Strong-Confinement Microring Resonator Photonic Circuits

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Abstract: Advances in microring-resonator-based photonic structures and novel architectures are described that demonstrate the first low-loss telecom-grade filters, wide tuning, polarization transparency, and fully transparent (dispersion-free) wavelength switching using high-index-contrast (SiN- and Si-core), strong-confinement waveguides.

A large number of photonic-circuit capabilities have been envisioned based on microring-resonator structures – including linear filtering, nonlinear optics, and 'slow-light' delay lines [1] – that enable applications such as chip-scale reconfigurable optical add-drop multiplexers (R-OADMs), high-rate photonic sampling systems, and intrachip communication networks for microprocessors. The majority of these applications requires strong-confinement (SC) waveguides based on high index contrast (HIC) in which bend loss is negligible for rings a few micrometers in size, providing high Q, free spectral ranges (FSR) of several THz (10's of nm), and sizes compact enough for dense photonic integration. However, in the SC regime, there are several design and fabrication challenges, including strong sensitivity to sidewall roughness, dimensional variations and polarization state.

In the course of our work [2-15], reviewed here, silicon- and SiN-core waveguide and microring resonator devices and architectures that overcome the major challenges to SC photonic circuits and microring technology have been developed. They demonstrate SC solutions for: tolerant, low-loss waveguide designs; frequency-aligned resonators; broadband polarization transparency; dispersionless, fully transparent (hitless) wavelength switching; wide-range, low-power tuning; and fabrication-compatible, efficient coupling from a fiber to a sub-micron HIC waveguide. Novel resonator and interferometer architectures have been proposed that are realizable in SC photonic circuits and enable new functionalities and optimal filter designs [12,13].

Channel add-drop filters based on SC coupled microring resonators are subject to two fundamental sources of impairment: coupling-induced resonance frequency shifting (CIFS) [2], and mode-reconfinement-induced loss in coupling regions [3,4]. With frequency compensation [2], low-loss coupler designs [3,4], a multistage architecture (Fig. 1a), and tailored electron-beam lithography [5] we demonstrated the first telecom-grade add-drop filters, using SiN waveguides, with flat-top passbands and >50dB in-band extinction [4]. These filters operate on the TE polarization. For polarization-transparent operation, a viable solution is a fully integrated polarization diversity approach (Fig. 1b) [7], enabled by an integrated polarization splitter-rotator (PSR) design (Fig. 1c) [8]. The first demonstration of a polarization-transparent SC photonic circuit – an add-drop filter – using the SiN microring-resonator filters and PSRs, gave nearly identical TE, TM and arbitrary-polarization telecom-grade responses [9].

Wide wavelength tunability of multiple THz (10's of nm), required for many applications including R-OADMs, can be achieved by thermooptic tuning in silicon-core waveguides. Si waveguides, with even higher index contrast than SiN, have high sensitivities. A novel, 6:1 aspect ratio, thin-core Si waveguide design was proposed that optimizes propagation loss, tolerances and tuning properties [6]. Based on this waveguide, we demonstrated the first high (4^{th}) order, tunable microring-resonator filters in Si [10] (Fig. 2a), with about 1dB drop-loss and 2 THz FSR.

Integrated SC photonic circuits enable new optical device topologies. A further important capability required by R-OADMs, and a challenge to achieve in any present technology, is the full disabling of both the amplitude and phase response of an add-drop filter during wavelength tuning, achieving so-called *hitless* tuning (i.e. without disturbing signal integrity in express channels). A general approach was proposed and demonstrated for disabling both the amplitude and phase response of resonant systems on a chip in a practical way for arbitrary-order structures [11] (Fig. 3a,b). The first demonstration of hitless switching in a SC microring circuit, using this approach and the silicon-core device design, is shown in Fig. 3c. Also, a new class of optical resonators has been proposed [12] (Fig. 4a), that makes use of "loop-coupling", has a new topological phase design parameter, allows optimally sharp filters, and permits nearly dispersionless passbands (Fig. 4b) that are superior to standard series-coupled microring structures which are fundamentally dispersive owing to Kramers-Kronig constraints. The new structures enable tolerant pole-zero filters and may have important applications as telecom add-drop filters, 'slow-light' structures and optical delay lines, sensors, modulators. As well, a new class of interferometers referred to as universally balanced interferometers (UBIs) has been proposed [13] (Fig. 5) that permits dispersion-free Vernier-like FSR multiplication, an alternative approach to hitless switching [14], and other new capabilities such as "hot-swapping" of photonic circuit subsystems. Efficient coupling from a fiber to an on-chip sub-micron Si waveguide may be achieved using grating-based vertical couplers, but requires a way to achieve unidirectional coupling which may be done by

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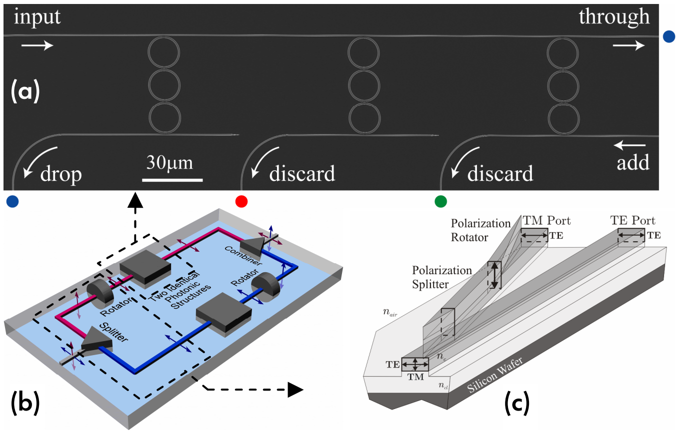

Fig. 1. First **polarization-transparent strong-confinement microphotonic circuit** [9] based on polarization splitter-rotators [8] and microring filters [4].

