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ABSTRACT

We address the potential of a system with gain and loss featuring a PT-symmetric configuration for the realization of tunable, reconfigurable and non-reciprocal devices. By using PT-symmetric coupled waveguides and Bragg reflectors as fundamental building blocks, it is possible to build a wide variety of functional optical devices such as switches, unidirectional Bragg gratings, reconfigurable modal demultiplexers etc. The use of nonuniform coupling or gain-loss modulation profiles further brings a number of advantages as compared to the uniform PT-symmetric structures. The disruptive paradigm of the PT-symmetry could thus provide a major boost to integrated optics and is expected to foster a new generation of tunable, reconfigurable and non-reciprocal devices.

Keywords: parity-time symmetry, optical switching, buffer memory, gain-loss modulation, Bragg grating, integrated optoelectronics.

1. INTRODUCTION

The concept of "non-Hermitian Hamiltonians" with complex conjugate potential profiles invariant under a parity-time (PT) inversion and having all eigenvalues real, quickly became an inspiring paradigm in theoretical physics [1,2]. Due to the similarity of quantum mechanics and paraxial limit of Maxwell equations, optics provides growing opportunities for the implementation and experimental investigation of PT-symmetric systems (PTSS) [3-8]. The distinctive feature of PTSS is that the refractive index profile of the structures is complex-valued due to the gain and/or loss, which are spatially separated in the system. To provide new features, the gain/loss regions must be combined by coupling two or more optical elements, such as resonators, waveguides, or in a similar manner two or more optical modes.

2. PT-SYMMETRY RELATED FUNCTIONALITIES

Apart from fundamental research motivations, the tremendous interest in these artificial systems is strongly driven by the practical outcomes from some unique properties of PTSS detailed below.

2.1 Gain-Loss Modulated Tunable and Reconfigurable Guided Wave Devices

In such a PTSS the effective detuning of the propagation constants between the odd and even supermodes (i.e., propagation eigenvalue difference β_1-β_2 between supermodes, and thus the inverse of their beat length) is gradually reduced upon increasing the level of combined gain/loss in the system until the imaginary part of these constants is above a critical point. This can be advantageously exploited for implementing switches and modulators. This avenue would largely mitigate the lack of electro-optical tunability in fiber optics, metamaterials and plasmonics. A simple platform for these concepts, detailed below, is a pair of coupled waveguides, one with gain and the other with losses, as illustrated in Fig. 1a. In the given example the design of the III-V waveguides is basically similar to that of twin semiconductor optical amplifiers (SOA) with separate electrodes. The gain and loss level of each waveguide is controlled by the injection current. The "gain waveguide" operates above the amplification threshold, the "loss waveguide" below. This two electrodes scheme is optimal for obtaining the balanced gain-loss condition required for a "perfect PT symmetry" switching operation. An amplification level in the gain waveguide of 18.6 dB required for switching [9] is quite achievable using SOAs. In addition, we have shown that the gain level required for switching can be reduced by increasing the loss contribution. This remarkable and unintuitive behavior is genuinely connected to the PT-symmetry.

2.2 Spatial Non-Reciprocity

PTSS below the symmetry breaking point can exhibit "spatial non reciprocity" or "unidirectionality", distinctly different from that based on the Faraday magneto-optical effect (this latter actually the more genuine non reciprocity). The same signal presented at one or the other (PT-symmetric) waveguide entrance of a PTSS results in two widely distinct intensity distributions at the guide outputs (Fig. 1b). This asymmetric flow can be exploited by adding a feedback loop for buffer memory implementation (Fig. 3a) [10]. This is a highly valuable function to hold information in optical fiber networks at nodes, to address for instance contention.

Another example of unidirectional behavior is obtained in the case of a PT-symmetric Bragg waveguide (Fig. 1c), for which the reflectivity can be extremely low for light incident from one side, and extremely high when light is incident from the opposite side [11,12]. This property can even be obtained without any gain by using a fully passive approach, provided that an appropriate amount of loss is incorporated in the system.

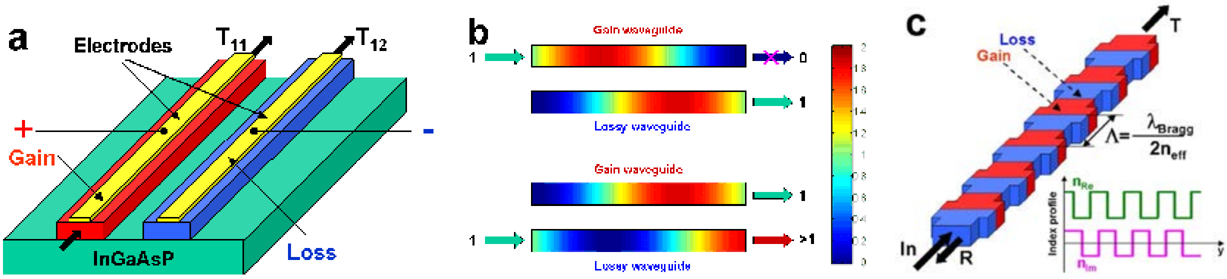

Figure 1: a) Sketch of a PT-symmetric directional coupler switch; b) Non-reciprocal operation from the two waveguide; c) Sketch of a PT-symmetric Bragg grating waveguide (PTSBG).

