Universally balanced photonic interferometers

Miloš A. Popović, Erich P. Ippen, and Franz X. Kärtner

Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139

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A new general class of optical interferometers is proposed, and the physical principle of their operation is explained. They split the spectrum entering one input port among the interferometer arms in an arbitrarily chosen wavelength- and/or time-dependent manner but guarantee broadband constructive interference into a single output port by symmetry. The design relies only on time reversibility of Maxwell's equations and a phase condition that holds for lossless, reflectionless four-ports. As an application, a new Vernier scheme is proposed to multiply the tuning and free spectral range of microphotonic add–drop filters. It provides effective suppression of both the amplitude and the phase response of unwanted resonant passbands.

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A new class of interferometer is proposed in which the spectrum entering one input port may be split among the interferometer arms in an arbitrarily chosen wavelength- and/or time-dependent manner but is fully recombined in a single corresponding output port by symmetry. On account of the guaranteed constructive interference, the proposed devices are referred to as universally balanced interferometers (UBIs). They are a generalization of a bypass switch proposed by Haus and described in Ref. 1. The types of interferometer that have proved useful in optics (Mach–Zehnder, Fabry–Perot, Michelson) have generally entailed fixed-reflectivity mirrors and adjustable arm lengths. In UBIs, illustrated in Fig. 1(a), the "mirror" design is largely arbitrary [and may contain couplers, resonators, switches, and nonreciprocal elements—see Fig. 1(b)], while the interferometer arms are fixed. Hence, UBIs are primarily suitable for microphotonic circuit realization.

An important application of UBIs is as a general bypass scheme for photonic devices. Inserting an optical processing device F into one interferometer arm [Fig. 1(a)] permits the device access to a part of the input spectrum routed to it by input mirror A. The part of the spectrum passing unaffected through the device F is recombined with the bypass signal in a single output port (of A'). New generalized filter designs emerge that address hitless tuning[1] and dispersion-free multiplication of the free spectral range (FSR) of microresonators, enabling their introduction into chip-scale tunable wavelength routers.

We first describe the physical principle of operation and show that UBIs guarantee broadband constructive interference into one output port for a general class of input mirror choices. Then, we propose a spectrum-slicing UBI that suppresses undesired resonances and provides a new way to multiply the effective FSR and wavelength tunability of a microphotonic add–drop filter, without adding excess dispersion. We sketch a proof that ideal UBIs using arbitrary cascaded Mach–Zehnder lattice filters[2] as mirrors contribute zero excess dispersion in general.

Consider a generic interferometer with a splitter "mirror" A and a combiner mirror A' [Fig. 1(a) without filter F], each having two input and two output ports. In a folded embodiment [Fig. 1(c)], A and A' are coincident. Sufficient conditions to construct a UBI are that combiner A' operate as a time-reversed and port-complementary replica of splitter A, A and A' be substantially lossless and reflectionless (LR), and the interferometer arms be fixed with a π differential phase shift (DPS). A general four-port A that is LR can be represented by a 2×2 unitary transfer matrix $\bar{\bar{\mathrm{U}}}$ (with $\bar{b}=\bar{\bar{\mathrm{U}}}\cdot\bar{a}$) of the general form:

$$\bar{\bar{\mathrm{U}}} = e^{i\theta_o}\begin{bmatrix} \sqrt{1-\kappa}\,e^{i\theta_1} & i\sqrt{\kappa}\,e^{i\theta_2} \\ i\sqrt{\kappa}\,e^{-i\theta_2} & \sqrt{1-\kappa}\,e^{-i\theta_1} \end{bmatrix} = \begin{bmatrix} e^{i(\theta_1+\theta_2)} & \\ & 1 \end{bmatrix} \times \begin{bmatrix} \sqrt{1-\kappa} & i\sqrt{\kappa} \\ i\sqrt{\kappa} & \sqrt{1-\kappa} \end{bmatrix} \begin{bmatrix} e^{-i\theta_2} & \\ & e^{-i\theta_1} \end{bmatrix} e^{i\theta_o}, \tag{1}$$

symmetrized so that $\theta_o \equiv (\phi_{11}+\phi_{22})/2$, $\theta_1 \equiv (\phi_{11}-\phi_{22})/2$, and $\theta_2 \equiv (\phi_{12}-\phi_{21})/2$, where elements of $\bar{\bar{\mathrm{U}}}$ are labeled $u_{mn} \equiv |u_{mn}|e^{i\phi_{mn}}$. One coupling ratio and three phases remain as free parameters, the fourth phase being fixed by the requirement of unitarity:

