September 1, 2006 / Vol. 31, No. 17 / OPTICS LETTERS 2571

Multistage high-order microring-resonator add–drop filters

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Received March 9, 2006; revised May 12, 2006; accepted May 23, 2006;
posted June 9, 2006 (Doc. ID 68841); published August 9, 2006

We propose and demonstrate a multistage design for microphotonic add–drop filters that provides reduced drop-port loss and relaxed tolerances for achieving high in-band extinction. As a result, the first microring-resonator filters with a rectangular notch stopband in the through port (to our knowledge) are shown, with extinctions exceeding 50 dB. Reaching 30 dB beyond previous results, without postfabrication trimming, such extinction levels open the door to microphotonic notch circuits for spectroscopy, wavelength conversion, and quantum cryptography applications. Combined with a low-loss, high-index-contrast electromagnetic design in SiN and frequency-matched microring resonators, this approach led to the first demonstration of flattop microphotonic filters meeting the stringent criteria for high-spectral-efficiency integrated add–drop multiplexers. The 40 GHz wide filters show a 20 nm free spectral range, 2 dB drop loss, and suppression of adjacent channels by over 30 dB. © 2006 Optical Society of America

OCIS codes: 130.3120, 230.5750.

High-index-contrast (HIC) microring resonators support high-Q modes with a large free spectral range (FSR). They enable microphotonic filters operating over the multiterahertz channel spectra of densely wavelength-division multiplexed (DWDM) networks. Previous work on high-order (multicavity) resonant filters was focused on achieving flattop drop-port responses with a sharp rolloff (>30 dB at closely spaced adjacent channels), low loss (<3 dB), or a wide FSR.[1–3] Equally important for add–drop applications is a high-extinction, boxlike notch response across the channel band in the through port—in excess of 30 dB—to avoid so-called coherent cross talk between drop and add data. High-extinction notch filters find other important applications in optical single-sideband modulation, fluorescence spectroscopy, astronomy, and quantum encryption schemes. But high extinction is yet to be achieved in microphotonic filters and requires overcoming the acute response sensitivity to fabrication imperfections in HIC devices.

In this Letter we propose and demonstrate high-order add–drop filters constructed by incoherently cascading reduced-order stages. Resulting through-port responses are shown to be less sensitive to the fine dimensional tolerances for coupling coefficients and resonance frequencies associated with HIC. The latter make it difficult to achieve high through-port extinction in a single, high-order, series-coupled-cavity (SCC) filter.[1] Multistage filters are also found to permit lower drop loss because of the partial divorce of the drop- and through-port synthesis. We present the design and experimental demonstration of one-, two-, and three-stage filters using identical three-ring stages, fabricated in SiN (Si-rich Si_3N_4). They show unprecedented performance: >50 dB in-band extinction in the through port, 20 nm FSR, flattop 40 GHz passbands with 2 dB drop loss, and 30 dB adjacent channel rejection in the drop port.

In multistage filters, unidirectional coupling of energy from earlier to later stages, along one [Fig. 1(a)] or multiple [Fig. 1(b)] response paths, bars any interstage resonance effects. This topology, with high-order filter stages, enables flat passbands with lower drop loss and higher through-port extinction tolerance than either cascaded single cavities[4] or a single SCC filter[1] of equivalent selectivity. Moreover, nonidentical stages can provide flattened passbands and high extinction through ports even with substantial cavity losses, unlike SCC filters or previous work with thin-film filters,[5] as we detail elsewhere.[6]

The advantages result from partial decoupling of the synthesis for multiple response functions, in contrast to SCC designs. In Fig. 1(a) the first-stage parameters influence the through- and drop-port responses, the last stage is shared by through and add responses, and intermediate stages affect only the through response. A trade-off results between the degree of spectral design decoupling, set by the input stage order, and loss.

Separate design leads to lower drop stage order and lower loss. A flattop response with both high out-of-band drop-port rejection and high in-band through-port extinction requires a filter of higher order than one meeting either single requirement. An SCC filter with 30 dB in-band extinction in the through port requires, by power conservation, <0.004 dB drop-port passband ripple. This calls for a high-order filter, leading to high drop loss. Con-

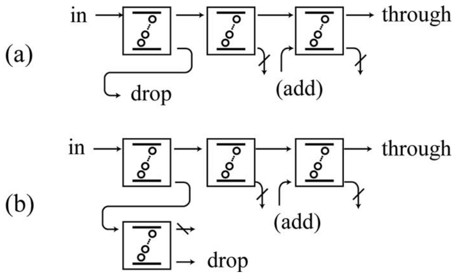

Fig. 1. Multistage add–drop filters: incoherently cascaded stages in (a) through path, (b) through and drop paths.

