Low Loss Propagation in a Metal-clad Waveguide via PT-Symmetry Breaking

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Abstract: We demonstrate passive PT symmetry breaking between the spatial modes within a single SOI waveguide with metal deposited directly on top. By leveraging this effect, we show low propagation loss of < 1 dB for a 100 µm long, 10 µm wide waveguide partially covered with 100 nm thick metal.
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Parity-time symmetry breaking has been shown to enable control of the coupling between different waveguides and resonators. By properly engineering the spatial distribution of gain/loss [1], many desirable functionalities such as single transverse mode lasing [2], enhanced sensitivity [3] etc. have been demonstrated.

Here, we demonstrate PT symmetry breaking in a single waveguide enabling propagation with low loss in a highly lossy medium. We show that beyond the widely investigated case of coupled waveguide/resonator systems, PT symmetry breaking can also be observed among the different spatial modes of a waveguide. By providing gain/loss to only a partial transverse extent of a multimode waveguide, we show that PT-symmetry breaking can be induced. The concept is shown in figure 1, where we consider loss in silicon waveguides for two cases – case I where the lossy region is equal to half the waveguide width and case II where the lossy region is only $1/8^{th}$ of the waveguide width (which is 10 µm). In both cases, for low loss, all the modes in the waveguide overlap over both the lossy and the lossless regions of the waveguide. As a result, with increasing applied loss, the modal losses increase. We show in figure 1, the loss of the fundamental mode as a function of increasing applied loss for both the cases. One can see that above a critical value of loss (marked by a star on the plots), the PT symmetry breaks and the fundamental mode experiences lower loss with increasing applied losses. We show the fundamental and first order modes for case I and the fundamental and sixth order modes for case II when the loss is low and when the loss is high, i.e. in the PT broken regime. In the PT-broken regime, the modes separate into low-loss and high-loss modes and are confined in the lossless and the lossy regions of the waveguide respectively [4]. One can see that for both cases, in the high loss regime, one of the modes can be launched into the waveguide and propagate with low loss since it is decoupled from the highly lossy modes of the system. The lossy modes for the two cases are the first order and the sixth order modes, determined by the width fraction of the lossy region. One can see that contrary to the conventional case of symmetric coupled waveguides, the lossy region of the waveguide can be much smaller than half the waveguide and the low loss (lossy) modes will still preferentially be confined in the lossless (lossy) region of the waveguide. Thus, this is a very powerful way to engineer both the spatial extent as well as the loss of transverse modes in a single multimode waveguide.

We demonstrate this effect in silicon on insulator waveguides and show low loss (<1 dB) propagation in a waveguide partially covered by a metal. The waveguide is shown in figure 2(a). The 10 µm wide waveguide is partially clad with 100 nm of metal (10 nm Ti and 90 nm of Pt) on top. The width of the metal is varied from 0.4 to 6 µm for different waveguides. The metal causes the modes of the multimode waveguide to be in the PT broken regime. The simulated transverse mode profile of the fundamental TE mode is shown in the figure 2(a). This PT-broken, low-loss mode is excited by an access waveguide butt coupled to the metal-clad waveguide. The access waveguide has no metal on top and its width is the same as the lossless part of the PT-broken waveguide (i.e. with no metal on top), as shown in figure 2(a). The fundamental TE mode of the access waveguide has a very good overlap with the fundamental TE mode of the metal-clad waveguide in the PT-broken regime because of its confinement to the lossless region. The metal-clad waveguide is put in one arm of a Mach-Zhender interferometer and the other arm is a very short single mode waveguide, which is considered lossless. We show the loss of the metal-clad waveguide extracted from the visibility of the MZI fringes in figure 2(b). One can see that the loss closely follows the expected trend from simulations. The MZI fringes showed no signs of any other interferences, which shows that the access waveguide is indeed able to very purely excite the fundamental mode of the PT broken regime of the metal-clad waveguide. For comparison, if the metal-clad waveguide were not to be in the PT broken regime, the fundamental mode would experience ~1000 dB loss for the dimensions that were tested here, whereas in the PT broken regime, the losses drop to below 3 dB.

