Hitless-Reconfigurable and Bandwidth-Scalable Silicon Photonic Circuits for Telecom and Interconnect Applications

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Abstract: We describe silicon microring-resonator-based microphotonic circuits that support complete (amplitude and phase) disabling of resonant states, enabling novel capabilities: *truly-hitless* switching/tuning of high-order, telecom-grade channel add-drop filters, dispersionless FSR multiplication, and "hot-swapping" of photonic subsystems.

OCIS codes: (230.5750) Resonators; (120.2440) Filters; (060.1810) Couplers, switches, and multiplexers.

1. Introduction

Microphotonic circuits based on strong-confinement (SC) waveguides and resonators are an enabling technology for high-bandwidth, agile wavelength routing networks – providing filters for broadband chip-scale tunable optical add-drop multiplexers (T-OADMs) for telecom applications and for chip-scale interconnects or entire photonic networks on a microprocessor [1-3]. SC photonic circuits are based on high index contrast (HIC) in which bend loss can be negligible for microring resonators a few micrometers in size, providing high Q, free spectral ranges (FSRs) of several THz (10's of nm), and compact device sizes enabling dense photonic integration.

A number of photonic circuit functionalities that will be required for high-bandwidth, large channel count photonic networks call for SC resonant circuits that admit configurations with what we'll refer to as "quenched" resonant states – states where the resonant system is disabled to a minimum-phase state such that it yields neither a substantial amplitude *nor* phase response. Two such functions are *hitless tuning* and *FSR multiplication* of resonant filters for telecom applications where both drop- and through-port responses are relevant. Hitless tuning requires that channel add-drop filters tune from one target wavelength to another without causing any bit errors in other wavelength channels. In previous work, hitless tuning of microring-resonator filters has been claimed [4] but not achieved because suppression of the phase response was ignored, whereas it is critical for tuning without introducing signal degradation and bit errors. Likewise, the standard "Vernier" FSR-multiplication approaches, that rely on FSR-mismatched resonators [8], have excessive dispersion at suppressed resonant bands, and dispersion-free designs are needed for truly transparent add-drop filtering and wavelength switching over large bandwidths. For hitless tuning, bypass approaches have also been investigated [5], to which we add a general new class of architectures [6,7].

In this paper, we review device concepts with quenchable resonant states based on: 1) variable input-cavity coupling and artificial cavity-loss mechanisms [9], and 2) universally-balanced bypass interferometers (UBIs) [6,7]. Their use is described for two important telecom applications: hitless switching of channel add-drop filters to a dispersionless off-state [6,7,9]; and multiplication of the effective FSR by dispersionless suppression of selected resonant bands [6,10]. Proof-of-principle device demonstrations are described in silicon and SiN microring-resonator photonic circuits. In the last section of the paper, we review recent advances in strong-confinement

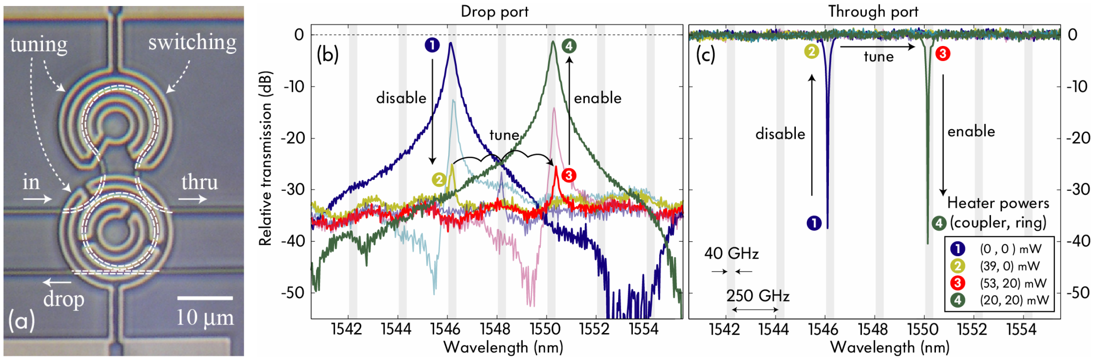

Fig. 1. Truly hitless switchable filter – based on a quenchable-resonant-state system – for tunable channel add-drop and interconnect applications. (a) The silicon microring filter with Ti microheaters has (b) a fully transparent off-state with disabled amplitude and phase responses. In the off state, the filter may be thermally tuned through wavelength channels without causing degradation in the data they carry [11].

