Multistage high-order microring-resonator filters with relaxed tolerances for high through-port extinction

Miloš A. Popović[†], Tymon Barwicz[‡], Michael R. Watts, Peter T. Rakich, Luciano Socci,
Erich P. Ippen, Franz X. Kärtner and Henry I. Smith
Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, Massachusetts 02139
[†]milos@mit.edu, [‡]tymon@mit.edu

Abstract: We demonstrate that add/drop filter designs comprising cascaded coupled-microring stages permit reduced drop-loss and relaxed tolerances for high through-port extinction. We report on high-index-contrast filters with 20nm FSR, 2.5dB drop loss and 30dB of extinction.

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

1. Introduction

Microring resonators hold promise as building blocks for planar integrated-optical add/drop filters for wavelength-division multiplexed (WDM) networks [1,2]. Add/drop filters require flat passbands with sharp rolloff (high-order cavities [2]), low loss (<3dB), high in-band extinction in the through port (30dB), and a wide free spectral range (FSR) that covers the optical band in use (~30nm). To support small radii associated with such large FSRs with low bending loss, rings of high core-to-cladding index contrast (HIC) are required (50%+). HIC, on the other hand, presents substantial new design and fabrication challenges. In [4], we demonstrated 40GHz-wide, flat-top HIC filters with 14dB through-port extinction. However, achieving high extinction requires precise dimensional control.

In this paper, we consider add/drop filters constructed by 'incoherently' cascading reduced-order stages. The resulting through-port responses are less sensitive to the fine dimensional tolerances for coupling coefficients and resonance frequencies associated with HIC, which make it difficult to achieve high through-port extinction in a high-order filter based on a single set of series-coupled cavities (e.g. [2]). The multistage add-drop filters also permit lower drop loss by virtue of partial decoupling of drop- and through-port design. We demonstrate one-, two-, and three-stage filters using identical 3-ring stages, fabricated in Si-rich SiN. They exhibit a 20nm FSR, a 40GHz passband with 2.5dB drop loss, 30dB adjacent channel rejection, and >30dB in-band extinction in the through port.

2. Multistage filters

In series-coupled rings [2], high through-port extinction (~30dB) is difficult to achieve due to sensitivity of the response to power-coupling and resonance-frequency deviations from design. Increasingly high levels of extinction within the channel band rely on precisely tuned suppression of the resonator poles by zeros of interference in the through-port. Furthermore, the response functions (in/add-to-thru/drop) of a lossless series-coupled-ring filter are constrained in that they are all determined by the same limited set of design couplings and resonance frequencies. For example, to satisfy 30dB in-band extinction in the through port, by power conservation, a corresponding drop response must be synthesized with <0.004dB passband ripple. This criterion typically calls for a higher-order filter than is needed to meet drop-port criteria alone (commonly <1dB in-band rolloff), leading to higher drop loss. We can consider the tolerance sensitivity and loss considerations through an example.

For 100GHz-spaced, 60GHz-wide channels, a 6th-order filter is required to provide 30dB rejection in both drop and through ports. Assuming a finite cavity loss Q of 25,000, Fig. 1a shows 100 overlaid responses representing a uniformly distributed random fractional error in power couplings (±15%). The extinction is severely limited by the random perturbations to ~10dB. By comparison, a multistage-cascade-type filter, without optical feedback from later to earlier stages (Fig. 1b-d), provides a partial decoupling of the design variables with respect to the response functions, and a more robust total through-port extinction. Incoherently cascaded single rings have been considered for spectrum cleanup and higher-order response design [5], but they do not support low-loss, flat-top passbands. Figs. 1c-d illustrate multistage arrangements of arbitrary filter blocks forming a cascade in the in-to-through signal 'path' only (c) or in both the through and drop paths (d). In Fig. 1c, the first-stage parameters influence the in-to-through and in-to-drop responses, the last stage is shared by in-to-through and add-to-through responses, while intermediate stages affect only the in-to-through response. Hence, design is partially decoupled. With at least two stages, add and drop ports are isolated in the common add-after-drop arrangement. Fig. 1b shows a 3-stage filter that meets the same requirements as Fig. 1a. A 4th-order first stage is sufficient (and others are set identically), resulting in lower drop loss (3dB instead of 4dB in this example), and the sensitivity of the through port is reduced permitting >30dB rejection with the chosen statistical variation.

