Broadband Hitless Bypass Switch for Integrated Photonic Circuits

Hermann A. Haus, Miloš A. Popović, and Michael R. Watts

***Abstract*—A new microphotonic hitless switch is proposed. By enabling continuous, uninterrupted transition to a bypass path, it permits tuning of wavelength add–drop filters without disturbing intermediate channels. The scheme comprises two symmetrically actuated, 2×2 $\Delta\beta$-type optical switches, antisymmetrically cascaded in a balanced Mach–Zehnder configuration, and a π differential phase shift in the interferometer arms. By symmetry, it provides for wavelength-independent hitless operation before, during and after switch reconfiguration, permitting slow switching independent of bit rate. Compact implementations using high-index-contrast microelectromechanical-system (MEMS)-actuated switches are proposed.**

***Index Terms*—Add–drop filters, hitless switching, resonators.**

DYNAMIC reconfigurability is increasingly important in wavelength-routing transparent optical networks [1]. As a result, *hitless* tuning has become a prerequisite for prospective reconfigurable optical add–drop multiplexers (R-OADMs). It requires that other wavelength channels be undisturbed (on the granularity of single bits) during the reconfiguration of an add–drop filter to a target wavelength or an off-state [2], [3]. Yet efficient means of hitless tuning for emerging microphotonic filter implementations are few [2]–[6], and a general approach is lacking. This is evidenced by the relatively commonplace adoption of the fundamentally lossy wavelength-blocker R-OADM designs [7]. We propose a new generic hitless switch that provides a general approach to broadband hitless tuning of microphotonic filters.

A bypass scheme is one way to facilitate hitless switching for a variety of reconfigurable devices. The input spectrum is uniformly diverted to a bypass optical path, without interruption in express channels, permitting the component to be reconfigured (e.g., a filter to be tuned to a new channel). Within this framework, one approach may involve fast 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 bit rate. A second approach is a "slow hitless switching" scheme where switching time can be much slower than the bit slot time. Here, a design must produce 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 [4], [5].

Manuscript received January 26, 2006. This work was supported by Pirelli Laboratories, Milan, Italy.

H. A. Haus, deceased, was with the Department of Electrical Engineering and Computer Science and the Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA.

M. A. Popović and M. R. Watts are with the Department of Electrical Engineering and Computer Science and the Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA (e-mail: mpopovic@alum.mit.edu).

Digital Object Identifier 10.1109/LPT.2006.873929

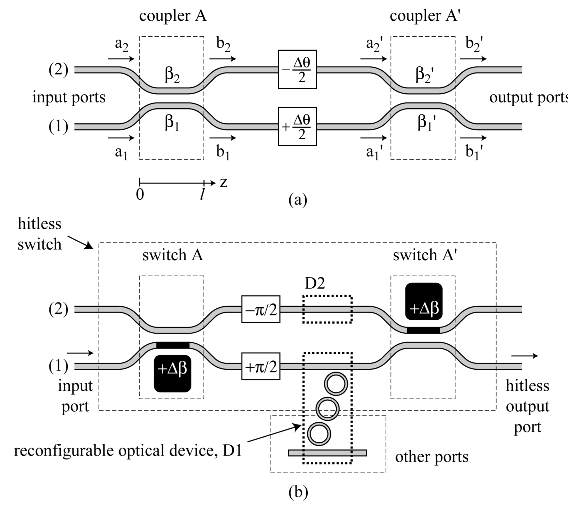

Fig. 1. (a) Basic waveguide geometry and (b) configuration of hitless switch based on $\Delta\beta$ switches, with embedded reconfigurable device $D1$.

In this letter, we propose a bypass scheme (Fig. 1) for a general class of reconfigurable optical components, 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 switch-state-dependent phase introduced by $\Delta\beta$ 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 [Fig. 1(b)]. 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 [5], [6]. For express channels, the hitless scheme proposed is as broadband as the π phase shift introduced, notwithstanding the bandwidth of the individual switches. We first demonstrate the hitless switching concept. Then we describe implementations of broadband π phase shifts and of the hitless switch using high-index-contrast (HIC) waveguides and dielectric microelectromechanical system (MEMS) actuation.