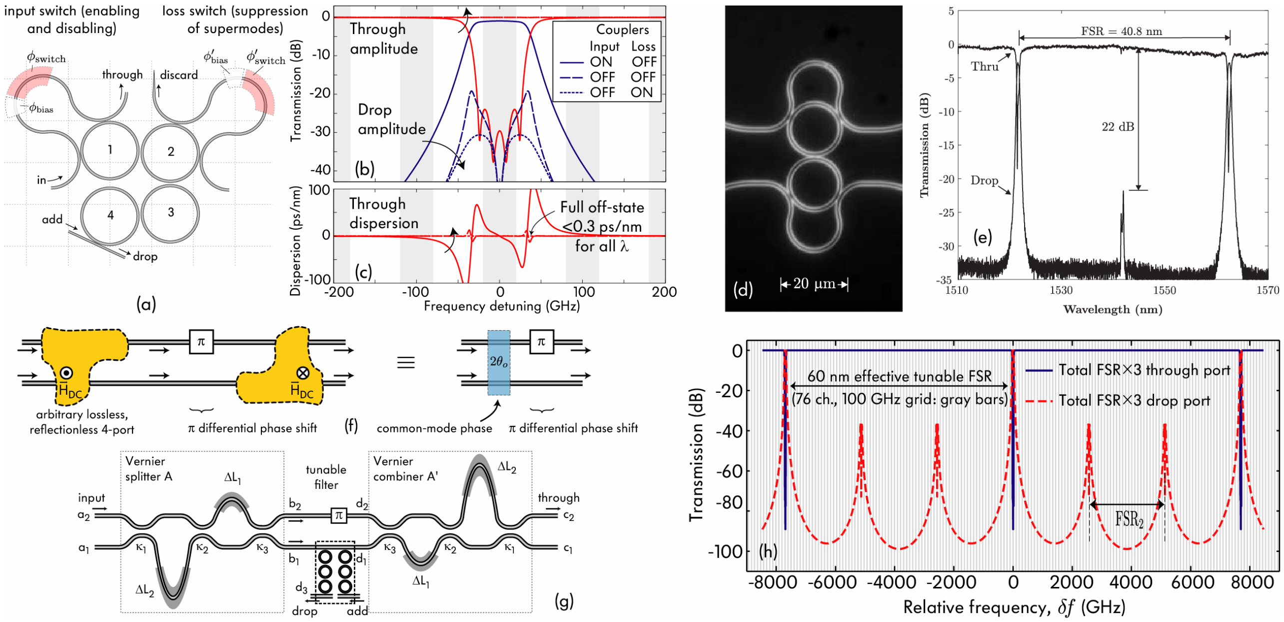

Fig. 2. Concepts and demonstrations of more advanced quenched-resonant-state systems [9,10,6,7]: (a) proposed higher-order design of hitless-tunable filter analogous to that in Fig. 1, based on push-pull actuation of a variable input coupling and internal cavity-loss coupler, and (b,c) its switching characteristic showing a dispersionless off-state [9]; (d) a fabricated FSR-doubled add-drop filter where the input coupling is wavelength dependent and suppresses every second resonant passband, and (e) its experimentally demonstrated FSR-doubled response [10]; (f) a proposed novel class of interferometers – universally balanced interferometers (UBIs) – that provide an general optical "amplitude-inverse" operator [6,7], (g) a proposed FSR-tripled filter based on the UBI architecture, with quenched resonant states at two of three resonant passbands, and (h) its simulated response [6,7].

photonic circuits [11] that demonstrate solutions to the central challenges with HIC photonics – polarization dependence [2], dimensional ultrasensitivity and propagation loss [12], tuning range [1,13] – and enable immediate application of the presented device concepts for a new generation of industrially relevant, telecom-grade devices.

2. Disabling the amplitude and phase response of a resonator; and optimal dispersionless filters

Two strategies for quenching the amplitude and phase response of a resonant system are presented: disabling the resonator-waveguide input coupling to take the system into a minimum-phase off-state [9]; and, interferometric bypass of the resonant system [6]. The first method, disabling the resonator input coupling at a resonant passband, is applied to show the first demonstration of dispersionless hitless tuning of a microring filter, in Fig. 1 [9]. The device is realized in rectangular silicon-core waveguides, and thermally actuated by Ti microheaters. Actuating the top microheater sets the device into an undercoupled (minimum-phase) state and turns off the filter amplitude and phase response. Subsequently, actuating both heaters (in this design) in unison tunes the resonant wavelength of the filter, which passes "under" various through-port channels without disturbing the data they carry. Finally, the top heater is actuated again to enable the filter at the target wavelength, demonstrating hitless tuning. The single-ring device can operate on an 8-channel link with 250GHz channel spacing (FSR = 2THz). For DWDM channel spectral densities (e.g. 40GHz filters, 100GHz spacing), higher order filters are needed. The disabling concept is generalized to higher order devices as shown in Fig. 2a-c, by introducing an additional, variable artificial-loss mechanism to suppress supermodes [9]. If the interferometric input coupling is made variable against wavelength rather than microheater state, this concept can also be used for doubling the FSR of microring filters with no substantial dispersion at suppressed resonances, as demonstrated in SiN microrings (Fig. 2d-e) [10]. This is important because the microring FSR is limited by the index contrast, and further increase in bandwidth utilization depends on strategies for scaling up the effective FSR by dispersionless Vernier schemes such as this one.