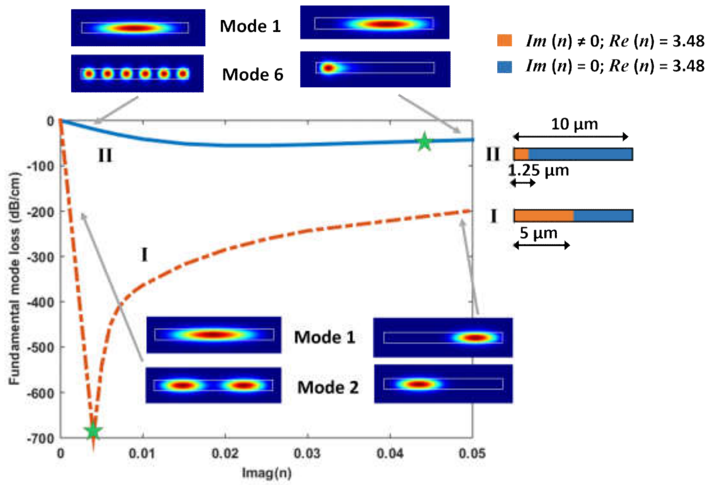

Figure 1. PT symmetry breaking in a 10 μm wide silicon waveguide. Loss of the fundamental mode as a function of increasing loss is shown for two cases with different extents for the loss as indicated. The stars indicate the position of the PT-symmetry breaking point for the respective cases beyond which the loss for fundamental mode loss decreases with increasing applied loss. Mode profiles for the fundamental and first order modes (case I) and for fundamental and sixth order modes (case II) are shown. In each case, the fundamental mode is confined to the lossless region of the waveguide in the PT-broken regime and can hence be used for low loss propagation through this highly lossy waveguide.

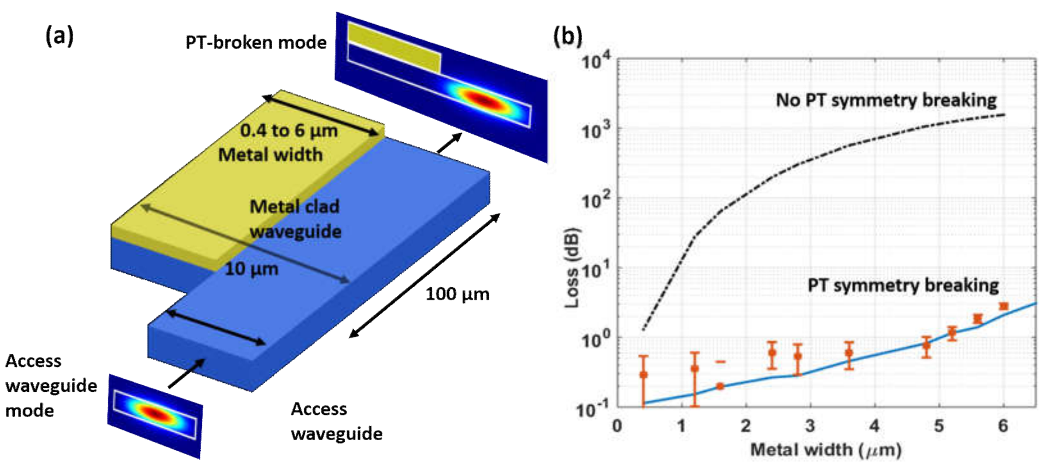

Figure 2. (a) Waveguide with metal covering some part of the width and connected to an access waveguide with no metal whose width is equal to the lossless part of the metal-clad waveguide. The access waveguide's fundamental mode is able to purely excite the PT-broken mode of the metal-clad waveguide, enabling low-loss propagation. (d) The extracted loss (dots) for 100 μm long multimode waveguide in the PT broken regime for various widths of the metal on top matches the expected loss from simulations (solid line) and are far below what would be expected in the absence of PT-symmetry breaking (dashed line).

In conclusion, we have demonstrated PT symmetry breaking in a single transverse multimode waveguide, resulting in very low losses even with the presence of metal in extreme proximity to the optical mode. This demonstration opens the door to the numerous applications where the presence of highly lossy materials such as metals placed essentially in contact with semiconductor waveguides is desired without incurring enormous losses. For example, thermo-optical phase shifters or modulators could benefit from being able to bring metals very close to the optical mode.

References:

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