Integrated Photonic Magic-T (with Twice the Magic)

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Abstract: We propose a photonic 4-port that doubly guarantees 50:50 signal splitting from either input port: by symmetry, analogously to the microwave "magic T", and by adiabaticity. Applications include coherent receivers, dual-output modulators and polarization diversity.

OCIS codes: (130.3120) Integrated optics devices; (130.4110) Modulators; (130.5440) Polarization-selective devices.

1. Introduction

Integrated optical interferometers are the fundamental building blocks of many kinds of photonic circuits, including broadband modulators and switches [1], and are especially important with the increased interest in coherent receivers and advanced modulation [2,3]. To provide high-extinction, interferometers require well-balanced 3dB power splitters/combiners, yet currently used integrated photonic devices have limited capabilities in this regard: they either split using means other than geometrical symmetry (directional coupler [1], 2x2 MMI, adiabatic coupler [4]) with the concomitant dimensional, wavelength, temperature, etc. sensitivity of the splitting ratio, or if they use symmetry, they do not have 4 ports (Y junction [5], 1x2 MMI) that are needed e.g. in heterodyne receivers.

In this paper, we propose a new fundamental building block for photonic circuits – a photonic device that has symmetry properties of the microwave magic T [6,7], but unlike the microwave magic T is also adiabatic. Illustrated in Fig. 1(b), the device takes light in either input port (TE or TM mode of input waveguide), and splits it 50:50 between the two outputs by symmetry. For lengths of practical interest, unlike the magic T it requires no impedance matching, and is reflectionless and broadband intrinsically. Adiabatic operation provides a second guarantee of 3dB splitting, so that deviations from perfect symmetry (in practical realization) can be tolerated. The authors are aware of one previous proposition of an optical magic T [8], but that design splits power between three output waveguides, and is not adiabatic. Here, we describe the concept, principle of operation, and applications of our proposed device.

2. Principle of Operation

In addition to providing balanced splitting that enables high-extinction interferometers, 3dB splitters should be close to lossless and, ideally, the loss should also be the same from the first or the second input port to the outputs. We have found that we can prove, based on properties of the scattering matrix, that no device can exist that guarantees

