Tunable, Fourth-Order Silicon Microring-Resonator Add-Drop Filters

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Abstract *We demonstrate the first tunable, high-order channel add-drop filters based on silicon microring resonators. They meet rigorous, telecom-grade spectral requirements for microphotonic R-OADMs (reconfigurable optical add-drop multiplexers). The design addresses 100GHz-spaced, 40GHz-wide channels over 16-32nm.*

1. Introduction

We demonstrate the first tunable high-order channel add-drop filters based on silicon microring resonators for chip-scale microphotonic reconfigurable optical add-drop multiplexers (R-OADMs). Microphotonic R-OADMs for dynamic transparent optical networks promise dense integration of add-drop filters, low-power tuning and switching, minimal filter cascading losses and the benefit of complex and phase-coherent device architectures not realizable in bulk optics. Important strides have been made through the demonstration of a high-order C-band-tunable (drop-only) demultiplexer [1], a 4th-order tunable (drop-only) filter in Si (for microwave photonics, with 15GHz FSR) [2] and a single-ring-filter tunable R-OADM [3]. However, telecom applications require add-drop filters with a large through-port extinction, large FSR (THz), and wide tunability.

In this paper, we report the first Si tunable high-order add-drop filter with suitable drop- and through-port characteristics for telecom applications. The filter is compatible with a dense wavelength-division multiplexed (DWDM) optical network with 40 GHz-wide channels and 100 GHz channel spacing. Based on strong-confinement silicon-wire waveguides and designed for full tunability of each of two adjacent resonances over its 16nm free spectral range (FSR), the filters can route channels on a 0.8/1.6 Tbps (20/40 channel x 40Gbps) aggregate R-OADM.

2. Optical and Thermal Device Design

The add-drop filter was designed for a 40GHz clear channel with a flat drop-port, >24dB through-port extinction and <30ps/nm in-band dispersion (leading to a ~70 GHz-wide passband), and >30dB extinction at 100GHz spaced adjacent channel edges. The filter employs a series-coupled design [4] (Fig. 1(a)). Fig. 1(b) is an optical micrograph of the fabricated filter in a folded, compact geometry, showing four Ti heaters (one per ring), and an outline of the waveguides.

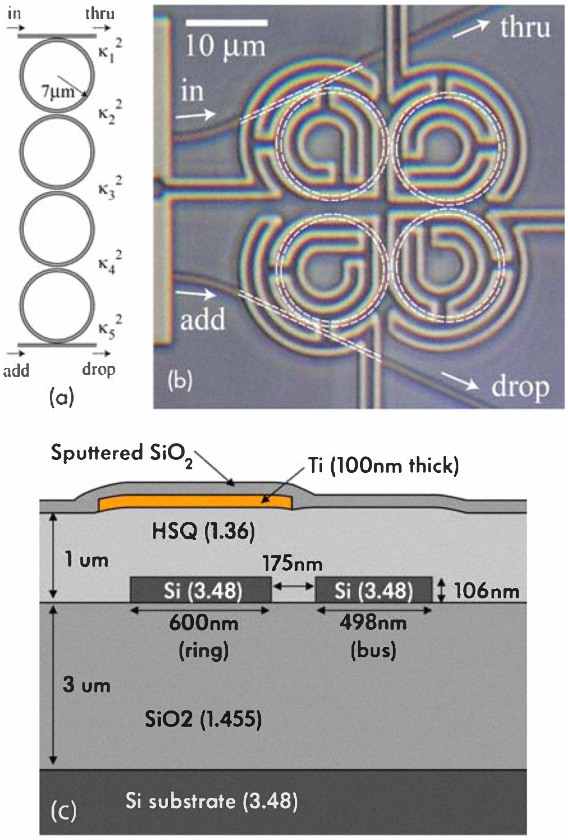

Fig. 1. (a) Fourth-order filter design configuration, having coupling coefficients $\{\kappa_1^2, \kappa_2^2, \kappa_3^2, \kappa_4^2, \kappa_5^2\} = \{18.6, 0.65, 0.36, 0.65, 18.6\}\%$ *at the center wavelength; (b) optical micrograph of fabricated tunable 4th-order microring-resonator filter based on Si waveguides, showing Ti heaters; (c) material layer stackup, showing Si guide cross-sections.*

A novel silicon waveguide design with 600x100nm cross-section (Fig. 1c), optimized for thermal tuning, was chosen [5]. It has reduced sensitivity to dimensional variation and sidewall roughness by a factor of ~3 in comparison to conventional cross-sections, and supports high microring Q's with proximate heaters. Cross-sections of 500x100nm are used for bus waveguides, and the microrings have a 7µm radius. An efficient electromagnetic filter design was produced by designing resonators and asymmetric couplers to suppress spurious mode coupling losses [6], arriving at device dimensions by 3D finite-difference modesolver and time-domain (FDTD) simulations. In spite of the strong confinement that leads to small critical dimensions, all coupling gaps are wider than 175 nm making these designs compatible with deep-UV lithography.