A second approach to disabling select resonant passbands is using bypass interferometers (BIs). A general class of BIs, UBIs, comprising an arbitrary splitter and its "amplitude-inverse" has been proposed [6,7]. These BIs allow all input signal at one port to be split arbitrarily (by a controllable switch or wavelength-dependent filter) between the two arms, and then recombined fully into one output port by symmetry (Fig. 2f). The resonant filter is placed in one interferometer arm to acquire a hitless tuning or dispersionless-Vernier FSR-multiplying function (Fig. 2g-h) [6,10]. Other UBI applications proposed include "hot-swapping" of arbitrary photonic circuits in a live network [7].

While the off-state through-port dispersion is eliminated in the above device concepts, the on-state dispersion of a typical coupled-cavity filter is directly related to the amplitude response by the Kramers-Kronig relation. A flat-

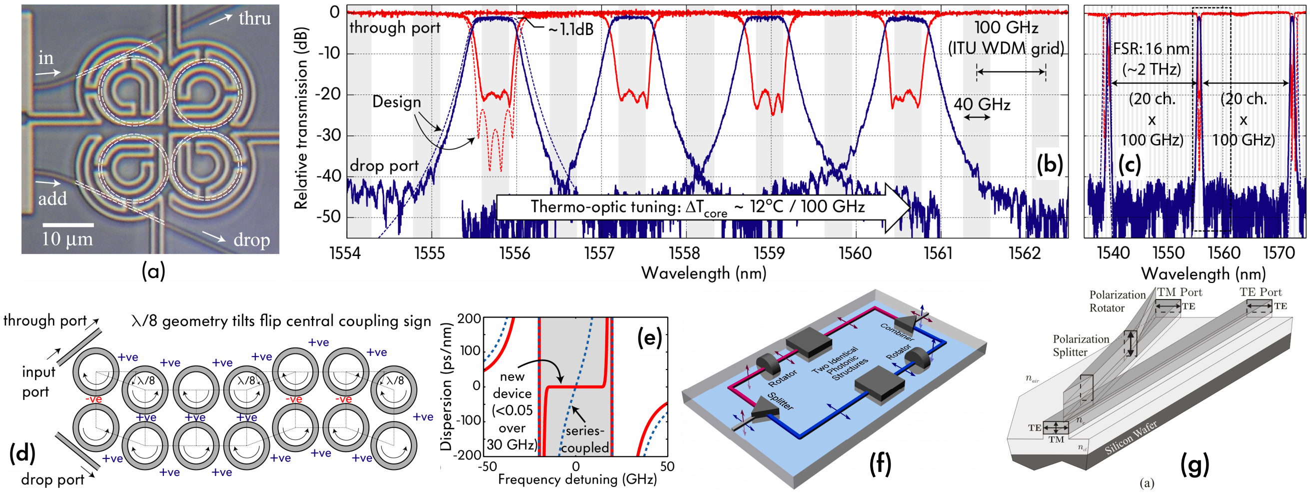

Fig. 3. Supplementary strong-confinement device concepts and demonstrations enabling the use of quenched-resonant-state devices for telecom-grade hitless tunable/switchable add-drop filters and interconnect switches: (a-c) silicon-core microring 4th-order tunable add-drop filter micrograph, and tuning demonstration [1], designed for full-FSR tuning [13]; (d) proposed novel, loop-coupled microphotonic filter architecture and (e) dispersion response of a resulting dispersion-free flat-top filter design [15]; (f) illustration of the layout of the first experimental demonstration of polarization-independent strong-confinement photonic circuits – using integrated polarization diversity [2], and (g) polarization splitter-rotator (PSR) device concept [17] that was fabricated as part of the integrated diversity demonstration.

top filter is intrinsically dispersive, and requires all-pass dispersion compensators. A new class of optical resonators relying on cavity coupling loops – loop-coupled resonators – was proposed that allows dispersionless flat-top responses over >85% of the filter bandwidth enabling the sharpest linear-phase responses for a given number of resonators [15]. Such structures take advantage of the topological freedom in a planar circuit and enable responses not demonstrated in bulk or thin film optics. They mimic features available in microwave circuits, but also offer new degrees of freedom. Further applications include slow-light delay lines and microwave-photonic channelizers.

