PT Symmetry Based Functional Devices for Integrated Optics

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ABSTRACT
The objective of the present work is to explore how the concept of gain/loss modulation can be used for switching and routing applications in the case of longitudinal type PT symmetry structures where the complex index profile is build along the direction of light propagation. In the spirit of our previous work we demonstrate that operation compatible with practical applications can be achieved with an imperfect PT-symmetry design, where only the gain is variable while the losses are set fix.
Keywords: optical switching devices, systems with special symmetry, photonic integrated circuits, plasmonics.

1. INTRODUCTION

The development of photonics enabled by the advent of nanofabrication technologies during the past decades, has triggered the emergence of new types of artificial materials such as photonic crystals, metamaterials, plasmonic, and more recently so-called PT-symmetric devices [1-3], referring to Parity-Time symmetry. Aside the purely fundamental research, the tremendous interest for these synthetic materials is also strongly motivated by the practical outcomes targeting functionalities that can be achieved by gain/loss modulation in such structures. In our recent contributions we showed that PT-symmetric couplers (PTSCs, obtained by coupling a lossy waveguide with another guide with gain) can operate as remarkably efficient switches when the proper amount of losses is included in the system [4-6].

The aim of the present contribution is to show that switching or modulation can be also achieved by considering a different type of PT-symmetric structures where gain/loss alternation is implemented along the direction of light propagation. In the spirit of our previous work [4-6], we demonstrate that operation compatible with practical applications can be achieved with an imperfect PT-symmetry design, where only the gain is variable while the losses are set fix.

2. PT-SYMMETRY BRAGG GRATING ASSISTED DIRECTIONAL COUPLER SWITCH

A sketch of a PT-symmetric Bragg grating (PTSBG) assisted vertical directional coupler is shown in Fig. 1. It consists of a uniform passive lossless waveguide coupled to a PTSBG waveguide with a complex variation of the refractive index profile. The variation of the real part of the index profile in such a PT-symmetric BG is quarter period shifted with respect to the variation of its imaginary part [7-9]. A practical realization of such a device can be envisioned for example by means of hybrid integration technology of III-V/SOI semiconductors [10-12].

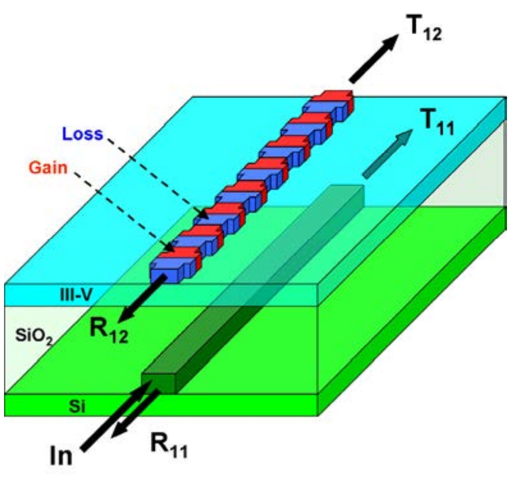

Figure 1. Sketch of the vertical coupling geometry PT-symmetry BG assisted directional coupler with rectangular grating profile. Gain and loss grating sections are indicated by red and blue colors, respectively.

The operation principle of such a device is based on the modification of the dispersion properties induced by the introduction of the PT-symmetry through the gain/loss level modulation in the grating structure. As known, the periodic modulation of the real part of a grating waveguide effective index leads to the formation of a stop-band around the Bragg wavelength (top graph Fig. 2b). By engineering the dispersion properties of the uniform waveguide it is possible to tune its effective index inside the forbidden stop-band of the BG assisted waveguide (Fig. 2a) [13,14]. The phase matching between the waveguides is frustrated in this case [15-18]. In consequence, as shown in Fig. 3a, there is no notable coupling or back-reflection due to the BG waveguide when the light is injected into the uniform waveguide.