In the proposed hitless switching scheme (Fig. 1), one arm of the interferometer contains the device to be reconfigured—a wavelength-tunable channel add–drop filter—and the other arm is free. Consider first the hitless switch without a filter. Each $\Delta\beta$ optical switch is a directional coupler with power transfer governed by the evanescent coupling strength and a controllable propagation constant mismatch [8]. The couplers of the interferometer can be described by solutions of the coupled-mode equations

$$\frac{\partial}{\partial z}\bar{u} = -j\begin{bmatrix} \delta & \kappa \\ \kappa^* & -\delta \end{bmatrix}\bar{u} \tag{1}$$

where $u_{1,2}$ are guided mode envelope amplitudes in the two waveguides, normalized with respect to true mode amplitudes $\bar{a}$ by the average propagation ($\bar{u} \equiv \bar{a}e^{+j\bar{\beta}z}$). Here, $\bar{\beta} \equiv (\beta_1 + \beta_2)/2$, $\delta \equiv (\beta_1 - \beta_2)/2$ is the propagation constant mismatch, and $|\kappa|$ is the coupling strength. Free choice of normalization allows $\kappa = \kappa^*$, real. The solution for propagation over a distance l is found as [9]

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} re^{-j\phi} & -jt \\ -jt & re^{+j\phi} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{2}$$

where r, t, and ϕ are real, $\bar{a} \equiv \bar{u}(z=0)$ are the incident waves, and $\bar{b} \equiv \bar{u}(z=l)$ are the transmitted waves, and

$$re^{-j\phi} = \cos(\sqrt{\kappa^2+\delta^2}l) - j\frac{\delta}{\sqrt{\kappa^2+\delta^2}}\sin(\sqrt{\kappa^2+\delta^2}l)$$
$$t = \frac{\kappa}{\sqrt{\kappa^2+\delta^2}}\sin(\sqrt{\kappa^2+\delta^2}l).$$

Note that $r^2 + t^2 = 1$, and transfer is controlled only by κl and δ/κ. Now consider the interferometer formed by coupler A, two waveguides dephased by $\pm\Delta\theta/2$, and a second coupler A' (primed). The net transfer matrix is

$$T_{11} = rr'e^{-j(\phi+\phi'+\Delta\theta/2)} - tt'e^{j\Delta\theta/2} \tag{3}$$
$$T_{21} = -j\left(t'r e^{-j(\phi+\Delta\theta/2)} + tr'e^{j(\phi'+\Delta\theta/2)}\right) \tag{4}$$

for $\bar{b}' = \overline{\overline{\mathbf{T}}}\bar{a}$, with $T_{12} = -T_{21}^*$, $T_{22} = T_{11}^*$. For hitless operation, two elements of $\overline{\overline{\mathbf{T}}}$ must have unity magnitude at all times during reconfiguration, i.e., at all, including transient, states of the $\Delta\beta$ switches. It is desirable to employ identical switches, actuated in unison, to improve fabrication error tolerance and simplify control; then, $r' = r$, $t' = t$. During actuation, r, t, ϕ, and ϕ' vary. For the switch to support hitless power transfer from one arm to the other, two features are required: 1) the inputs of coupler A' must be reversed relative to coupler A, so that $\phi' = -\phi$, and 2) a differential phase shift in the intermediate arms must be introduced, $\Delta\theta = \pi$.

Then, matrix elements T_{11} and T_{22} have unity magnitude and the other two are zero, in all states of the compound switch. On the other hand, operation varies the fraction of total power in waveguide 1 as r^2. To further enable full transfer of power between one arm and the other, $\kappa l = \pi/2$, and δ/κ which controls the switching, varies from 0 for full transfer to $\sqrt{3}$, higher nulls, or asymptotically high values for null transfer. Fig. 2(a) shows that regardless of the switch state δ/κ, the output port contains all input power (without $D1$, $D2$).