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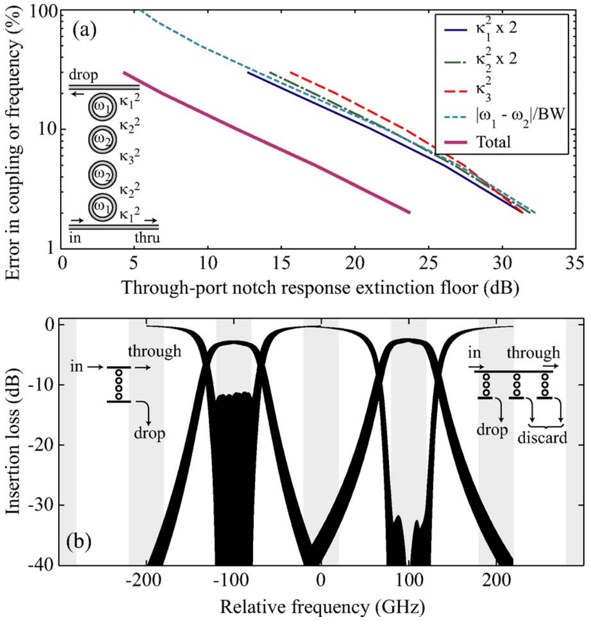

Fig. 2. (Color online) (a) Through-port extinction sensitivity to fractional error in couplings and resonance frequencies; (b) loss and tolerance to errors of comparable single-stage (left) and multistage (right) filters.

versely, since the allowable passband ripple in add–drop filters is up to (of the order of) 1 dB, drop-port criteria alone could be met by a lower-order filter.

Through-port extinction in SCC filters is particularly sensitive to errors, and a high extinction is much more difficult to realize in practice than a sharp rolloff in the drop port. Drop-port rejection through a chain of N coresonant coupled resonators is guaranteed to roll off at a rate of 6N dB per octave of detuning, independent of the precise details of coupling and frequency matching. Passband flatness does depend on these parameters but is also fairly robust to variations. On the other hand, both precise matching and coupling control are required for high extinction to be achieved in the through port. Alternative parallel-coupled ring geometries[7] provide higher tolerance of through-port extinction but lower tolerance of drop-port out-of-band rejection.

In Fig. 2(a), we illustrate theoretically the through-port sensitivity for a fourth-order filter example that meets typical WDM criteria for the four relevant parameter types: inner and outer ring resonance frequencies and couplings. A Chebyshev filter with $\sim$35 dB in-band extinction and a normalized bandwidth of 1 rad/s employs energy couplings[1] $\{\mu_1^2,\mu_2^2,\mu_3^2\}=\{1.5,0.36,0.18\}$ (proportional to power coupling coefficients κ_i^2). The plot shows the worst case through-port extinction within the channel band due to fractional error in each of the coupling coefficients and due to resonance frequency mismatch (between outer and inner resonators) as a fraction of the filter bandwidth, separately, and the total extinction floor due to the net effect of all parameters. The symmetric geometry is assumed to be preserved when errors are introduced. This is the most likely case in fabrication. All parameters contribute similarly, and an error of 15% in all parameters leads to an extinction floor at 10 dB. In practice, it is difficult to fabricate HIC filters within smaller error margins, particularly with respect to the frequency mismatch.

We may compare the fourth-order SCC filter, suitable for a 100 GHz spaced WDM channel grid, with a multistage filter meeting comparable requirements. Incorporating finite cavity loss Q's of 25,000, Fig. 2(b) shows 1000 overlaid responses representing a uniformly distributed random fractional error in power couplings and in frequency mismatch as a fraction of bandwidth (±15% in both cases). The extinction is limited by the random perturbations to $\sim$10 dB. By comparison, in a multistage filter [Fig. 2(b), right] a third-order first stage is sufficient (and others are set identically), resulting in lower drop loss (here, 2.5 dB instead of 3 dB) and a more robust total through-port extinction of 30 dB. In higher-order filters, multistage designs provide a greater drop loss reduction.

