Strategies for fabricating strong-confinement microring filters and circuits

H.I. Smith[†], T. Barwicz, C.W. Holzwarth, M.A. Popović, M.R. Watts, P.T. Rakich, M. Qi, R. Barreto, F.X. Kärtner and E.P. Ippen

Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, Massachusetts 02139

[†]hismith@nano.mit.edu

Abstract: We describe strategies for fabricating strong-confinement microring filters and circuits, and assert that techniques specifically tailored to microphotonics requirements provide a more efficient path to commercialization than techniques developed for semiconductor electronics.

OCIS codes: (130.3120) Integrated optics devices; (230.5750) Resonators; (220.4000) Microstructure fabrication.

1. Introduction

Strong confinement in microphotonic circuits, achieved via high-index-contrast materials, enables compact, densely-integrated waveguide structures and high-Q resonators with large free-spectral ranges (FSR), suitable for optical signal filtering over large bandwidths. However, high-index contrast introduces a number of challenges in both design and fabrication. Here we focus on the latter, where achieving the desired geometries, dimensional control and edge roughness are often beyond the capabilities of tools developed for the semiconductor industry. We describe our solutions to some of the unique challenges of microphotonic systems, using microring-based reconfigurable optical add-drop multiplexers (ROADM) in SiN and in Si as test vehicles.

2. Lithography

The ROADM includes fiber-to-waveguide couplers, polarization splitters and rotators, waveguides, and third-order three-stage ring-resonator filters [1]. Circular and smoothly curving geometries are widely employed with feature sizes below ~50 nm (e.g., in the couplers and the polarization splitter and rotator). As discussed below, the average width of ring-resonator waveguides needs to be controlled to better than 0.1 nm in order to match the resonant frequencies in the 3rd-order filters [2,6,7]. These requirements are significantly different than those faced by integrated Si transistor circuits where rectangular geometries are the rule, and only transistor gate lengths need to be precisely controlled. In fact, the resolution-enhancement techniques developed to meet the needs of Si electronics (e.g., phase-shift masks and quadrupole illumination) assume, and depend on, rectangular geometries. Thus, although it is tempting to assume that fabrication of microphotonic circuits should employ the existing and extensive fabrication infrastructure of the semiconductor industry, this assumption may actually inhibit the development of microphotonics. Microphotonic components generally depend on coherent interference effects and phase fidelity (e.g., resonators, interferometers, grating couplers). In transistor circuits, the electron coherence length is negligible compared to transistor dimensions, and hence transit time is the key parameter. In our view, the unique requirement of phase fidelity in microphotonic circuits calls for the development of fabrication technologies specifically attuned to this requirement.

For the ROADM research, we used scanning-electron-beam lithography (SEBL) in a Raith 150 system. SEBL is ideal for such research and development due to its patterning flexibility, high resolution, and ability to control feature dimensions via precise dose control. Other forms of maskless lithography currently under development that provide higher throughput than SEBL may be ideal for both research and moderate-volume manufacturing [3].

3. Polarization Splitter and Rotator (PSR)

It is difficult to design strong confinement microphotonic components that handle TE and TM polarizations with equal fidelity and insertion loss. Since the output polarization of an optical fiber is unpredictable, we chose to incorporate polarization splitters and rotators (PSRs) into the ROADM so that the on-chip components process only TE or TM polarization [4,5]. Figure 1 illustrates the PSR and its performance, and depicts its fabrication process. The devices were fabricated using SEBL.

4. Ring Resonator Filters

Figure 2 is a scanning-electron micrograph of a 3rd-order ring-resonator filter. In order to achieve smooth edges and precise control of ring-waveguide width the SEBL writing is not done in the conventional Cartesian-raster format but instead in a circular format. Moreover, the starting and ending points of successive circles are staggered in