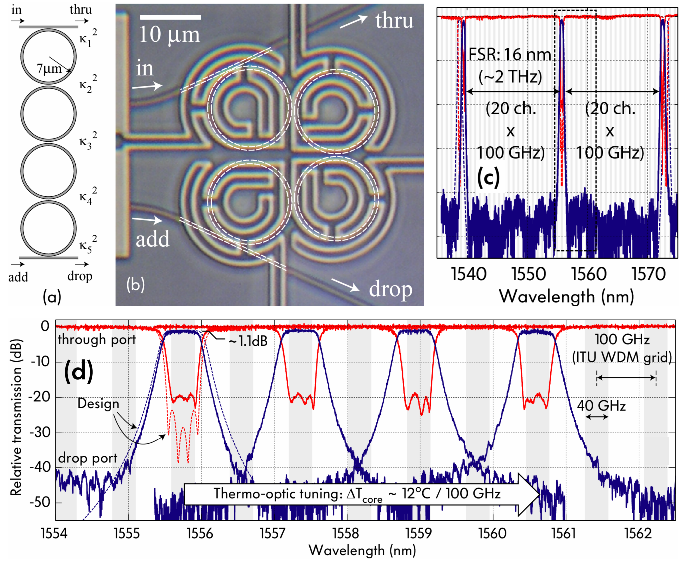

Fig. 2. Widely-tunable, high-order telecom grade add-drop filters: first demonstration in strong-confinement (silicon-core) microring resonators [10].

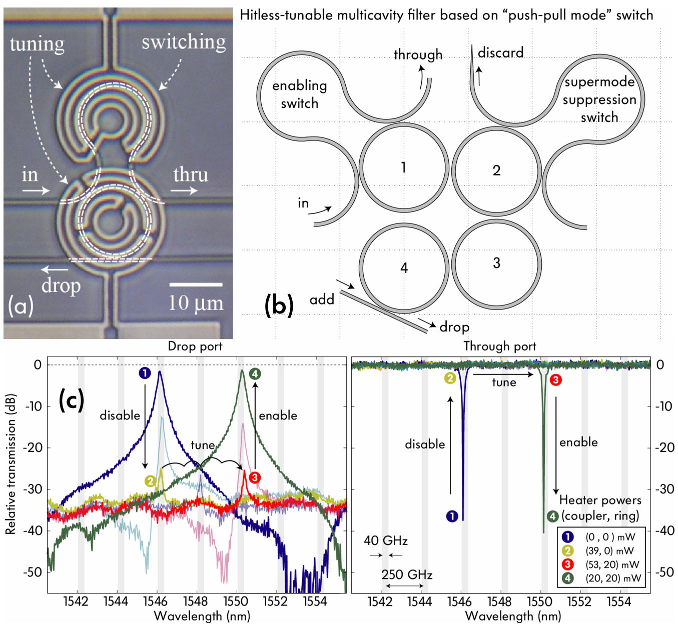

Fig. 3. Dispersionless hitless switching of microring filters: first demonstration based on new approach for transparent amplitude and phase disabling [11].

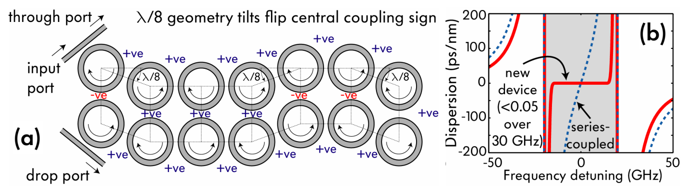

Fig. 4. Loop-coupled resonators: a new proposed class of optical resonators that allows dispersionless flat-top filters and 'slow-light' delay lines [12].

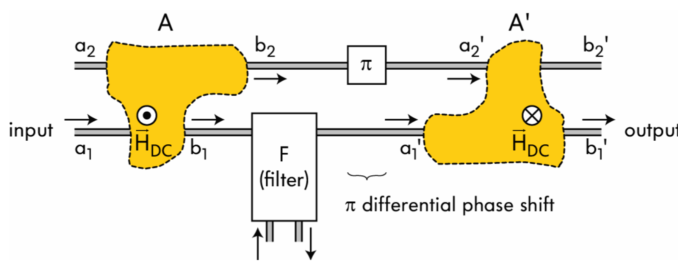

Fig. 5. Universally balanced interferometers (UBIs): a proposed new class of photonic interferometers; uses include dispersionless Vernier schemes[13,14].

integrating a mirror under/over the waveguide layer, complicating fabrication. We have proposed a coupler design utilizing only two lithographic layers that requires no mirrors, can be efficiently realized using available fabrication techniques, and couples light into or out of the chip in one direction only at up to a 50:1 up-to-down ratio [15].

Taken together, this work has addressed the major challenges of SC waveguides and demonstrates original SC photonic circuit solutions and novel device proposals for a number of important problems in the telecom field.

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