$$\phi_{11}+\phi_{22}-\phi_{12}-\phi_{21} = \pm\pi. \tag{2}$$

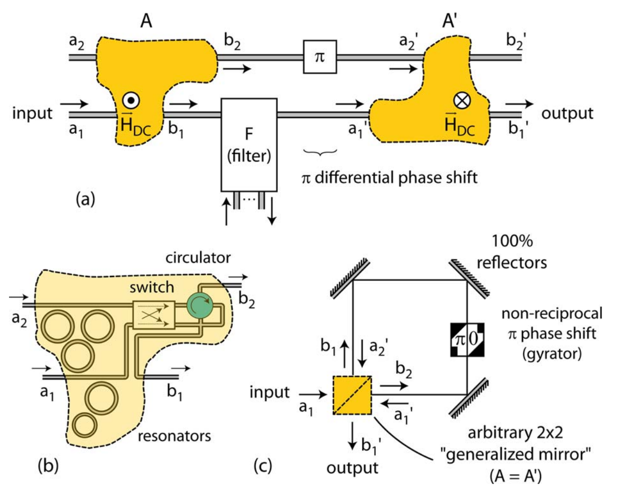

Fig. 1. (Color online) (a) General universally balanced interferometer, with a filter inserted in one arm. (b) Illustration of arbitrary splitting "mirror" A (may be nonreciprocal). (c) Folded UBI (requires a nonreciprocal π DPS).

This π unitary phase condition contributes in an essential way to the construction of a UBI. Otherwise, the design of the "mirror" A is arbitrary, and A may contain couplers, resonators, switches, and nonreciprocal elements (circulators, gyrators). It may be wavelength dependent and controllable in time (tunable filter, switch), i.e., $\bar{\bar{U}} \equiv \bar{\bar{U}}(\lambda, p)$, where p parametrizes the configurations. The λ and p dependence is understood and omitted henceforth.

A general physical argument for the design of a UBI can be given by considering a canonical physical model for splitter A. Only the leftmost two of the three matrices in the decomposition in Eq. (1) are relevant to interference in Fig. 1(a). Thus, the arbitrary splitter A may at any one (λ, p) be described as an ideal directional coupler with coupling ratio κ and a characteristic phase shift $\phi_o \equiv \theta_1 + \theta_2$ in one output arm, shown in Fig. 2(a) excited from one port.

With the objective of recombining all signal from the interferometer arms into one waveguide, it is instructive to think in terms of the time reversibility of Maxwell's equations. Reversing time shows that properly phased arm excitations re-enter the upper waveguide to the left. However, an interferometer constructed from a splitter A and a combiner that is a mirror-image replica with respect to a vertical reflection axis is inconvenient. The arm lengths have a phase difference of $2\phi_o$, dependent on the arbitrary design of A, that must be compensated for, and ϕ_o may be wavelength (or time) dependent. A more profitable approach is to consider the same splitter A excited from the complementary input port [Fig. 2(b)]. The splitting ratio is the same, but the phase difference between higher- and lower-intensity outputs, as illustrated, is now $\pi/2 + \phi_o$ instead of $\pi/2 - \phi_o$. This is enforced by the phase condition (2). Now, we take the time-reversed operation of Fig. 2(b), mirror imaged with respect to both a vertical and a horizontal axis of reflection, for the output combiner A'. Then, the arbitrary phases ϕ_o cancel and only a π phase shift remains [Fig. 2(c)]. If this shift is compensated for by inserting a broadband π phase shift in one arm, a general UBI device of the form of Fig. 1(a) is derived.

The matrix formalism shows this rigorously. In the time-reversed solution (indicated by subscript tr) corresponding to a particular excitation of splitter A, the outputs become the inputs ($\bar{b}^* \to \bar{a}_{\mathrm{tr}}$), the inputs become the outputs ($\bar{a}^* \to \bar{b}_{\mathrm{tr}}$), and the time-reversed transfer matrix is $\bar{\bar{U}}_{\mathrm{tr}} = [\bar{\bar{U}}^*]^{-1}$ (material-response phasor tensors are conjugated as $\bar{\bar{\epsilon}} \to \bar{\bar{\epsilon}}^*$ and $\bar{\bar{\mu}} \to \bar{\bar{\mu}}^*$). For lossless ($\bar{\bar{\epsilon}} = \bar{\bar{\epsilon}}^\dagger$, $\bar{\bar{\mu}} = \bar{\bar{\mu}}^\dagger$), reciprocal ($\bar{\bar{\epsilon}} = \bar{\bar{\epsilon}}^T$, $\bar{\bar{\mu}} = \bar{\bar{\mu}}^T$) media, the time-forward and time-reversed solutions are supported by the same structure. For nonreciprocal lossless media, the time-reversed solution is supported by a structure with a reversed orientation of the built-in (and any applied) DC bias magnetic fields [$\bar{H}_{\mathrm{DC}} \neq 0$ in Fig. 1(a)]. Thus, A and A' may be nonreciprocal, except in folded arrangement [Fig. 1(c)], where they are coincident.