The filters are tuned thermally. Titanium heaters (Fig. 1(b)) were designed to raise the ring core temperature to about 250°C, permitting tuning over a full FSR with about 40 mW of power per ring.

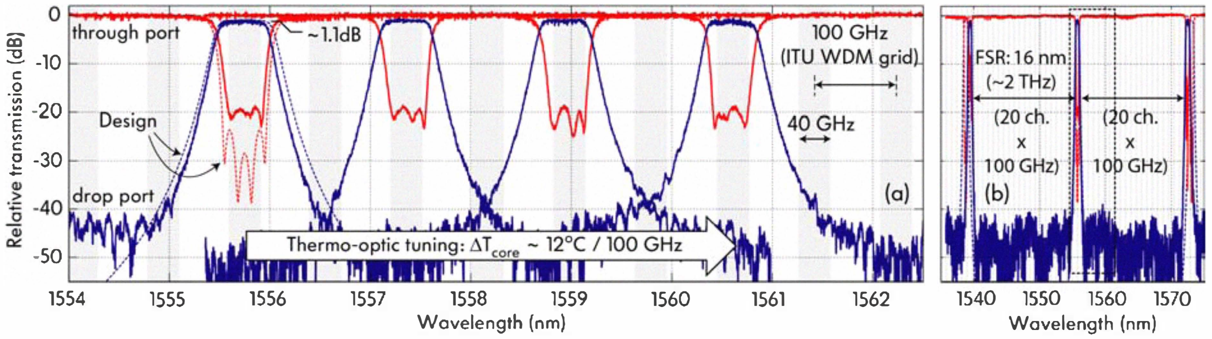

Fig. 2. (a) Tuning spectra of the first fabricated higher-order, tunable Si microring-resonator add-drop filter show: high-quality responses (see Table), matching design and experiment, efficient thermal tuning, and (b) two 16nm-FSR spectral bands.

3. Fabrication of Optical Devices and Heaters

The devices were fabricated on a Unibond silicon-on-insulator (SOI) wafer with 3μm buried-oxide undercladding and a 220 nm silicon layer, thinned to 106 nm by calibrated steam oxidation and HF stripping. The waveguides were defined by e-beam lithography using 60-nm-thick hydrogen silsesquioxane (HSQ) as e-beam resist and mask for reactive-ion etching in pure HBr. The e-beam exposed HSQ was removed and the structure was spin-coated with a 1μm layer of HSQ used as overcladding [7]. Next, 100-nm-thick Ti heaters were formed on top of the HSQ by aligned contact photolithography, e-beam evaporation and liftoff. A second photolithography and liftoff step defined 100-nm-thick gold contact pads. The waveguide material stackup is shown in Fig. 1(c). A 100 nm SiO_2 layer was sputtered as crude passivation to slow the oxidation of the Ti heaters when in operation.

4. Experimental Results

Characterization of fabricated weakly-coupled (loss-dominated) Si microrings showed loss Q's of ~250k without and ~130k with an overhead Ti heater present (as designed), translating to about 2-2.5 dB/cm and 4.5 dB/cm propagation loss in the rings, respectively.

In the drop- and through-port responses in Fig. 2(a), this is consistent with the ~1dB drop loss seen in the 4th-order add-drop filter. There is general agreement with the design response. Each ring requires <50mW to tune the full 16nm FSR due to the high Si thermooptic coefficient and a thermooptically efficient heater-waveguide system design. Detailed inspection of the Si filter passbands (Fig. 2(a)) shows that the filter meets all spectral criteria required for telecom applications, as summarized in Table 1. The through-port extinction reaches ~20dB. The commonly used two-stage, add-after-drop configuration then provides ~40dB as needed for telecom applications [6]. In-band dispersion was estimated by taking the Hilbert transform of the measured amplitude response and verified to be near the expected design value. In these filters, about 4nm tuning bias needed to be applied to the middle two rings to align the resonances and form the passband, correspondingly reducing the tuning range. This frequency mismatch can be corrected in future fabrication as previously demonstrated [8].

Property	Design	Experiment
Drop loss	n/a	1 - 1.5 dB
Drop-port out-of-band rejection	> 30 dB	> 32 dB
Single-stage through-port extinction center (edge)	29 (24) dB	20 dB
FSR	2125 GHz	2050 GHz
3dB bandwidth	74 GHz	66 GHz
Dispersion (drop, inband)	< 30ps/nm	<45ps/nm(KK)
Wavelength tuning range	2125 GHz	TBD
Tuning: power per ring	35 mW/THz	28 mW/THz
Tuning: ring-core temp.	105 K/THz	TBD

Table 1. Summary of filter characteristics in Fig. 2.

5. Conclusions

The first high-order silicon-microring-resonator add-drop filters meeting telecom specifications for DWDM applications and supporting full-FSR tunability were demonstrated. Since these filters were designed to meet the requirements in Table 1 over two FSRs (starting at 1534 and at 1550nm) these filter may be combined with an FSR doubling scheme [9] to enable C-band operation over 32nm.

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