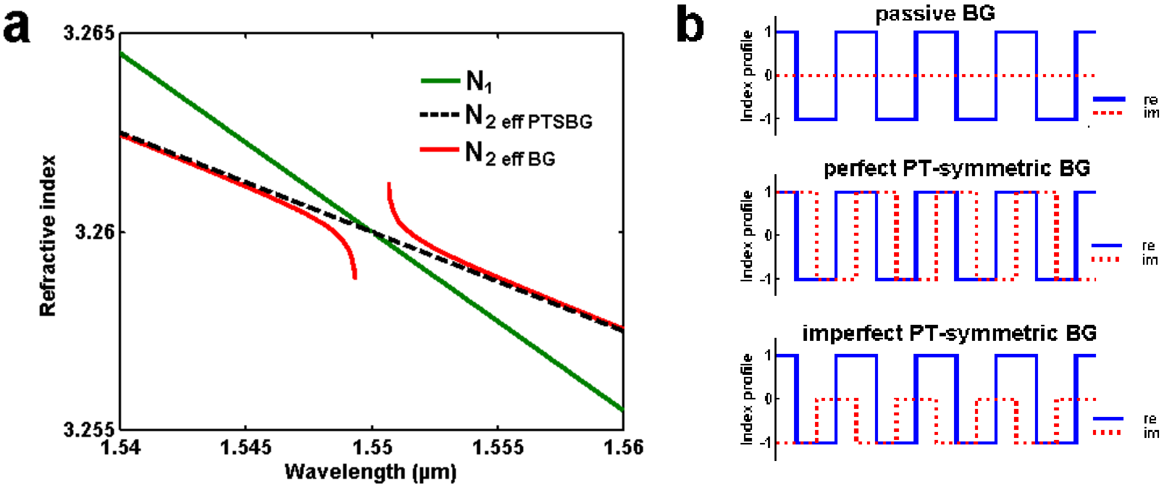

Figure 2: a) Effective indices of the uniform waveguide (green), the conventional Bragg grating assisted waveguide (red) and the PTSBG (dashed); b) Real (blue solid) and imaginary (red dotted) parts of the grating complex coupling profile. Top: without gain and loss modulation. Middle: equal gain/loss and index modulation. Bottom: without gain, loss modulation is half of index modulation.

This picture considerably evolves when the passive grating waveguide is replaced by a PTSBG whose gain as well as losses are quarter-period-shifted with respect to the variation of the real part of its index (middle graph on Fig. 2b). The characteristic feature of such a PTSBG is that the forbidden stop-band disappears and its dispersion relation becomes akin to that of a uniform waveguide [7-9]. In this case, the phase becomes matched at the intersection point of the passive uniform and PTSBG dispersion curves (Fig. 2a). By modulating the gain and losses between the passive state of Fig. 2b (for which a stop-band is present and frustrates coupling) and the PTSBG state of Fig. 2b (no stop-band, coupling restored), it is therefore possible to switch the signal between the two waveguides forming the vertical coupler.

The implementation of simultaneous gain and loss modulation required for a perfect PT-symmetric device is however not easy. For a practical realization, it is much more convenient to vary the gain only while fixing the losses to a constant value. This situation is illustrated by the bottom graph of Fig. 2b which shows the spatial repartition of the regions with fixed losses in the absence of gain. It turns out that the dispersion characteristic of such an imperfect PTSBG is essentially similar to that of a lossless grating waveguide with a recognizable stop-band. This stop-band, even though it is spectrally narrower than without any loss modulation, is still sufficiently broad to frustrate phase matching. Consequently, as shown in Fig. 3a, there is no notable coupling or back-reflection due to the PTSBG waveguide when the light is injected into the uniform waveguide.

It is important to note that while transmission is identical, irrespective to the choice of initial light input waveguide, this is not the case for reflection. When changing the light injection from the bottom waveguide to the upper, or from the input-side to the back-side, the reflection properties are substantially different. A negligibly small direct or cross reflection is observed for the case shown in Fig. 3b and an amplified reflection in the spectral region corresponding to the BG stop-band is observed for the case shown in Fig. 3c. The reflection non-reciprocity is essentially similar to that of a PTSBG, but in our case it occurs for both direct and coupling mediated reflections. It is interesting to note that in all cases the direct reflection R_{11} is higher than coupling mediated R_{12}. Such a behavior is totally counterintuitive for the case when light injection is performed into the uniform waveguide that neither bear gain/loss or refractive index modulation.

