General approach to hitless switching and FSR extension for resonators in integrated photonic circuits

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Abstract: A hitless bypass switch for microphotonic channel add-drop filters that is based on $\Delta\beta$ switches is described. We generalize the design to a large class of devices enabling variants of the switch and application to free-spectral-range extension in tunable filters.

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1. Introduction

Microphotonic channel add-drop filters in several proposed implementations have made significant inroads toward meeting optical network requirements [1-3]. High-index-contrast (HIC), flat-top microring-resonator filters with a wide free spectral range (FSR) and suitable for 100GHz-spaced wavelength-division-multiplexed (WDM) channel grids have been demonstrated, with low loss and high drop- and through-port extinction [3]. Filters employing integrated polarization diversity schemes promise to mitigate the inherent polarization dependence of HIC devices by design [4]. However, dynamic reconfigurability is increasingly important in wavelength-routing transparent optical networks; and microphotonic add-drop filter implementations must support this aspect of network functionality, through wideband wavelength tunability (C-band) and hitless switching capability [5].

We propose a hitless bypass switch for add-drop filters that permits switching to be slow on the bit timescale and employs simple, symmetric actuation to achieve hitless, broadband operation in the through-port by symmetry. We present its properties and an example design. We then describe a generalization of this device to a class of devices that exhibit similar properties and may be employed in a multitude of ways. We show examples of device designs for hitless switching and for dispersion-free resonance suppression that allows extension of the FSR of a resonant add-drop filter (from 20 to 60nm in the present example), and of its range of wavelength tunability.

2. Broadband hitless bypass switch

A bypass scheme is one general approach that may facilitate hitless switching for a variety of reconfigurable devices. The input spectrum is uniformly diverted to a bypass optical path without interruption of express channels, permitting the embedded filter to be reconfigured (tuned to a new channel). Within this framework, one approach may involve switches that change state much faster than the bit slot time to avoid bit loss. Such switches are challenging to realize and do not scale up with bitrate. A second approach, taken here, is a "slow hitless switching" scheme where the switching time can be much slower than the bit slot time. Here, a design is required that produces no bit loss before, during and after switching. Integrated optics is naturally suited to support such designs via on-chip interferometry, and schemes of this type have been investigated previously [6-7].

We present a bypass switch design for reconfigurable optical components (Fig. 1a), that is based on a pair of identical $\Delta\beta$-type switches and is hitless and broadband for the express spectrum by symmetry. To circumvent the switch-state-dependent phase that is introduced in $\Delta\beta$ switches, the inputs of the second switch are reversed with respect to the inputs of the first; and, a π differential phase shift is introduced in the interferometer arms. One arm contains the device to be reconfigured – a wavelength-tunable channel add/drop filter, and the other arm is free. For hitless operation, the switches are synchronously actuated. This is in contrast to approaches that imply feedback control or careful adjustment of a phase element and/or one switch state depending on the position of the other [7-8]. For express channels, the hitless scheme proposed is as broadband as the π phase shift introduced, notwithstanding the bandwidth of the individual switches. On the other hand, broadband switches are required to ensure complete extraction of dropped channels by the tunable add-drop filter.

The switch-state-dependent bar-state phase that is inherent in $\Delta\beta$-type switches makes it challenging to achieve complete, broadband recombination of a signal entering one input port in either single output port without active, and potentially wavelength dependent, phase compensation. We show that this can be done with an antisymmetric arrangement of the two switches (Fig. 1a), symmetric actuation, and in addition a π differential phase shift in the interferometer arms connecting the switches. In general, these conditions are sufficient and necessary for complete