For experimental demonstration, one-, two-, and three-stage filters [Fig. 1(a)] were designed for 40 GHz channels on a 100 GHz WDM grid. Identical third-order stages were employed to simplify stage-to-stage resonance alignment. Each stage has a drop passband with 0.05 dB ripple, rolling off to 0.2 dB at the channel band edges and 30 dB rejection 80 GHz from center-band, and a through-port extinction of 22 dB over mid-channel (15 dB near band edges). For three stages, the extinction is thus 66 dB (45 dB). A 20 nm FSR calls for 8 μm ring radii and ring–bus and ring–ring couplings of 10.3% and 0.22%.

The electromagnetic design follows Ref. 8 and was tailored to measured core and cladding indices (2.181, 1.455) and core-layer thickness, 396 nm. Wide, thin waveguide cross sections reduce ring sensitivity to width tolerances and sidewall roughness and curb polarization mixing.[8] The filter is designed for TE input. A polarization diversity scheme is to be used for polarization-independent operation.[9] In previous work, we found a 1.5 dB drop loss intrinsic in the design[8] (bending, coupler scattering). Here we chose a wider (900 nm × 396 nm) ring waveguide with a deeper (200 nm) overetch, increasing the radiation Q due to bend loss of the fundamental (TE$_{11}$) resonance to $\sim$250,000 at 1530 nm. Spurious TM$_{11}$ and TE$_{21}$ resonances were kept to low Q's under 2000 and 25, respectively, to prevent them from contributing to coupler losses.[8] With narrower, 702 nm bus waveguides, rigorous three-dimensional finite-difference time-domain (FDTD) simulations produced design ring–bus and ring–ring gap spacings of 120 and 372 nm corresponding to the desired coupled-power ratios. Coupler loss was reduced by a factor of 5 from Ref. 8, and 10 from Ref. 3. With total design insertion loss at 0.35 dB, coupler loss accounts for 0.1 dB and bend loss accounts for 0.25 dB.

One-, two-, and three-stage filters were fabricated by a process based on direct-write scanning-electron-beam lithography (SEBL), described in Ref. 10, using a Raith 150 SEBL system. Waveguides were formed by a 590 nm deep reactive-ion etching step using a gas mixture of CHF$_3$ and O$_2$ and a Ni hard mask. Figure 3(a) shows a scanning electron micrograph

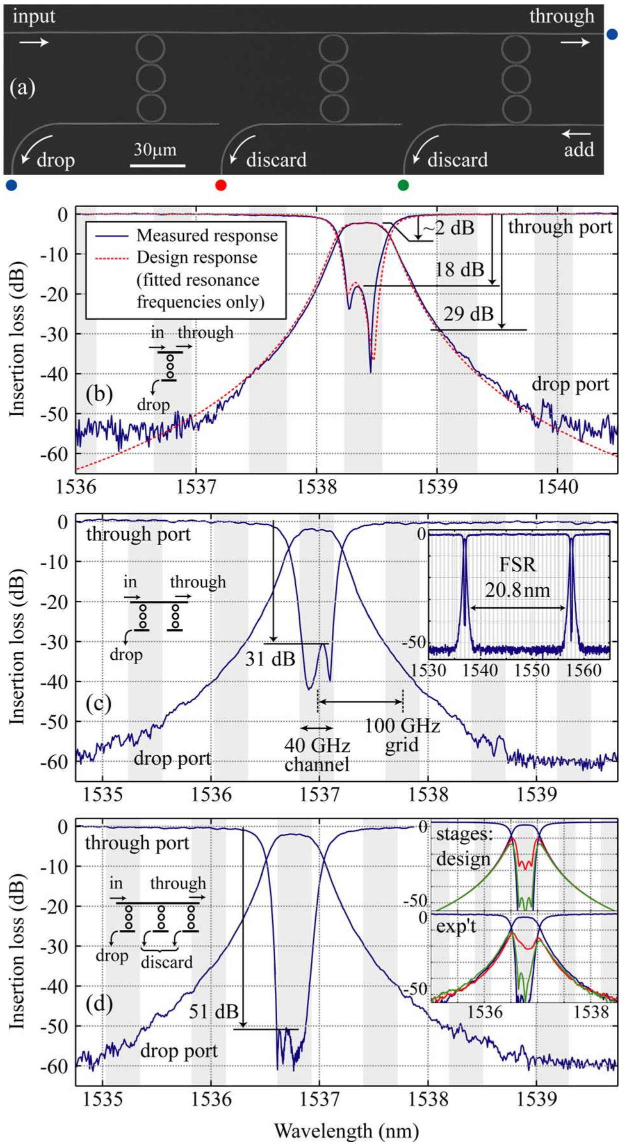

Fig. 3. (Color online) (a) SEM of fabricated three-stage filter. Measured response spectra of (b) one- (with design plot), (c) two- (inset shows FSR), and (d) three-stage filter showing high in-band extinction (inset, individual stage responses showing <5 GHz stage alignment).

