hardmask was removed. Fig. 2a is a Nomarski optical micrograph of a

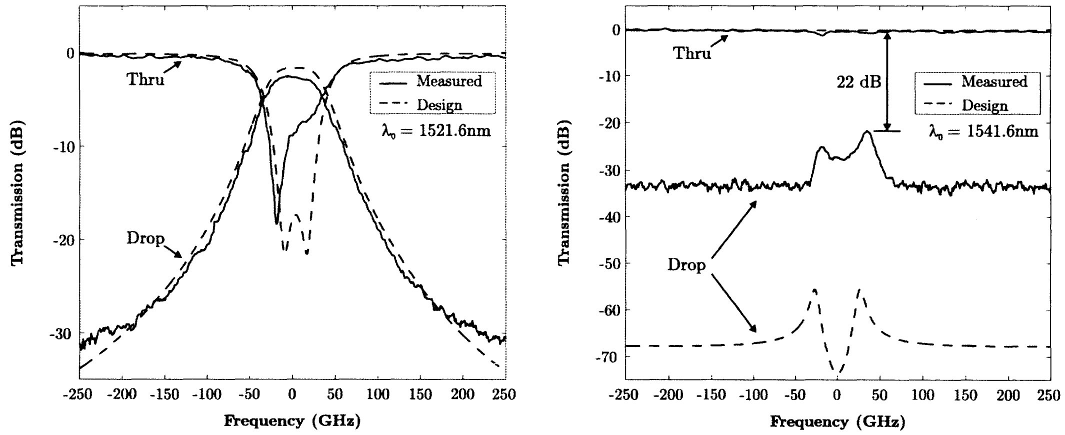


(a) (b)

Fig. 2. (a) A Nomarski optical micrograph of FSR doubled filter. Each bright line represents an edge of the waveguide. (b) Measured filter response

fabricated filter.

The measured filter response (Fig. 2b) demonstrates an effective 40.8 nm FSR. A close-up of the measured and designed unsuppressed resonance at 1521.6 nm is depicted in Fig. 3a. The drop response is similar in both bandwidth and shape to the design with the primary difference being 0.8 dB excess loss (2.5 dB total loss). The propagation losses were measured with the cutback technique to be 10 dB/cm and are most likely due to bulk loss in the waveguide core. Curve fitting reveals the excess loss to be largely the result of a 4 % narrower than expected bandwidth and an asymmetry in the filter response. The asymmetry is more evident in the thru response and was found on all fabricated second-order filters. Curve fitting further indicates that the asymmetry is due to a frequency mismatch of 23 GHz between the two rings of the filter. As this asymmetry is highly repeatable and does not appear in third-order filters [5], it is likely the result of an digital-to-analog-converter error in the Raith 150.



(a) (b)

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

A close-up of the measured suppressed response along with its corresponding design response is depicted in Fig. 3b. The drop response was reduced to ~ 22 dB below the thru response or 19.5 dB suppression compared to the unsuppressed drop response. While short of the > 55 dB exhibited by the design response, 22 dB is close to the 30 dB required by many *add-drop* applications. Curve fitting indicates that the imperfect extinction is likely the result of a $\lambda/20$ imbalance in the Mach-Zehnder path length. This imbalance is systematic and can be easily compensated in fabrication to achieve higher suppressed resonance extinction.

4. Conclusions

The free spectral range of second-order ring resonator filters was 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. The measured extinction of 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. Moreover, it can easily be improved by more closely matching the path lengths in fabrication.

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