This property depends only on the imposed symmetry conditions and introduced π phase shift, and is subject only to the bandwidth of the required π phase shift, in the particular chosen realization. For various values of phase error with respect to an ideal π phase shift, Fig. 2(b) (left axis) shows the range of excess insertion loss values that the hitless port traverses during a switching operation. In the full or null transfer states, all light traverses one arm and the π shift is irrelevant. The 3-dB state is most sensitive and incurs a 1-dB "hit loss" for 30% error in the phase shift. This still permits bandwidths in the hundreds of nanometers to be realized.

The simplest realization of a π differential phase shift is a half-guided-wavelength length ($\Delta L = \pi/\beta$, at center-band) of waveguide. Group delay causes the phase shift to vary with wavelength, but the short length ensures reasonably large bandwidth. As an illustration, identical 0.5-μm-thick slab waveguide arms (TE) with core index 2.2 and cladding index 1.445 give under 5% error in the π phase shift over 140 nm, and negligible hit loss (Fig. 2(b), right).

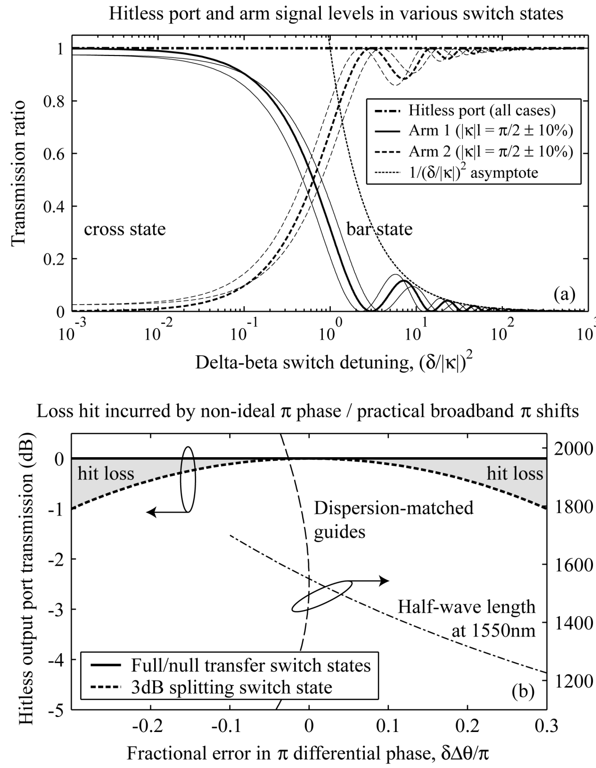

Fig. 2. (a) Response in arms and at hitless output in various states of the symmetrically actuated $\Delta\beta$ switches. Symmetric error in coupling $|\kappa|l$ of $\pm 10\%$ affects arm responses, but hitless output remains unity; (b) deviation from π differential phase shift deteriorates hitless output (left); deviation versus wavelength for example phase shift realizations (right).

For wider bandwidths or lower hit loss, the dispersion of the waveguides in the two interferometer arms may be engineered by using nonidentical cross sections. In the ideal case, $\beta_1(\omega)L_1 - \beta_2(\omega)L_2 = \pi + 2\pi m$. In a band of interest near ω_o, a first-order Taylor-series expansion of $\beta(\omega)$ in frequency yields two requirements: a π phase shift at a center frequency ω_o, and equal group delay transit times across the two lengths. Such designs are realizable. A pair of slabs as above, this time of identical length, but of widths 0.5 and 0.9μm, yields a π phase difference within 5% over more than 900 nm [Fig. 2(b)].

