Comment on "Nonreciprocal Light Propagation in a Silicon Photonic Circuit"
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Comment on "Nonreciprocal Light Propagation in a Silicon Photonic Circuit"

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We show that the structure demonstrated by Feng *et al*. (Reports, 5 August 2011, p. 729) cannot enable optical isolation because it possesses a symmetric scattering matrix. Moreover, one cannot construct an optical isolator by incorporating this structure into any system as long as the system is linear and time-independent and is described by materials with a scalar dielectric function.

In (*1*), Feng *et al*. consider a two-mode waveguide with a spatially varying but time-independent dielectric constant (Fig. 1), and numerically and experimentally demonstrate a one-way modal conversion effect: The odd mode is strongly excited when an even mode is incident along the backward direction from the right end of the waveguide (Fig. 1b). In contrast, the odd mode is not excited when the same even mode is incident along the forward direction from the left end (Fig. 1A). Related to (*1*), we note that a similar one-way modal conversion effect, with the same pattern of spatially varying dielectric constant, was previously considered theoretically in (*2*, *3*).

The results in (*1*) have generated widespread interest. Based on the results, Feng *et al*. claim the existence of nonreciprocity in their design and suggest the possibilities of applying the observed effect toward creating on-chip optical isolators. However, one must ask: (i) Is the observed effect of one-way photonic modal conversion truly a proof of optical nonreciprocity? (ii) Can the structure in (*1*) indeed be used toward creating an optical isolator?

Unfortunately, the answers to both of the questions above are "no." The structure in (*1*) is in fact reciprocal. As a result, one cannot construct an optical isolator this way.

It is well known that any time-independent linear system, described by a symmetric electric permittivity tensor $\varepsilon(r)$ and a symmetric magnetic permeability tensor $\mu(r)$, is constrained by the Lorentz reciprocity theorem (*4*–*6*). Such a system is reciprocal in the sense that its scattering matrix is symmetric (*4*–*6*). Very importantly, the reciprocity theorem applies even when $\varepsilon(r)$ or $\mu(r)$ is complex, that is, even when the system has gain or loss.

The experimental structure studied in (*1*) consists of silicon, silicon dioxide, germanium, and chromium. No magnetic field is applied. All these materials are known to have symmetric permittivity tensors (and diagonal permeability tensors), and indeed in (*1*) both $\varepsilon(r)$ and $\mu(r)$ are treated as scalars theoretically. Thus, the structure in (*1*) is subject to the reciprocity theorem and has a symmetric scattering matrix.

In Fig. 1, A and B [which are equivalent to fig. S1 in the SOM of (*1*)], one injects the even mode along either forward or backward directions. Notice that the power transmission coefficients T_{ee} to the even mode (red curves in Fig. 1, A and B) are the same for both propagation directions for any given length d of the spatially varying region, as expected from the reciprocity theorem. Likewise, the power transmission coefficient T_{oe} to an odd mode, when an even mode is injected from the right (blue curve in Fig. 1B), is the same as the power transmission coefficient T_{eo} to an even mode, when an odd mode is injected from the left (red curve in Fig. 1C).

Why doesn't the structure in (*1*) function as an optical isolator? Certainly, in this structure, the even mode injected from the left is strongly attenuated without exciting the odd mode (Fig. 1A), whereas the even mode injected from the right excites the odd mode and hence has a substantial power transmission coefficient T_{oe} (Fig. 1B). Thus, there appears to be a contrast between the two propagation directions. However, one should not confuse such a contrast with what is required of an optical isolator. An optical isolator needs to suppress back-reflection irrespective of modal content. A simple way to suppress back-reflection is to attenuate it, but in reciprocal structures this implies, unfortunately, that the forward light is also attenuated. The only way to have a good transmission for the forward propagating light and to simultaneously suppress the back-reflection is to use a device in which at least one trans-

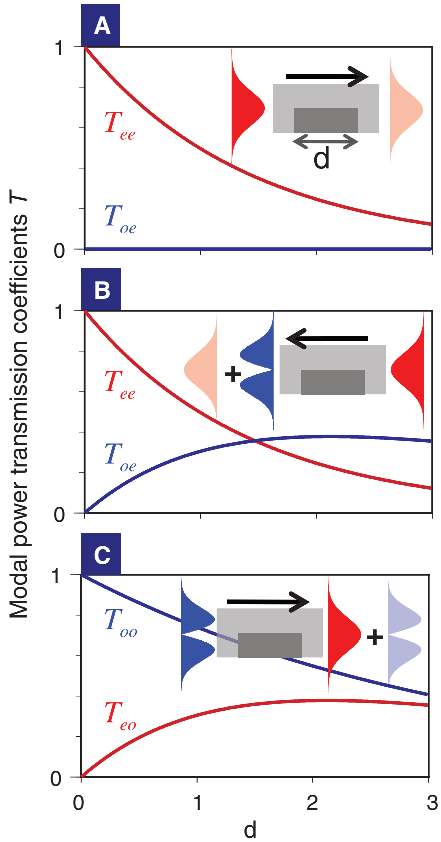

Fig. 1. Modal power transmission coefficients in a waveguide (gray region in the insets) supporting an even and an odd mode, as a function of length d of a region (dark gray region in the insets) in the waveguide where the dielectric constant varies with a profile $\delta\varepsilon \propto \exp(+ikx)$, with x being along the axis of the waveguide. Red and blue curves are transmission coefficients to even or odd modes, respectively. In the inset, the light gray regions have a real dielectric constant. The bold arrows indicate the propagation directions. (**A**) Even mode injected from the left. Power transmission coefficient T_{ee} from even to even mode and T_{oe} from even to odd mode. (**B**) Even mode injected from the right. Power transmission coefficients T_{ee} from even to even mode and T_{oe} from even to odd mode. (**C**) Odd mode injected from the left. Power transmission coefficients T_{oo} from odd to odd mode, and T_{eo} from odd to even mode.

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mission from a given input mode to a given output mode is asymmetric, that is, different for forward and backward propagation direction. In the structure in (*1*), however, all mode-to-mode transmissions are symmetric. Consequently, light reflected back into the odd mode at the left end will necessarily pass through the structure with the same high power transmission coefficient T_{eo}, equal to T_{oe} (Fig. 1C, red curve). Therefore, the structure cannot function as a part of an isolator: It has equal backward and forward transmission coefficients between any two modes of the system.

More generally, one cannot construct an optical isolator with any structure having a symmetric scattering matrix. Therefore, one cannot construct an optical isolator by incorporating the structure of Feng *et al*. into any system containing any combination of components or signal processing elements as long as the overall system is linear and time-independent and is described by materials with a scalar dielectric function.

To summarize, the structure in (*1*), which is linear and time-independent, is reciprocal in the sense that it has a symmetric scattering matrix, which fundamentally differentiates it from optical isolator structures, including magneto-optical isolators, as well as nonlinear (*7*, *8*) or time-dependent structures (*9*, *10*) where reciprocities are broken. One cannot construct an optical isolator by simply enclosing the structure in (*1*) with a system containing any combinations of components or signal processing elements, as long as the overall system is linear and time-independent and is constructed only from materials with symmetric permittivity and permeability tensors. To achieve true optical isolation, the scattering matrix of the system must be nonsymmetric.

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