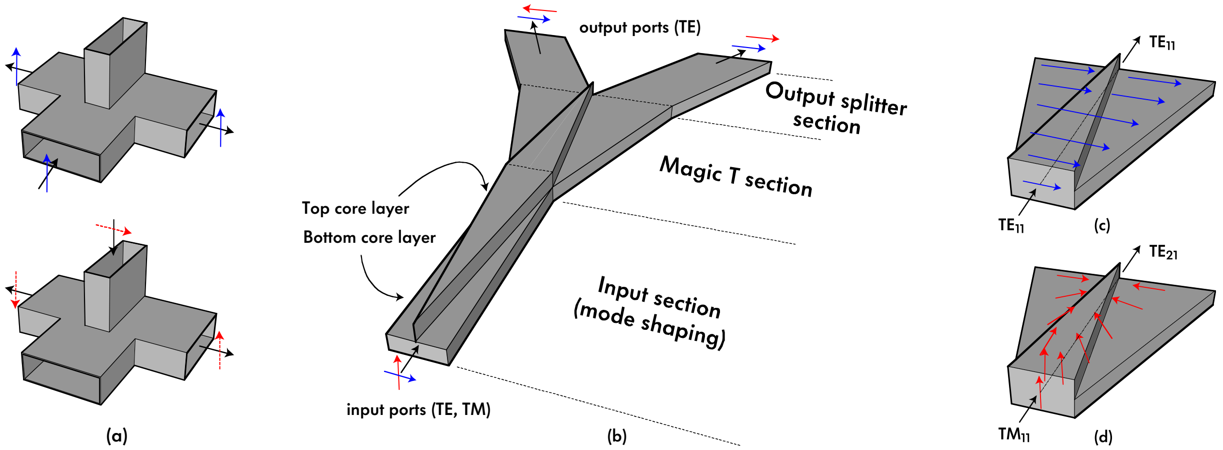

Fig. 1. Integrated photonic "magic tee" concept: (a) microwave waveguide magic T junctions [6,7] evenly split into the output ports any signal entering either the front or the top input port, by symmetry; (b) the adiabatic optical magic T proposed here guarantees 3dB splitting by two independent mechanisms: symmetry and adiabatic evolution. (c) For a TE input mode, the proposed device outputs a fundamental TE mode that results in a pair of in-phase outputs. (d) For TM input, the mode polarization is "rotated" in parts into the second TE mode at the output, which corresponds to a pair of out-of-phase outputs. This mechanism is naturally reflectionless (impedance matched), broadband and tolerant to fabrication errors.