The total transfer matrix of Fig. 1(a) involves splitter A ($\bar{\bar{U}}$), a π DPS matrix, and the matrix of the second, time-reversed element ($\bar{\bar{U}}_{\mathrm{tr}}$), sandwiched by matrices representing reflection about a horizontal axis:

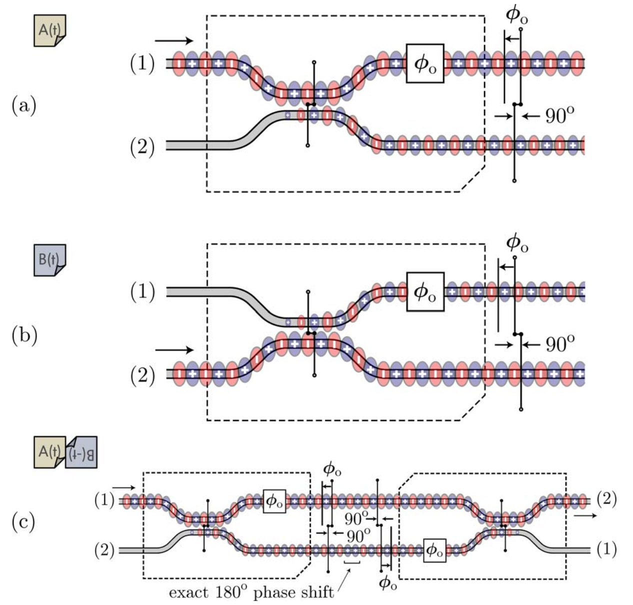

Fig. 2. (Color online) Canonical model of arbitrary LR four-port mirrors and constructed UBI. (a), (b) Excitation at port 1 or 2 gives $\pi/2 \mp \phi_o$ phase; (c) cascading the splitter from (a) and the time-reversed and 180°-rotated version of (b) cancels arbitrary phase ϕ_o. If the remaining broadband π phase shift is compensated for, a UBI is obtained.

$$\bar{\bar{T}} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \bar{\bar{U}}_{\mathrm{tr}} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi} \end{bmatrix} \bar{\bar{U}}. \tag{3}$$

From unitarity, $\bar{\bar{U}}_{\mathrm{tr}} \equiv [\bar{\bar{U}}^*]^{-1} = \bar{\bar{U}}^T$, and using Eq. (1),

$$\bar{\bar{T}} = e^{i2\theta_o} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}. \tag{4}$$

Thus, all signal entering an input port recombines in one output port, regardless of the splitting within the interferometer. No assumptions about the particular design of splitter A were made beyond unitarity of $\bar{\bar{U}}$. It is interesting, from Eqs. (3) and (4), to see that A', preceded and followed (not shown) by a π DPS, is a kind of inverse—in the sense of amplitude only—to the arbitrary unitary operator corresponding to splitter A; however, a common-mode phase spectrum $\theta_o(\lambda, p)$ is not canceled by A' in general.

Clearly, the π phase shift plays an essential role. Haus's hitless switch[1] relies on this principle and thus belongs to the general class of UBIs. In earlier work, Henry *et al.* employed a π DPS to flatten the wavelength response of a Mach–Zehnder Bragg grating filter.[3] (Point-symmetric structures for flattened cross-state passbands[4] do not rely on a π DPS or fall in this class of devices.) Broadband UBI operation depends on a broadband π DPS realization. A half-wave arm length difference (at a central wavelength) provides sufficient bandwidth ($\sim$150 nm) to cover communications bands.[1] Phase shift errors of ±10% incur <0.2 dB recombination loss.[1] The recombining response is first-order insensitive to small asymmetries between A and A'. For lossy (but reciprocal) A and A' Eq. (2) is violated, yet the UBI principle still holds in the sense of zero cross-port transmission.