Now, for a hitless-switchable device, the device ($D1$ or $D2$) is inserted in one arm of the switch [Fig. 1(b)]. Then, a second concern is that the inserted device, e.g., an add–drop filter, may alter the phase balance. If the device adds excessive parasitic phase and dispersion over the express wavelength range that requires hitless operation, it must be compensated by design in one of the arms to restore a π phase shift. Fig. 3 shows simulated drop- and through-port responses of a third-order microring-resonator example filter within a hitless switch, for various switch states r^2. The filter, shown on a 100-GHz channel grid, has 4-THz free-spectral range and ring-bus and ring-ring couplings of 7%, 0.08%. Hitless switching from dropping a channel to complete bypass is shown, whereupon the filter may be tuned to a new channel. The filter has excess dispersion outside its channel

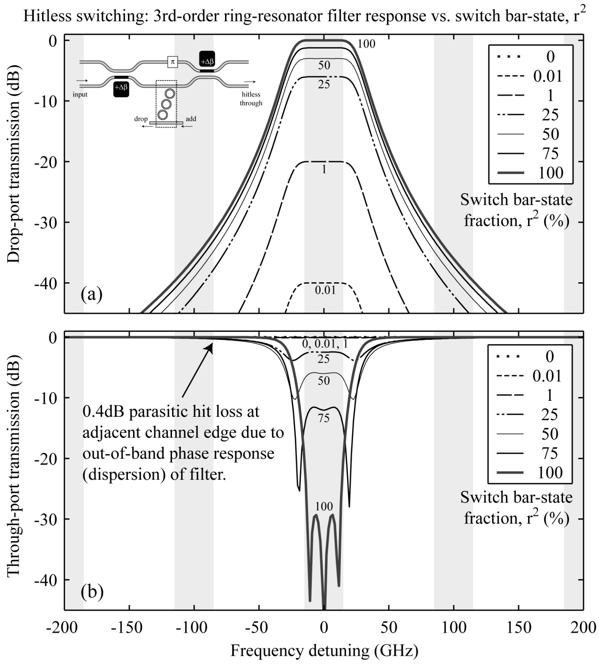

Fig. 3. Hitless switching of a third-order microring-resonator filter: (a) drop- and (b) through-port responses versus switch bar-state r^2.

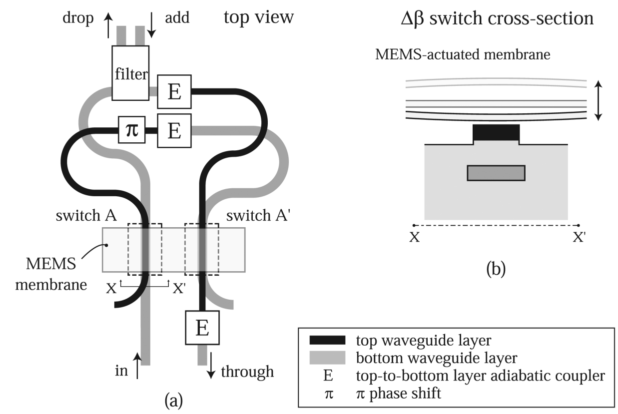

Fig. 4. MEMS-actuated hitless switch implementation: (a) multilayer waveguide switch layout, in folded geometry using one membrane, and (b) a vertically actuated MEMS $\Delta\beta$ switch cross section.

window. It contributes a phase that leads to a parasitic hit loss of 0.4 dB at adjacent channel edges. This may be reduced by improved designs of the filter.

Broadband $\Delta\beta$ switches were not required for hitless recombining, but are necessary to route the operating spectrum fully to the tunable filter or the bypass path.