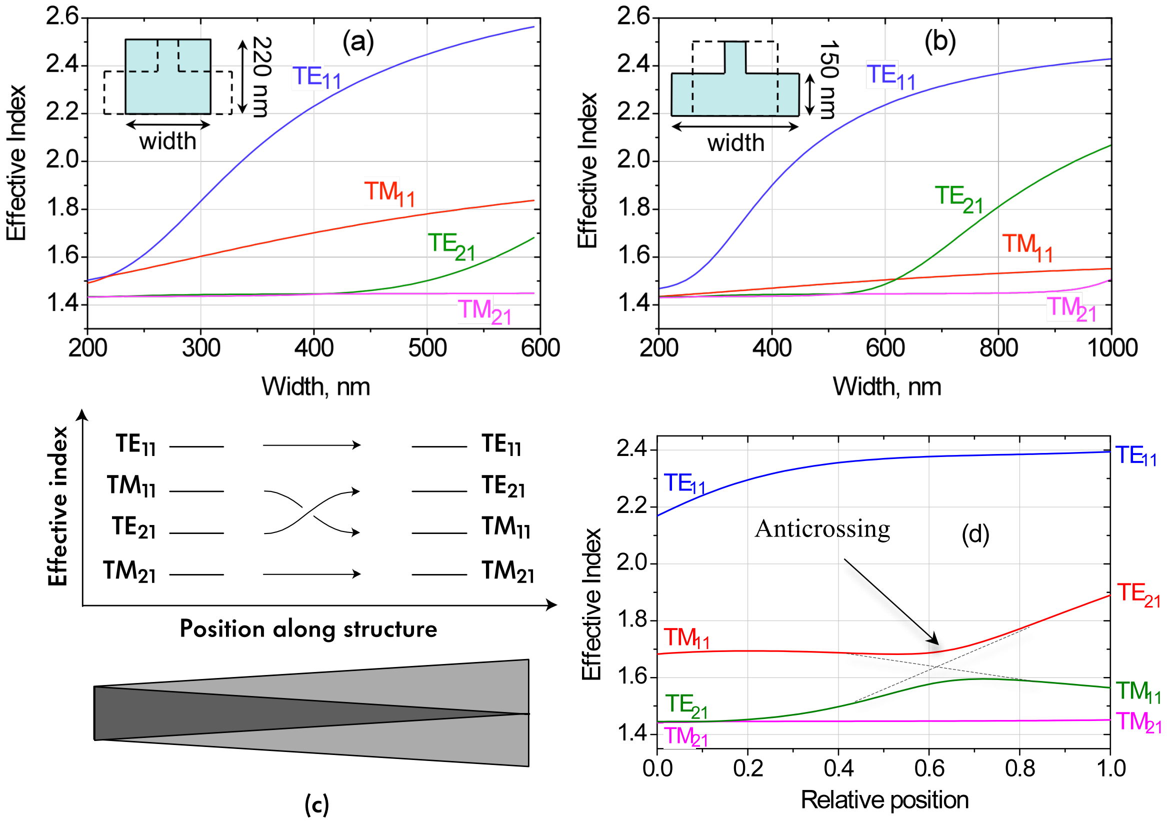

Fig. 2. Physical principle of operation of proposed adiabatic magic T: (a) a tall, wide input waveguide cross-section makes TM_{11} the second guided mode and TE_{21} the third, while (b) a shallower, wider waveguide switches the order of TE_{21} and TM_{11} (in a list of guided modes sorted by effective index). (c) This approach of keeping TE_{11} as the fundamental mode throughout the structure, and swapping the TE_{21} and TM_{11} mode in a tapered structure that couples these modes to create an anti-crossing, allows 50:50 splitting from either input state into two TE waveguides on chip. (d) Effective index vs. length of simulated structure, showing desired anti-crossing.

both even splitting by symmetry, and equal loss from either input port by symmetry. The next best thing, it turns out, is the microwave magic T, which accomplishes only the first. Shown in Fig. 1(a), the magic T splits (by symmetry) the signal entering the front or the top input port equally between the two output ports on the sides (arrows represent the polarization at ports and along the structure, or propagation direction). Losses are in general different, but nevertheless this is useful for many applications like coherent receivers and dual-output modulators.

The photonic magic T device concept is illustrated in Fig. 1(b). It can be obtained coarsely by taking the magic T, rotating the top input forward, and the side outputs toward the back. The two input ports are the TE and TM polarized modes of the input waveguide, and the two output ports are the fundamental TE modes of the two output waveguides. This device preserves geometrical symmetries employed by the magic T that guarantee 50:50 splitting, but is a planar structure suitable for integrated photonics. However, there is a bit more to it – this device can be adiabatic and hence (1) intrinsically phase matched, (2) can achieve 50:50 splitting even if we break its geometrical symmetry but keep it long enough for adiabatic operation – both properties the magic T doesn't have.

The proposed device operates by providing a symmetric geometry that ensures 50:50 power splitting for each of two input polarizations. This is accomplished by engineering an adiabatic structure as shown in Fig. 2(c), which has a crossing of propagation constants between the fundamental TM and second-order TE modes along its length. A simulation of an example design shows this in Fig. 2(d). The TE_{11} mode is kept as the fundamental (highest n_{eff}) mode all along the structure. The tapered structure in Figs. 1(c-d), 2(c) provides coupling between the TM_{11} and TE_{21} modes that provides an anticrossing so that under adiabatic operation, the TM_{11} input mode is adiabatically converted to the antisymmetric TE_{21} mode in the output waveguides. Thus, the input TE and TM modes each split 50:50, and each split into the same output waveguide modes (but with different relative phases).

The desired ordering of modes in terms of propagation constant (effective index) at the start and end of the structure [Fig. 2(c)] is engineered by choice of cross-sectional dimensions. A tall, narrow waveguide at the input favors a high effective index for TM modes, and lower effective index for TE modes [Fig. 2(a)]. However, TE_{11} is