We next propose a novel filter design making use of the UBI principle. The limited FSR and wavelength tunability of resonant microphotonic add–drop filters[5] must be increased considerably (to >35 nm) before they can enable chip-scale reconfigurable wavelength routers. Vernier schemes previously employed to extend the FSR are inadequate for add–drop filters because they either do not preserve throughput channels[6] or do introduce excessive dispersion or group delay.[7,8]

The proposed example device [Fig. 3(a)] multiplies the effective FSR and tuning range (for a given index change) of a microring-resonator add–drop filter by a factor of 3. The microring filter is designed with a 20 nm FSR, typical of high index contrast,[5] and a 40 GHz wide, flattop passband suitable for 100 GHz wavelength-division multiplexed channel spacing. Here, splitter A and combiner A' are lattice filters[2] with a transmission maximum aligned with one ring filter resonance and transmission nulls aligned with two adjacent resonances [Fig. 3(b)]. Their slow-

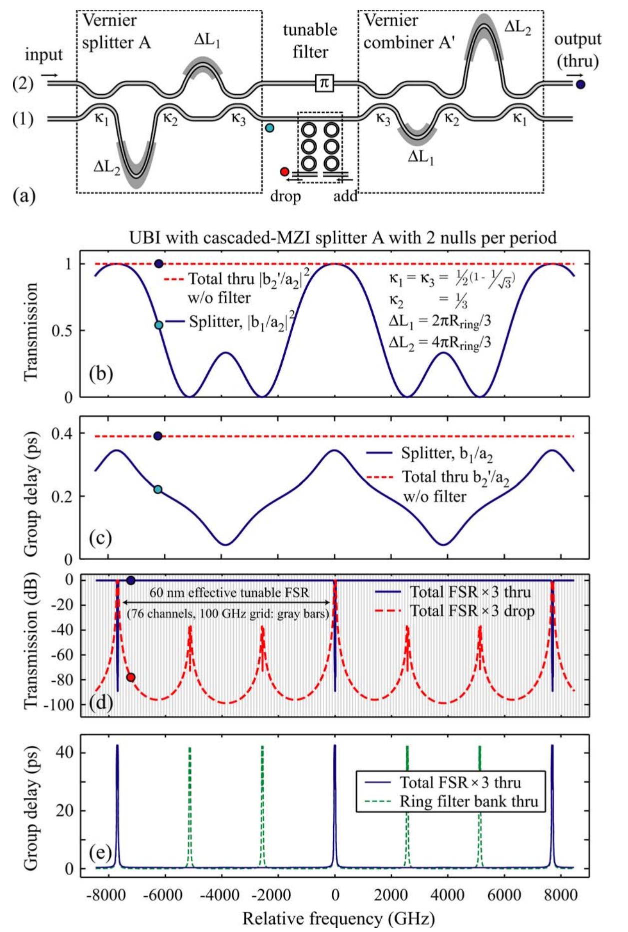

Fig. 3. (Color online) Nondispersive FSR multiplier ($\times 3$) for an add–drop filter: (a) UBI with lattice-filter splitter/combiner and microring filter in one arm; (b), (c) splitter A and total output port amplitude and group delay responses without a ring filter show dispersionless broadband UBI operation; (d), (e) drop and output port responses with a filter show a small group delay at suppressed resonances.

rolling passbands give minimal group delay and dispersion. Without a ring filter inserted, all signal reaches one final output port [Figs. 3(a), 3(b)]. Inserted, the ring filter has access to channels at one of every three resonant wavelengths, while the other two resonant channels bypass in the top arm and are suppressed in the drop port by over 35 dB [Fig. 3(d)].

The through-port group delay is negligible at the suppressed resonances [Fig. 3(e)]. Therefore, a usable add–drop filter with a tripled effective FSR and tunability (for a given index change) is achieved.

The final output (without the ring filter in the bottom arm) has flat group delay [Fig. 3(c)] and contributes identically zero excess dispersion, even though splitter A and combiner A' are dispersive. If A is a lattice-type filter this is generally true, as proved by a simple geometrical argument. The innermost couplers (κ_3) and interferometer arms are themselves a UBI, and according to Eq. (4) they may as a unit be replaced by a waveguide pair with a π DPS. Repeating the procedure collapses the entire structure into the latter, with only the dispersion due to the waveguide itself contributing. Suitability of concrete designs for optical network applications requires more detailed discussion to be pursued elsewhere.

The new class of interferometers proposed here is expected to enable new device designs for multiple applications. We showed that it permits general 2×2 switch mechanisms to be used with hitless bypass tuning schemes of the type proposed in Ref. 1, as well as improved Vernier-type schemes using resonator-based or interferometric splitters A. Not discussed in detail in this paper were resonant, nonreciprocal, or folded UBIs [Fig. 1(c)]. Yet these embodiments demonstrate the extent of generality of the principle of operation.

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