(SEM) of a three-stage device. The exposure pattern was designed for lithographic field distortions to affect the filter stages in common mode such that they remain frequency aligned. To compensate for the resonance frequency mismatch reported in Ref. 3, a 3.8%–4.2% higher electron-beam dose was applied to the middle ring of each stage to increase its dimensions and match its frequency to the outer rings.

Figures 3(b)–3(d) show measured drop- and through-port TE responses of one-, two-, and three-stage frequency-compensated filters. Close agreement between the intended design and the measured result for a single-stage filter [Fig. 3(b)] validates the design and demonstrates the fabrication accuracy. The only fitted parameters were the center wavelength of 1538.36 nm and the middle-to-outer ring resonance frequency mismatch of 2.3 GHz. Excess ring propagation loss of 12 dB/cm was extracted by independent measurement and included in the model. The single-stage filter has a 40 GHz 1 dB passband with 2 dB drop loss, 30 dB out-of-band rejection, and 18 dB through-port extinction—the highest reported in a high-order microring filter to our knowledge—owing to the frequency matching and low loss. Dispersion is zero near center band with an average slope of ~$0.3\ \mathrm{ns/nm^2}$.

The two-stage filter [Fig. 3(c)] shows a similar drop response with increased through-port extinction of over 30 dB across the channel, meeting typical requirements for WDM add–drop filtering. The inset shows a realized FSR above 20 nm. In three-stage filters, the observed extinction [Fig. 3(d)] is above 51 dB across a 32 GHz window, limited by frequency mismatch. Rings in compensated filters are synchronous to ~2 GHz, corresponding to a matching of average ring widths to better than 70 pm. The three-ring filter stages are frequency aligned to <5 GHz [Fig. 3(d) inset], a critical requirement for practicability of multistage filters without postfabrication or active adjustment of individual rings. Adjacent channel insertion loss in the through port of a single stage is <0.3 dB. This limits the tolerable number of stages.

The present multistage add–drop filters demonstrate what we believe to be the first high-extinction, rectangular notch spectra achieved in microring resonators, exceeding 50 dB. These are also the first microphotonic filters to show low-loss, high-fidelity flat-top responses that meet the full spectral requirements of WDM add–drop filtering. The ease of increasing complexity in microphotonics promises a path to higher extinction levels and spectral selectivity where macroscale approaches are limited.

We thank C. Manolatou for use of her FDTD code. This work was supported by Pirelli Labs, Italy. M. A. Popović's e-mail address is milos@mit.edu.

References

1. B. E. Little, S. T. Chu, H. A. Haus, J. Foresi, and J.-P. Laine, J. Lightwave Technol. **15**, 998 (1997).
2. B. E. Little, S. T. Chu, P. P. Absil, J. V. Hryniewicz, F. G. Johnson, F. Seiferth, D. Gill, V. Van, O. King, and M. Trakalo, IEEE Photon. Technol. Lett. **16**, 2263 (2004).
3. T. Barwicz, M. A. Popović, P. T. Rakich, M. R. Watts, H. A. Haus, E. P. Ippen, and H. I. Smith, Opt. Express **12**, 1437 (2004).
4. S. T. Chu, B. E. Little, W. Pan, T. Kaneko, and Y. Kokobun, IEEE Photon. Technol. Lett. **11**, 1423 (1999).
5. M. Scobey and R. Hallock, in *Optical Fiber Conference*, Vol. 5 of 2000 OSA Technical Digest Series (Optical Society of America, 2000), p. 335.
6. M. Popović, "Theory and design of high-index-contrast microphotonic resonators and circuits," Ph.D. dissertation (MIT, to be published).
7. B. E. Little, S. T. Chu, J. V. Hryniewicz, and P. P. Absil, Opt. Lett. **25**, 344 (2000).
8. M. A. Popović, M. R. Watts, T. Barwicz, P. T. Rakich, L. Socci, E. P. Ippen, F. X. Kärtner, and H. I. Smith, in *Optical Fiber Conference*, Vol. 5 of 2005 OSA Technical Digest Series (Optical Society of America, 2005), p. 213.
9. M. R. Watts, Ph.D. dissertation (MIT, 2005).
10. T. Barwicz, M. A. Popović, M. R. Watts, P. T. Rakich, E. P. Ippen, and H. I. Smith, J. Lightwave Technol. **24**, 2207 (2006).