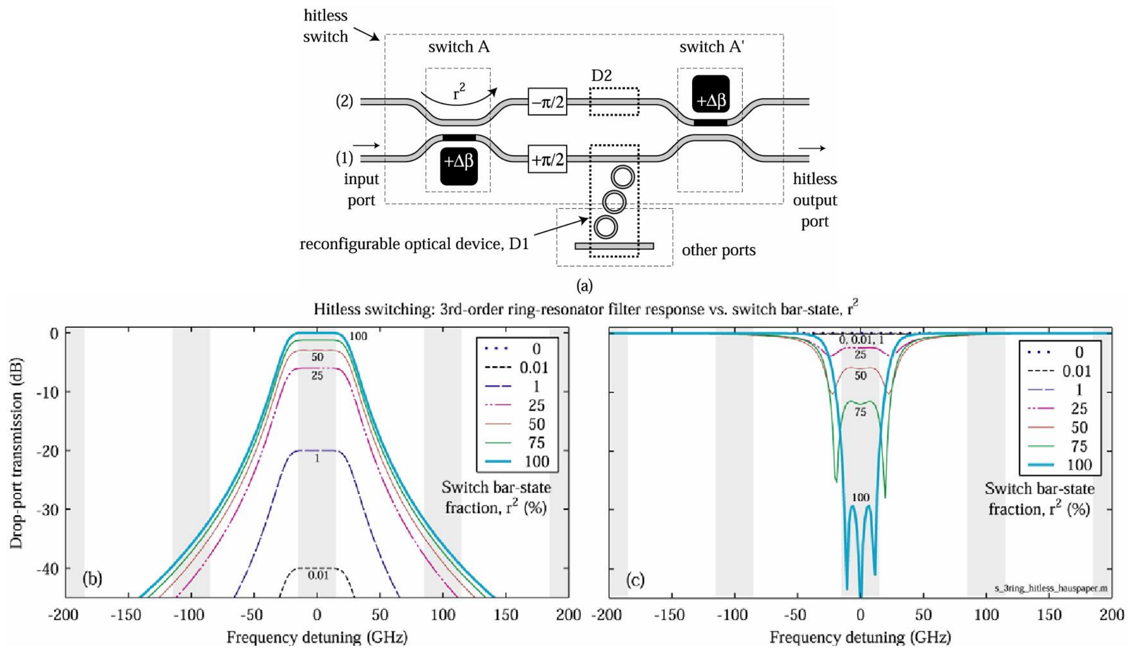

Fig. 1. (a) Hitless bypass switch consisting of two antisymmetrically cascaded, symmetrically actuated Δβ switches, and a π differential phase shift in the arms connecting them. With a third-order resonant add-drop filter in one arm, (b),(c) actuation of the switches causes smooth switching on-off of the add-drop filter [9].

recombination in one output port, independent of wavelength and switch state. We address the design rigorously in [9]. Here, we state the salient points and present an example.

Operation varies the fraction of total power in waveguide 1 as r^2. Regardless of the state of the switch (r^2), the output port contains all input power (without filter(s) D1,D2 present). This property depends only on the imposed symmetry conditions and the introduced π phase shift, and it is subject only to the bandwidth of the required π phase shift in any particular realization. The 3dB transient state is most sensitive to phase error and incurs a 1dB "hit loss" for 30% error in the phase shift. This still permits realizing π phase shifts with bandwidths in the hundreds of nm.

Fig. 1b,c shows simulated drop- and through-port responses of a third-order microring-resonator filter within the hitless switch, for various switch states r^2. Shown on a 100-GHz channel grid, the filter has 4 THz FSR and ring-bus and ring-ring couplings of 7% and 0.08%, respectively. Hitless switching is evident from the complete dropping a channel to complete bypass, whereupon the filter may be tuned to a new channel. The filter has some excess dispersion outside its channel window that leads to a parasitic hit loss of 0.4dB at adjacent channel edges. This may be reduced by improved filter designs. Broadband Δβ switches are not required for hitless recombining, but are necessary to route the operating spectrum fully to the tunable filter or the bypass path. Compact implementations are proposed that employ a HIC waveguide switch with MEMS-actuated dielectric slab Δβ perturbation.

3. General two-spatial-path diversity devices and FSR extension

We present a more general device geometry in Fig. 2, comprising arbitrary but identical devices A and A'. It can be

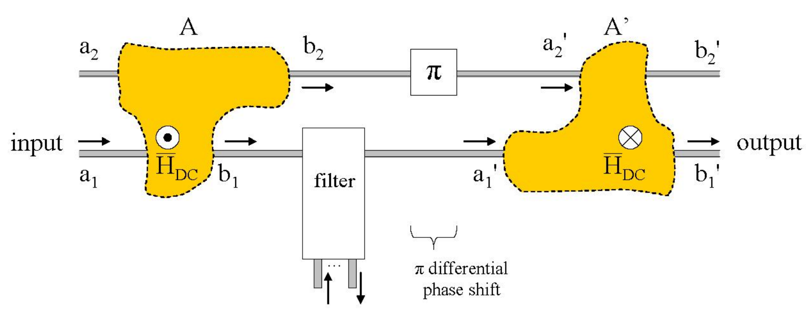

Fig. 2. Generalized two-spatial-path diversity scheme: arbitrary, identical (lossless and reflectionless) 2-input, 2-output devices A and A', cascaded as shown, with a π differential phase shift in the connecting arms, guarantee recombination of all signal in one input port into one output port, for all wavelengths. For non-reciprocal A,A', A' must have opposite bias.