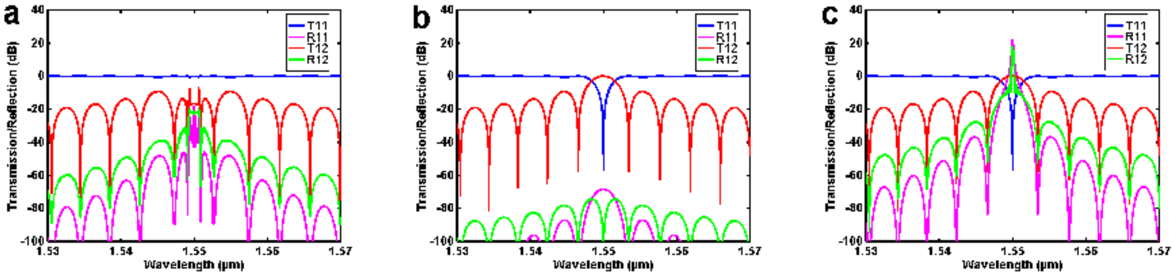

Figure 3: a) Frustrated coupling regime spectral response; b) & c) Phase matching allowed PTSBG operation differing by the choice of the light injection from the input-side or back-side, respectively.

This means that the description of the device behavior cannot just boil down to a framework of two-waves interactions and accounting for all four interacting waves is crucial. This point marks an important difference with respect to the previously reported works on PT-symmetry grating assisted devices. Even though some of them are treating devices involving a four-wave interaction, the analysis of their properties is still based on a conventional two-waves approach [18].

The necessity for taking into account the essentially four waves nature of interactions in such structures becomes particularly evident when considering a vertical directional coupler where both top and bottom waveguides are bearing PTSBG. A practical realization of such a device can be envisioned for example by considering III-V waveguides with different quaternary alloys composition [19]. The gain/loss distribution of the complex index profile between the top and bottom waveguides can in such a case be done either symmetric (Fig. 4a) or anti-symmetric (Fig. 4b). Though the dispersion curves of uncoupled PTSBG for top and bottom waveguides are strictly identical for both cases, the spectral behavior of coupled symmetric and anti-symmetric PTSBG are totally different (Fig. 5). The two waves treatment is completely inappropriate and would provide erroneous results in this case.