We describe a compact implementation employing an HIC waveguide switch with MEMS-actuated dielectric slab β perturbation. Due to exponentially vanishing evanescent fields of a guided mode, short couplers are more broadband than long ones. For $\kappa l = \pi/2$ strong coupling, hence high index contrast, is desirable. Then, large $\Delta\beta$ is required to achieve switching. A dielectric slab that interacts with the evanescent field of a waveguide and can be physically positioned by a MEMS assembly into proximity or contact with the waveguide can provide strong $\Delta\beta$ perturbation. Operation of one such switch, in a vertical geometry where the coupler waveguides are in different lithographic layers and the slab moves up and down, is illustrated in Fig. 4(b). In addition to a strong $\Delta\beta$ detuning, the slab "pulls" the guided mode of the top waveguide toward it, thus also reducing the coupling κ and further increasing the δ/κ ratio that is relevant for switching. A disadvantage of a two-layer configuration is that the waveguides must swap layers in the intermediate arms in order to provide an opposite $\Delta\beta$ for the second switch as required. This requires interlayer optical coupling that can be achieved with adiabatically tapered coupler designs. A symmetric hitless switch design with equal lengths of each layer guide ensures balanced losses and optical length. A folded geometry may then provide symmetric switch actuation, where one MEMS slab acts over both the input and output switch-coupler [Fig. 4(a)].

We have proposed a hitless switch design to enable broadband hitless tuning of microphotonic filters in R-OADMs, and a compact realization based on MEMS. Alternatively, single-lithographic-layer MEMS-perturbation schemes may be pursued akin to similar ones used for variable resonator coupling [10]. More generally, any realization of a $\Delta\beta$ switch and a π phase shift will work. The present hitless switch concept can be generalized, to address a larger class of problems. This will be the subject of a future publication.

Acknowledgment

The authors would like to thank L. Socci and M. Romagnoli for pointing them to the problem of hitless switching. This letter is the direct outgrowth of a research memo written by H. A. Haus with the present coauthors in March 2003. It was last revised by him the day before his death, and the authorship order has been preserved in acknowledgment of his leading role in this work.

References

[1] R. Ramaswami and K. Sivarajan, *Optical Networks: A Practical Perspective*, 2nd ed. San Francisco, CA: Morgan Kaufmann, 2000.

[2] T. Shiragaki, N. Henmi, M. Fujiwara, M. Misono, T. Shiozawa, and S. Suzuki, "Optical cross-connect system incorporated with newly developed operation and management system," *IEEE J. Sel. Areas Commun.*, vol. 16, no. 7, pp. 1179–1189, Sep. 1998.

[3] C. R. Doerr, L. W. Stulz, D. S. Levy, R. Pafchek, M. Cappuzzo, L. Gomez, A. Wong-Foy, E. Chen, E. Laskowski, G. Bogert, and G. Richards, "Wavelength add–drop node using silica waveguide integration," *J. Lightw. Technol.*, vol. 22, no. 12, pp. 2755–2762, Dec. 2004.

[4] R. E. Scotti, C. K. Madsen, C. H. Henry, G. Lenz, Y. P. Li, H. Presby, and A. White, "A hitless reconfigurable add–drop multiplexer for WDM networks utilizing planar waveguides, thermo-optic switches and UV-induced gratings," in *OFC Tech. Dig.*, 1998, pp. 142–143.

[5] M. Margalit and E. Cohen, "Hitless Filter Tuning," U.S. Patent Application US2003/0 156 780A1, 2003.

[6] B. Meekers and R. Maerz, "Arrangement for the Implementation of an Add/Drop Method in Wavelength Division Multiplex Transmission of Optical Signals," U.S. Patent 6 025 943, 2000.

[7] K. Buse, F. Havermeyer, W. Liu, L. Moser, and D. Psaltis, "Holographic filters," in *Photorefractive Materials and Their Applications*, P. Gunter and J. P. Huignard, Eds. New York: Springer, 2006, vol. 2–3.

[8] S. Kurazono, K. Iwasaki, and N. Kumagai, "A new optical modulator consisting of coupled optical waveguides," *Electron. Commun. Jpn.*, vol. 55, pp. 103–109, Jan. 1972.

[9] H. A. Haus, *Waves and fields in optoelectronics*. Englewood Cliffs, NJ: Prentice-Hall, 1984.

[10] M. M. Lee and M. C. Wu, "MEMS-actuated microdisk resonators with variable power coupling ratios," *IEEE Photon. Technol. Lett.*, vol. 17, no. 5, pp. 1034–1036, May 2005.