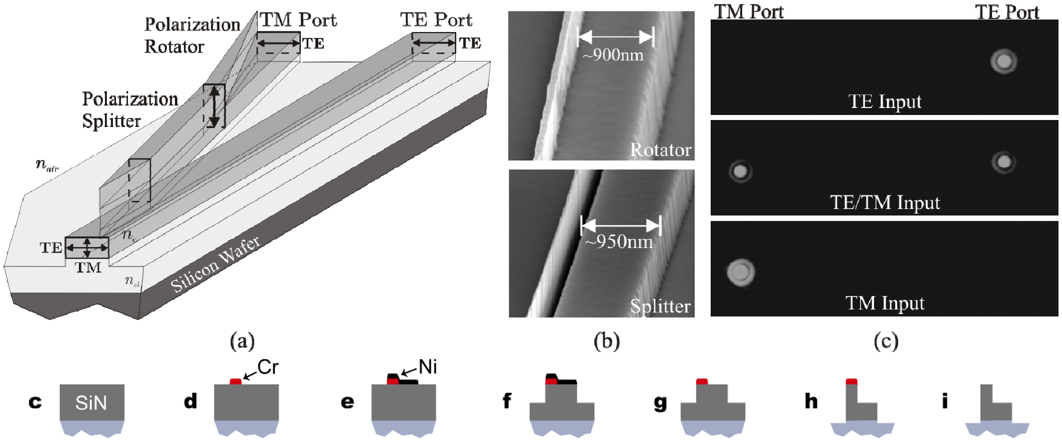

Fig. 1. (a) Schematic of adiabatic integrated polarization splitter and rotator suitable for integrated polarization diversity [4,5]; (b) scanning electron micrographs showing a detail in fabricated devices; (c) end-facet camera image showing correct experimental operation of device; (c)-(i) illustration of the novel fabrication technique employed to create the bi-level structures, described in [1].

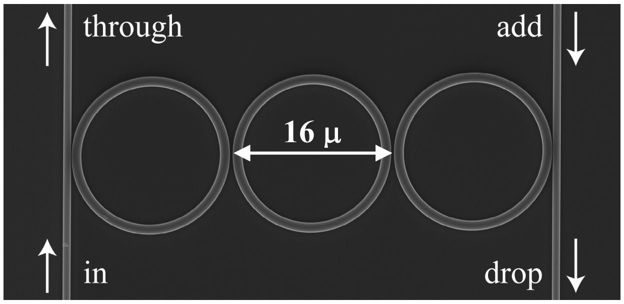

Fig. 2. Scanning-electron micrograph of a third-order microring-resonator filter with a silicon-rich SiN waveguide core [6,8].

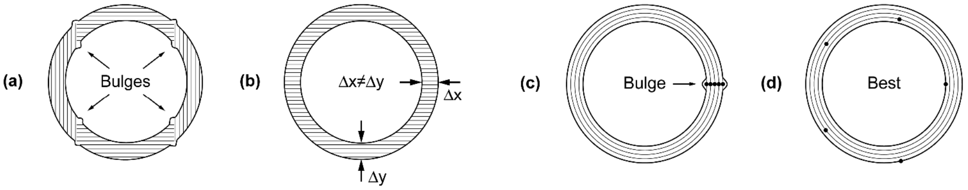

Fig. 3. E-beam vector-scanning strategies for microrings and observed problems in practice. (a) Default writing strategy in many vector-scan SEBL systems. Bulges appear at the intersections between vertically and horizontally scanned lines. (b) Scanning the e-beam in only one axis removes the bulges but affects the width uniformity of the microrings. (c) Defining the microring with circular single pixel lines offers the best results but a bulge may appear near the starting/stopping point of the circular lines. (d) Angularly distributing the starting/stopping points removes the bulge [6].

azimuthal angle in order to avoid bulging of waveguide width as illustrated in Fig. 3 [6]. In a 3rd-order ring-resonator filter the resonant frequencies of the three rings must be matched in order to achieve the desired flat-top response. To achieve such matching the coupling-induced frequency shift (CIFS), which is different for the middle ring, must be taken into account [7], as well as effects due to electron scattering and pattern discretization. Frequency matching was done experimentally by carefully controlling the electron beam dose [6].

Because electrons forward scatter within the resist, and backscatter from the substrate, the width of a written line is affected by the beam dose as well as the dose delivered to nearby patterns. (Nearby means within the electron-scattering range, which can be several micrometers.) This is referred to as proximity effect. From measurements of the point-spread function of the electron beam (or any other maskless, sequential-writing tool) the dose compensation needed to achieve frequency matching can be calculated. However, the final correction is best done empirically since the ROADM specification on drop-port loss and through-port extinction corresponds to matching ring resonator frequencies to within 1 GHz. This corresponds to matching the average ring-waveguide widths to within 0.026 nm of an ideal relative width offset. This is a startlingly small dimension, well beyond anything

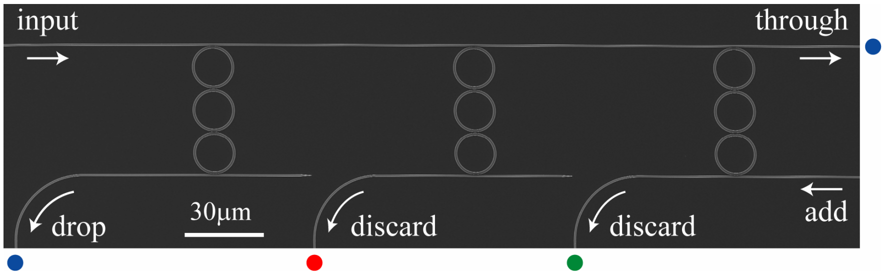

Fig. 4. Scanning electron micrograph of a multistage add-drop filter based on third-order ring-resonator stages [8].