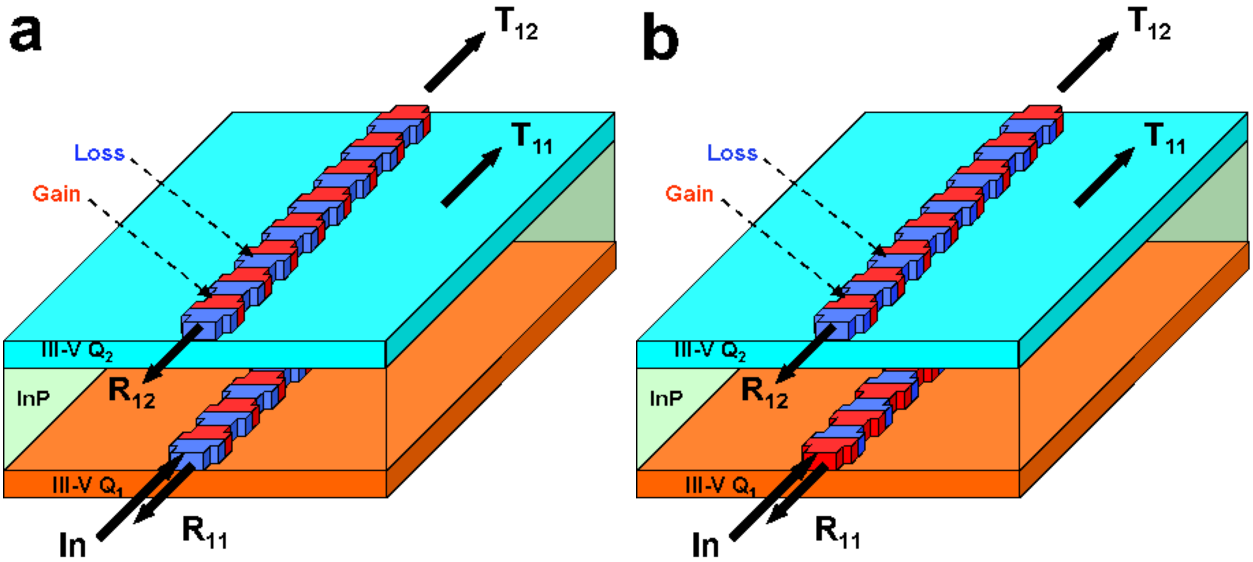

Figure 4. Sketch of a PTSBG assisted directional coupler with rectangular grating profile. Gain and loss grating sections are indicated by red and blue colors, respectively: a) Symmetric gain/loss index profile distribution between top and bottom waveguides; b)Anti-symmetric gain/loss index profile distribution between top and bottom waveguides.

It is worthful mentioning that using two PTSBG coupled waveguides provides also an additional degree of freedom for structure design and opens prospects for additional functionalities but requires a deeper insight on the treatment of phase matching conditions.

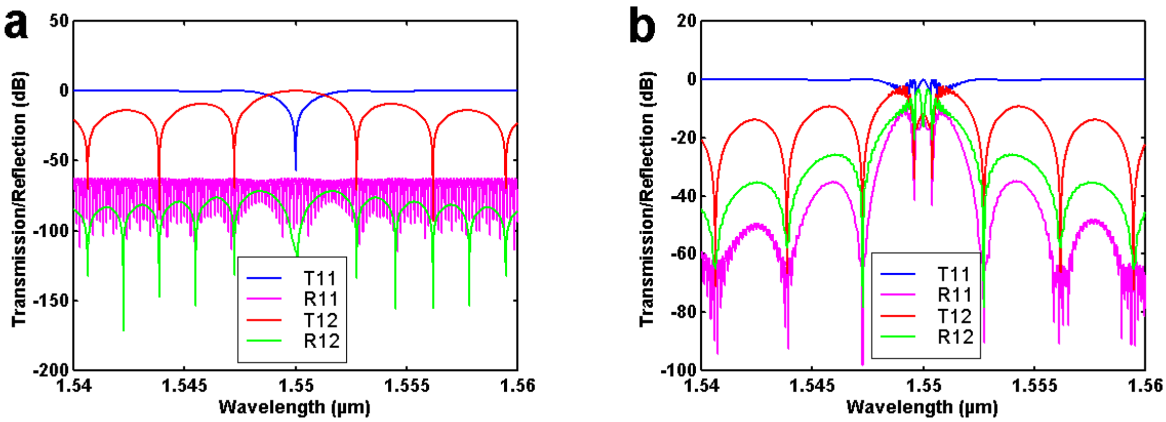

Figure 5. Spectral response of a PTSBG assisted directional coupler with rectangular grating profile. Gain and loss grating sections are indicated by red and blue colors, respectively: a) Symmetric gain/loss index profile distribution between top and bottom waveguides; b)Anti-symmetric gain/loss index profile distribution between top and bottom waveguides.

3. SUMMARY AND CONCLUSIONS

We propose a new strategy to implement switching or routing in PT-symmetric couplers. The operation principle is based on the modification of the PTSBG dispersion properties used for controlling phase matching between two waveguides. The four waves interaction between waveguides is an essential condition required for switching. It opens up new prospects for PT symmetry devices that are currently essentially limited to two-wave interactions. A very interesting aspect of our approach is that all the described behavior and properties also hold for the case of imperfect PT-symmetry operation, corresponding to the important practical case of fixed losses. By a proper engineering of the complex index profile, it is still possible to maintain the frustrated-coupling regime in the absence of gain. As explained, this corresponds to the forbidden phase matching. By bringing gain into the system, perfect PT-symmetry is restored and so is the phase matching condition. Switching or add-drop operations are thus achieved from the sole gain variation, which is much more convenient for practical applications. The calculated examples shown in Figs. 3a-3c correspond to this case of fixed losses and variable gain operation mode, with indices typical of III-V materials. The requested tuning ranges for switching being of the same order of magnitude as those typical in optoelectronics, practical realizations exhibiting such frustrated or favored coupling behaviors for further assessment seem at hand.

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