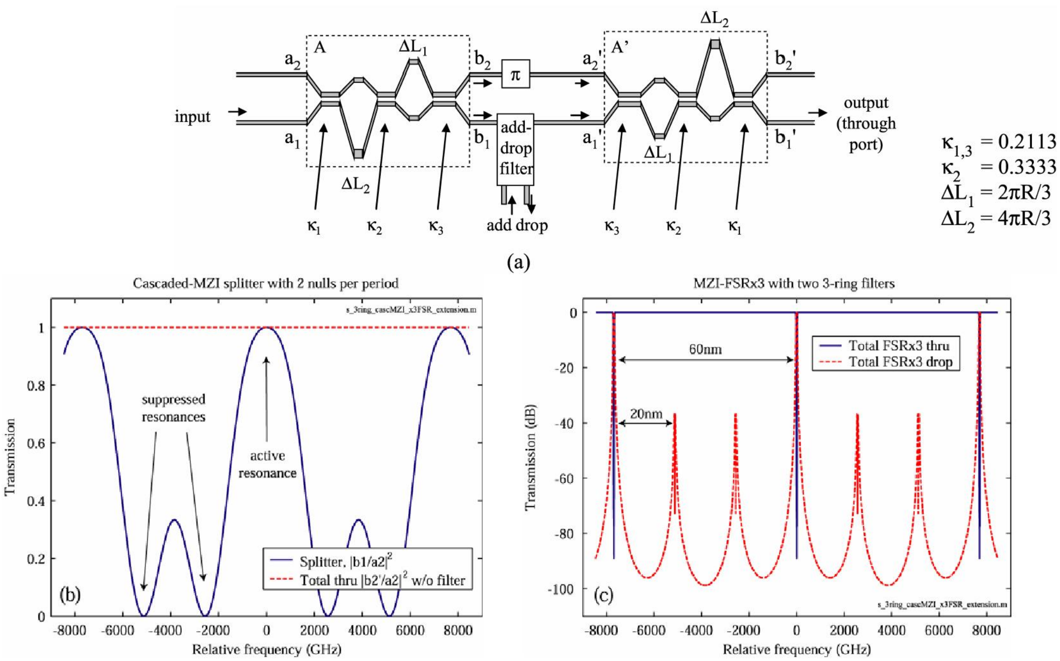

Fig. 3. Dispersion-free free-spectral-range tripling in a resonant add-drop filter of Fig. 1b,c: (a) cascaded Mach-Zehnder filters comprise splitter A and combiner A', (b) giving a 2-way splitting response that bypasses the filter at two of every three resonances; (c) the resulting filter response has a tripled FSR to 60nm without parasitic through-port dispersion.

shown using only time reversal and an assumption that A and A' are substantially lossless and reflectionless, that the device in Fig. 2 fully recombines all signals entering one input into one output, after an arbitrary splitting between the two arms according to the particular choice of device A. The only requirements are that A and A' be identical, arranged as indicated, and supplied with a π differential phase shift between the two waveguides connecting them. We prove the case in the presentation and here for brevity illustrate the operation with examples. In this context, A and A' may be any lossless, reflectionless device with two input and two output ports, such as a switch, Mach-Zehnder interferometer (MZI), microring-resonator filter, or any combination thereof. The hitless switch of Fig. 1 is an example of the generic device of Fig. 2, where A,A' are broadband switches. Thus, more generally other types of switches may be employed, regardless of their geometry and switch-dependent phase, or wavelength dependence.

Wavelength dependent devices A and A' may be employed to suppress resonances of a channel add-drop filter and effectively extend its FSR, as well as its tuning range. For A and A' set to be ring resonator filters, improved Vernier FSR-extension schemes may be constructed that fully recombine the spectrum, even at passband edges. However, they still introduce significant group delay and dispersion into some express channels. In another example, shown in Fig. 3, we construct low-group-delay and low-dispersion Vernier schemes by using cascaded-MZI feed-forward-type filters for A, A', with slowly-varying passbands (Fig. 3b). The resulting response of a high-order resonant filter exhibits a tripling of the FSR from 20 to 60nm (Fig. 3c) with resonances suppressed by 40dB.

It can further be proven that such FSR extending devices, made using A and A' that are feed-forward type (cascaded-MZI) structures, add no net dispersion to the express spectrum, even if each of A,A' is dispersive. Finally, we note that in general A,A' may be non-reciprocal, but A' must have a DC bias magnetic field oppositely oriented from that of A. The proposed hitless switch and generalized device class, including FSR-extension schemes, enables further progress toward reconfigurable microphotonic channel add-drop filters.

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