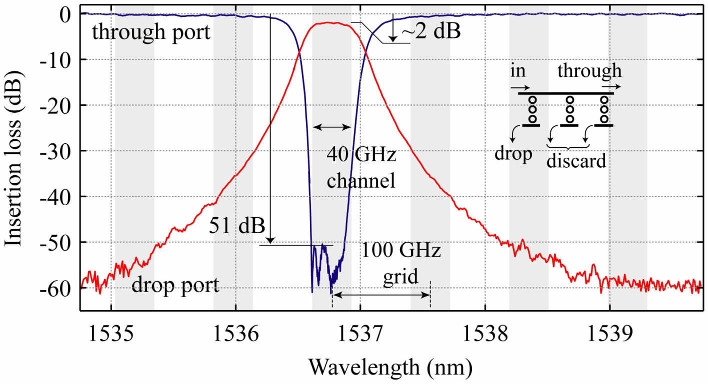

Fig. 5. Drop- and through-port responses of the filter in Fig. 4, showing >50dB extinction [8]. The filter has a 20nm FSR.

required in semiconductor-industry lithography. Yet, we achieved it, reinforcing our conviction that microphotonic fabrication techniques need to be specifically tailored to microphotonic requirements.

To increase the through-port extinction to greater than 30 dB, as required in a telecom application, we chose to employ 3 stages of 3rd order filters, as illustrated in Fig. 4. This three-stage configuration is particularly forgiving of fabrication errors in the second and third stages. Figure 5 shows the optical response of the multistage filter [8].

5. Reactive-Ion Etching and Edge Roughness

The etching of SiN and Si ROADM components was done with conventional reactive-ion etching. For SiN we used a liftoff process to produce a Ni hard mask and CHF_3-O_2 to etch the SiN at a bias voltage of 500 V. For the Si etching we directly exposed hydrogen silsesquioxane (HSQ) with the SEBL and used it as a hard mask for HBr reactive-ion etching at a bias voltage of 150 V. The spectral density of edge roughness was studied to minimize the amplitude of the spatial frequencies of roughness responsible for optical loss. Careful process optimization allowed us to reduce the standard deviation of waveguide sidewall roughness to below 1.6 nm [6]. Moreover, a three-dimensional analysis of scattering losses due to sidewall roughness was developed to more accurately predict loss and better understand the effects of the waveguide cross-section on scattering losses [9].

References

1. T. Barwicz, M.R. Watts, M.A. Popović, P.T. Rakich, L. Socci, F.X. Kärtner, E.P. Ippen and H.I. Smith, "Polarization-transparent microphotonics in the strong confinement limit," *submitted to Nature Photonics*.
2. 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 Communication Conference (OFC/NFOEC) Technical Digest (Optical Society of America, Washington, DC, March 6-11, 2005), paper OFK1, vol. 5, pp. 213-215.
3. H.I Smith, R. Menon, A. Patel, D. Chao, M. Walsh and G. Barbastathis, Microelectronic Engineering **83**, 956-961 (2006).
4. M.R. Watts, H.A. Haus and E.P. Ippen, "Integrated mode-evolution-based polarization splitter," Opt. Lett. **30**, 967 (2005).
5. M.R. Watts and H.A. Haus, "Integrated mode-evolution-based polarization rotators," Opt. Lett. **30**, 138 (2005).
6. T. Barwicz, M.A. Popović, M.R. Watts, P.T. Rakich, E.P. Ippen and H.I. Smith, "Fabrication of Add-Drop Filters Based on Frequency-Matched Microring Resonators," J. Lightwave Technol., vol. 24, no. 5, May 2006, pp. 2207-2218.
7. M.A. Popović, C. Manolatou and M.R. Watts, "Coupling-induced resonance frequency shifts in coupled dielectric multicavity filters", Opt. Express **14**, 1208-1222 (Feb. 2006), http://www.opticsinfobase.org/abstract.cfm?URI=oe-14-3-1208.
8. M.A. Popović, T. Barwicz, M.R. Watts, P.T. Rakich, L. Socci, E.P. Ippen, F.X. Kärtner and H.I. Smith, "Multistage high-order microring-resonator add-drop filters," Opt. Lett., vol. 31, no. 17, pp. 2571-2573, September 2006.
9. T. Barwicz and H.A.Haus, "Three-dimensional analysis of scattering losses due to sidewall roughness in microphotonic waveguides," J. Lightwave Technol. 23, 2719-2732 (2005).