3. Overcoming the sensitivities of strong-confinement photonic circuits, tuning and applications [11]

To overcome the intrinsic ultrasensitivity of SC waveguides and resonators to resonant frequency alignment, multistage geometries [16], as well as novel (low-sensitivity, low-loss) silicon waveguide designs [12] have been proposed and demonstrated that enable the practical design of telecom-grade filters in SC photonics based on SiN or Si microrings. Furthermore, the SC ultrasensitivity translates to polarization dependence that would require atomic-scale absolute dimensional control to achieve aligned TE and TM resonances in a single SC resonator [2]. To achieve polarization-independent operation, a fully-integrated polarization-diversity scheme (Fig. 3e) was demonstrated that relies on the high degree of symmetry under replication of structures in lithography [2]. Finally, silicon resonant filters with telecom-grade passbands (Fig. 3a-c) [1], and with full-FSR tunability [13] were experimentally demonstrated. These developments address all of the major challenges in SC photonic circuits and enable the immediate realization of the presented device concepts with quenchable resonant states for hitless tuning and FSR multiplication applications in telecom and on-chip photonic network applications.

Support: Primarily funded by Pirelli Labs, Italy. Completion of the silicon work made possible through discretionary funding of the MIT Nanostructures Lab, the DARPA Program on Integrated Photonics Networks for Compact, Energy Efficient Supercomputers W911NF-06-1-0449, and the DARPA Electronic-Photonic Integrated Circuits (EPIC) Program W911NF-04-1-0431.

References

[1] M.A. Popović, T. Barwicz, *et al.*, presented at European Conference on Optical Communication, Berlin, Germany, Sep 2007, paper 1.2.3.
[2] T. Barwicz, M.R. Watts, *et al.*, "Polarization-transparent microphotonic devices […]," *Nature Photonics* **1**, 57-60 (Jan. 2007).
[3] L.P. Carloni *et al.*, "On the design of a photonic network-on-chip," 1st Int. Symposium on Networks-on-Chip (NOCS), p.53–64 (May 2007).
[4] Y. Goebuchi, T. Kato and Y. Kokobun, IEEE Photon. Technol. Lett. **18**, 538 (2006); L. Domash *et al.*, J. Lightwave Technol. **22**, 126 (2004).
[5] R.E. Scotti, C.K. Madsen, *et al.*, in Optical Fiber Commun. Conference Technical Digest, pp. 142-143 (1998).
[6] M.A. Popović, E.P. Ippen and F.X. Kärtner, "Universally balanced photonic interferometers," *Opt. Lett.* **31**, 2713 (September 2006).
[7] M. Popović, "Theory and Design of High-Index-Contrast Microphotonic Circuits," Ph.D. Thesis, MIT (Cambridge, MA), Sep. 15, 2007.
[8] Y. Yanagase, S. Suzuki, Y. Kokubun and S.T. Chu, *J. Lightwave Technol.* **20**, 1525-1529 (2002).
[9] M.A. Popović, T. Barwicz, et al., in Conference on Lasers and Electro-Optics (CLEO), Baltimore, MD, 2007, postdeadline paper CPDA2.
[10] M.R. Watts, T. Barwicz, *et al.*, in Proceedings of the Conference on Lasers and Electro-Optics (CLEO), vol. 1, pp. 273 (2005).
[11] M.A. Popović *et al.*, "Strong-confinement microring resonator photonic circuits (Invited)," presented at the 20th Annual Meeting of the IEEE Lasers and Electro-Optics Society (LEOS), Lake Buena Vista, Florida, Oct 2007, paper TuCC3.
[12] M.A. Popović, T. Barwicz, E.P. Ippen and F.X. Kärtner, in Conference on Lasers and Electro-Optics (CLEO), 2006, paper CTuCC1.
[13] F. Gan, T. Barwicz, *et al.*, presented at IEEE/LEOS Photonics in Switching Conference, San Francisco, CA, Aug 2007, paper TuB3.3.
[15] M.A. Popović, in Conference on Lasers and Electro-Optics (CLEO), 2007, paper CThP6.
[16] M.A. Popović, T. Barwicz, M.R. Watts, P.T. Rakich, L. Socci, E.P. Ippen, F.X. Kärtner and H.I. Smith, *Opt. Lett.* **31**, 2571 (2006).
[17] M.R. Watts et al., presented at Optical Fiber Communication Conference, 2005, postdeadline paper PDP11.