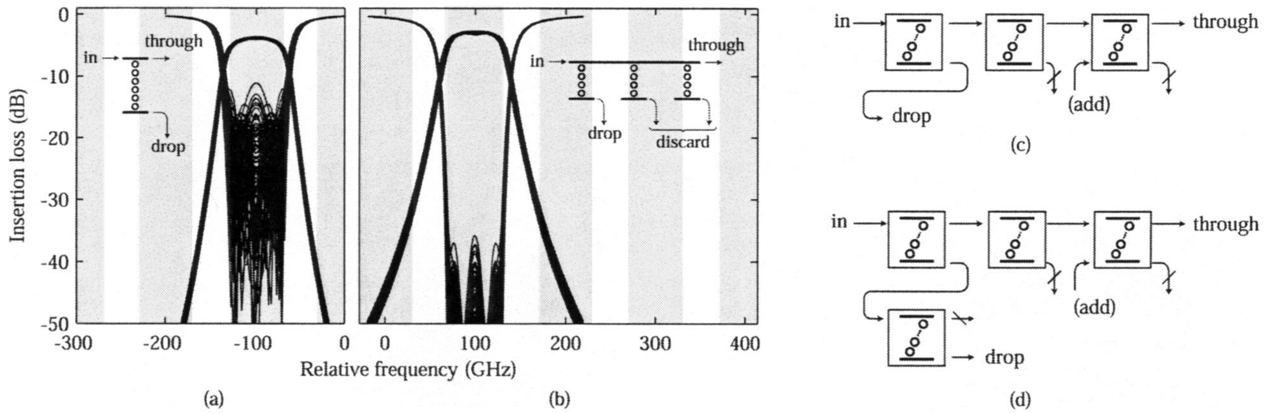


Fig. 1. Illustration of tolerability to coupling error (random ±15%, 100 samples) of (a) a single 6th-order filter, and (b) multistage (3×4th-order) filter. Multistaging arrangements: (c) in through-port path, (d) in through and drop signal paths.

3. Filter response and HIC ring/waveguide design

In this work, one-, two- and three-stage filters (as Fig. 1c) were designed for 40GHz channels on a 100GHz WDM grid. Identical 3rd-order stages were employed to simplify stage-to-stage resonance alignment. Each stage has a drop response with 0.05dB in-band ripple, rolling off to ~0.2dB at the channel band-edges; 30dB rejection 80GHz from center-band; and through-port extinction of 22dB over mid-channel (~15dB near band edges). For a three-stage filter, the extinction is thus 66dB (45dB). For a 20nm FSR, ring-bus and ring-ring coupled power is 10.3%, 0.22%.

The electromagnetic design follows [4] and was tailored to measured core and cladding indices (2.181, 1.455) and core-layer thickness, 396nm (Fig. 2a). Wide, thin waveguide cross-sections reduce ring sensitivity to width tolerances and sidewall roughness, and curb polarization mixing [4]. The filter design is "TE only" and relies on an integrated polarization diversity scheme for polarization-independent operation [6]. In previous work, we found 1.5dB drop-loss intrinsic in design (bending, coupler scattering) [4]. Here, we chose a wider (900x396nm) ring waveguide with a deeper (198nm) overetch, increasing the radiation Q of the fundamental (TE_{11}) resonance associated with bending loss to ~250,000 at 1530nm. Spurious TM_{11} and TE_{21} resonances were kept to low Q's under 2000 and 25, respectively, preventing them from contributing to coupler loss [4]. With narrower, 702nm bus waveguides, rigorous three-dimensional finite-difference time-domain (FDTD) simulations, as in [4], produced design ring-bus (Fig. 2a) and ring-ring gap spacings of 120nm and 372nm (rounded to 6nm e-beam pixel size) corresponding to the desired coupled-power ratios. Coupler loss was reduced by 5x from [4] and 10x from [7]. With total "design insertion loss" of 0.35dB, coupler loss accounts for 0.1dB, bending loss for 0.25dB.