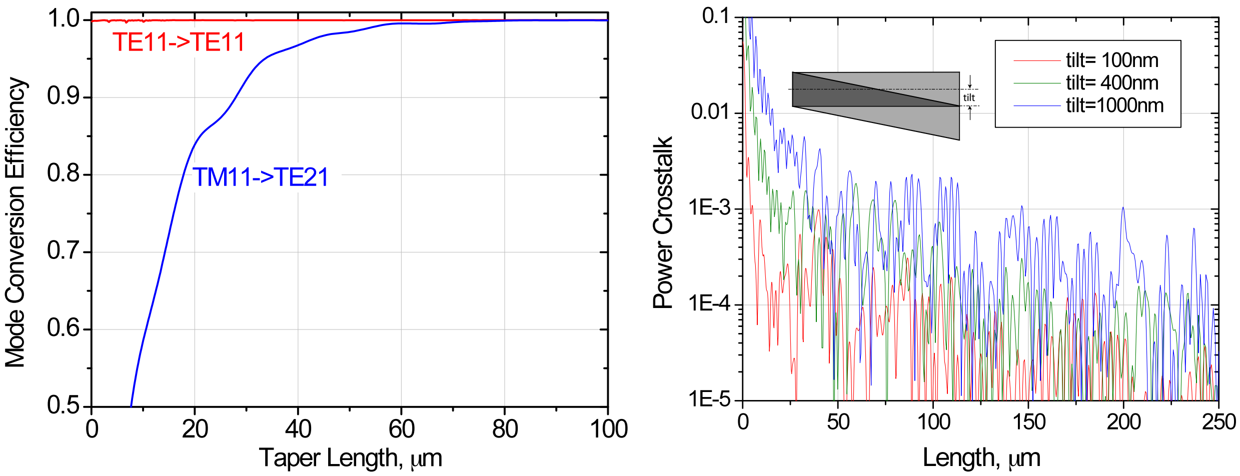

Fig. 3. Simulations, using 3D mode-matching method, of the proposed magic T device implemented in strong-confinement silicon channel waveguides (width under a 1 μm, total height 220 nm): (a) Transmission loss depends on the device length, but above 60 μm, the device is nearly lossless. However, perfect splitting is ensured by symmetry and is 50:50 even for lengths approaching zero, from either input port. (b) Deviations from a symmetric geometry, shift the burden of ensuring 50:50 splitting to adiabaticity, hence longer device lengths are needed for more tilted structures to avoid substantial crosstalk between supermodes which leads to deviation from 3dB splitting.

the fundamental mode for all widths larger than the height, i.e. wider than 220nm here, so we use a width of 380nm at the input. At the output we use a wide and thin waveguide that switches the order of the TE_{21} and TM_{11} modes [Fig. 2(b)], with a width of 840nm in this example. The structure is designed to cut off the fourth, TM_{21}, mode.

Fig. 3 shows simulations of the performance of the proposed magic T structure. In Fig. 3(a), an ideal design is simulated, showing transmission efficiency from either a TE or TM input into its corresponding 50:50 split output state (note that TE input provides in-phase outputs, while TM input provides out-of-phase outputs). For lengths above 60 μm, the device is nearly lossless. For shorter lengths, some power remains in the TM11 mode at the output, which is not used. This is because the power splitting is done by a sort of polarization rotation, see Fig. 1(d), which cannot occur adiabatically if the structure is too short. This part of the device is like two coupled polarization rotators [9], however the TE_{11} mode in the magic T does *not* rotate due to the mode structure design [Fig. 2(c,d)]. Note that splitting ratio is perfectly 50:50 by symmetry for both inputs, because $TE_{11}\rightarrow TE_{21}$ and $TM_{11}\rightarrow TE_{11}$ mode conversions are identically zero in Fig. 3(a), at all lengths – this is the magic behind the magic T.

Even if the geometric symmetry of the device is broken, e.g. due to imperfections in fabrication, adiabaticity still ensures even splitting. Fig. 3(b) illustrates $TE_{11}\rightarrow TE_{21}$ crosstalk when the structure is tilted, i.e. the central axis of the output cross-section is laterally shifted from the central axis of the input cross-section. For larger asymmetry (tilt), a longer device is needed to maintain the same maximum crosstalk (imbalance in splitting), but the order of length of the device is the same – tens of microns.

3. Conclusions

We have proposed a new photonic device that leverages symmetry properties of the microwave magic T junction and adiabatic operation that is practical in optical structures. The optical magic T device proposed could be used in coherent receivers to provide even splitting and mixing of the signal and local oscillator. We propose as additional applications its use as the output section of a broadband Mach-Zehnder amplitude modulator to provide dual outputs with high extinction ratio for photonic analog-to-digital converter applications [10] and as an alternative approach to polarization diversity, where circular/diagonal polarizations are split by the magic T, rather than vertical/horizontal.

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