4. Fabrication and experimental results

Fig. 2b shows the layout for a single set of one-, two- and three-stage filters. The fabrication process is based on direct-write scanning-electron-beam lithography (SEBL) and is similar to that 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 590-nm-deep conventional reactive-ion etching step using a gas mixture of CHF_3 and O_2. Finally, the Ni hardmask was removed.

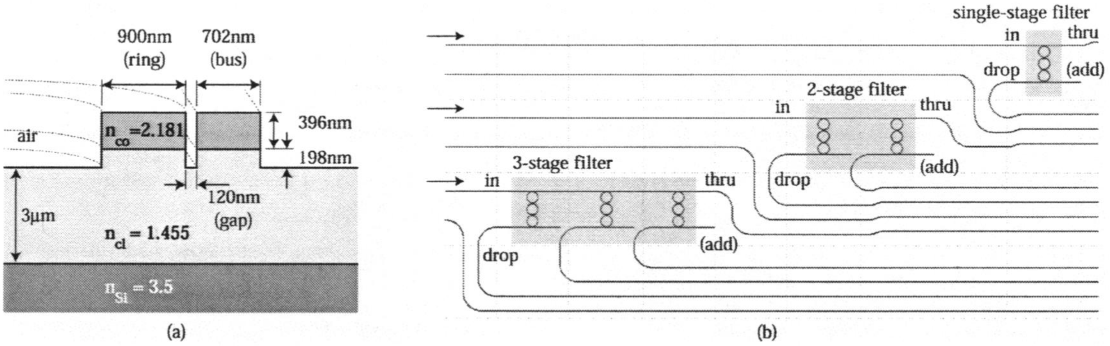
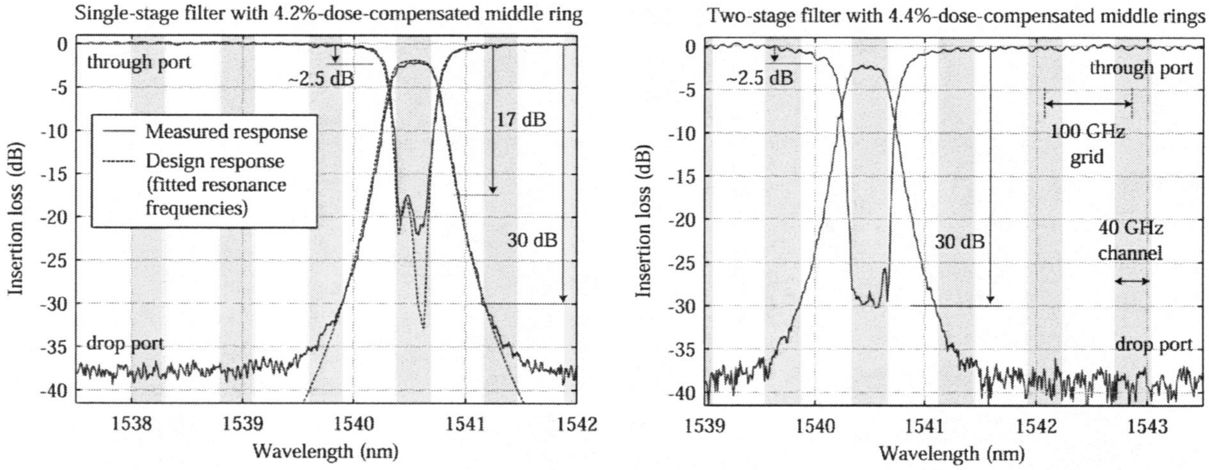


Fig. 2. (a) Ring and bus waveguide cross-sections, dimensions and indices, (b) layout of one-, two- and three-stage filters using identical 3-ring stages. Middle rings (red) were resonance-frequency compensated by e-beam dose adjustment.



(a) (b)

Fig. 3. (a) Single 3-ring stage filter responses, with center-ring resonance frequency compensated to within 1.8 GHz of synchronism; (b) drop- and through-port responses of two-stage add/drop filter with 3-ring stages.

To compensate for the resonance frequency mismatch reported in [7], a 4.2-4.4% higher e-beam dose was employed on the middle ring of each stage to increase its dimensions and match its frequency to the outer rings.

Fig. 3 shows measured drop- and through-port responses of single-stage and two-stage frequency-compensated filters. Care was taken during characterization to ensure that the responses have the same insertion loss scale. Fig. 3a shows close agreement between the intended design and measured result, validating design and demonstrating the fabrication accuracy. The only fitted parameters were the center wavelength of 1540.5nm, and the middle-to-outer ring resonance frequency mismatch of 1.8 GHz. Excess ring propagation loss of ~10dB/cm was extracted by independent measurement and included in the theoretical plot. Improving on [4], the single-stage filter has a 40GHz 1dB-passband with 2.5dB drop loss, 30dB out-of-band rejection, and 17.5dB through-port extinction – the highest reported in a high-order microring filter.

The two-stage filter (Fig. 3b) shows a similar drop response with increased through-port extinction of ~30dB over most of the channel, meeting typical requirements for WDM add/drop filtering. While theory predicts an extinction >60dB for compensated 3-stage filters, the observed extinctions (not shown) are also more consistently flat near 29-30dB, limited, we believe, by our measurement configuration. Adjacent channel insertion loss in the through port of a single stage is <0.3dB. This puts a limitation on the number of stages that can be tolerated. Rings in compensated filters are synchronous to <2 GHz, corresponding to a matching of average ring widths to better than 70pm. The 3-ring filter stages are frequency aligned to <5 GHz (~12% of the bandwidth), a critical requirement for practicality of multistage filters without post-fabrication or active adjustment of individual rings or couplings.

5. Conclusions

Multistage filters based on high-order microring stages were demonstrated. High-index-contrast filters with 3 rings per stage showed stage-to-stage resonance alignment and accurate realization, matching design, of 40GHz flat-top responses with ~30dB extinction and 20nm FSR. The filters satisfy basic requirements for a 100GHz WDM grid, without the need for post-fabrication trimming or active adjustment of the subcomponents.

References

1. J.V. Hryniewicz, P.P. Absil, B.E. Little, R.A. Wilson and P.-T. Ho, "Higher order filter response in coupled microring resonators," IEEE Photon. Technol. Lett. Vol. 12, pp. 320-322, 2000.
2. B.E. Little, "A VLSI photonics platform," in *Optical Fiber Comm. Conf.* on CD-ROM (Optical Society of America, Washington, DC, 2004).
3. Y. Yanagase, S. Suzuki, Y. Kokubun and S.T. Chu, "Box-like filter response and expansion of FSR by a vertically triple coupled microring resonator filter," J. Lightwave Technol. Vol. 20, 1525-1529 (2002).
4. M.A. Popović, M.R. Watts, T. Barwicz, P.T. Rakich, L. Socci, E.P. Ippen, F.X. Kärtner and H.I. Smith, "High-index-contrast, wide-FSR microring-resonator filter design and realization with frequency-shift compensation," in *Optical Fiber Comm. Conf. on CD-ROM* (Optical Society of America, Washington, DC, 2005), OFK1.
5. S.T. Chu, B.E. Little, W. Pan, T. Kaneko and Y. Kokobun, "Cascaded microring resonators for crosstalk reduction and spectrum cleanup in add-drop filters," IEEE Photon. Technol. Lett., Vol. 11, no. 11, pp. 1423-1425, Nov 1999.
6. M.R. Watts, "Wavelength switching and routing through evanescently induced absorption," MS Thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA, 2001.
7. T. Barwicz, M. Popović, P.T. Rakich, M.R. Watts, H.A. Haus, E.P. Ippen and H.I. Smith, "Fabrication and analysis of add/drop filters based on microring resonators in SiN," in *Optical Fiber Comm. Conf. on CD-ROM* (Optical Society of America, Washington, DC, 2004), TuL4.