2.3 Tailoring of the spectral and dispersion properties through local engineering of PT-symmetric profile

As was learnt over decades in the case of conventional passive type coupled waveguides or Bragg gratings, the modulation of the coupling coefficient along the light propagation direction for two co- or contra-propagative optical modes brings an additional room for the tailoring of spectral or dispersive properties of such type of devices. For instance, the use of Bragg gratings as filters in Wavelength Division Multiplexing (WDM) requires the efficient control of the whole spectral shape, related namely to the reduction of the secondary sidelobes level. Such reduction is usually achieved by tapering the coupling strength profile, a process known as apodization.

In our recent work [13] we considered the example of nonuniform PT-symmetric Bragg gratings with a complex index profile modulated by a slowly varying envelope function, with the aim of combining the apodization techniques of classical Bragg gratings with the advantages of PT-symmetry such as unidirectionality. The basic issue is whether real and imaginary parts are apodized the same way. We demonstrated in these two-port devices the possibility to achieve an efficient apodization of the PT-symmetric Bragg grating spectral response with a standard Hamming window function. To ease implementation of the apodization in real structures with local binary nature of the real and imaginary index contributions, this approach was extended to the duty-cycle modulated periodic or deterministic aperiodic binary PT-symmetric gratings. It appears that many conventional techniques previously developed for passive type Bragg gratings or related devices can be transposed and adapted to a PT-symmetric case, provided the constraints of real and imaginary part modulation are properly combined.

One substantial difference, however, is that the complex index profile of the PTSS brings an additional degree of freedom. As hinted above, the possibility to independently modulate the real and imaginary components of the index profile leads to consider a pseudo PT-symmetric index profiles where the modulation of real and imaginary index components are balanced on average across the structure but not balanced locally. The local engineering of such gain-loss modulated complex index profiles brings additional functionalities (tolerances, rejections, etc.), hence well beyond the simple idea of sidelobes level reduction.

To illustrate the behavior of such nonuniform pseudo PTSS we take the example of one-dimensional (1D) Bragg grating of length L with the PT-symmetric refractive index distribution, $n(z) = n_o + \Delta n_R(z)\,R(z) + i\Delta n_I(z)\,I(z)$ in the interval $|z| < L/2$. The system is embedded in a homogeneous medium having a uniform refractive index $n_0 = 1.4$ for $|z| > L/2$. The considered case loosely corresponds to that of a Bragg grating written in an optical fiber. Here, $\Delta n_{I,R}(z)$ represent the fast variating index contrast shifted by a $\Lambda/4$ for the real and imaginary parts (e.g. $\Delta n_R(z) \propto \cos(2\pi z/\Lambda)$ and $\Delta n_I(z) \propto \sin(2\pi z/\Lambda)$ for a sinusoidal variation), while $R(z)$, $I(z)$ are the slowly varying tapered envelopes of the real and imaginary modulations of the refractive index, respectively. The fact that the index contrast here is two orders of magnitude larger than in a usual fiber grating does not affect the generality of obtained results and offers some computational advantages.

We consider that R(z) and I(z) are described by two independently chosen raised cosine type function:

$$f(z) = 1 + A_{R,I}\cos\left(2\pi z / L\right) \qquad (1)$$

where the amplitude coefficients $|A_{R,I}| \leq 1$ may differ in magnitude and even in sign for the real and imaginary components of the grating index profile.

An interesting behavior exemplifying the functionalities of nonuniform pseudo PTSS can be observed for an antisymmetric modulation of real and imaginary components of the complex index profile, i.e. when $A_R \approx -A_I$. The spectral response of such nonuniform pseudo PT-symmetric Bragg grating where $A_R = -A_I = 0.95$ is shown in Fig. 2a. The strong modulation of the imaginary part of the index profile towards the ends of the grating and enhanced modulation of the real part in the middle of the grating results in an amplified by 36 dB single mode transmission while rear side reflection level is by 15dB lower. This operation regime can be used for the realization of narrow band single mode amplifier.

A distinctly different behavior is obtained for the opposite case, i.e. when $A_R = -A_I = -0.95$. A higher modulation of the real part of the index profile towards the ends of the grating combined with enhanced modulation of the imaginary part in the middle of the grating results here in the selection at the Bragg wavelength of a single and narrow longitudinal mode with more than 30 dB reduction over satellites lobes. This regime is highly desirable for a single-mode Distributed-Feedback (DFB) laser.

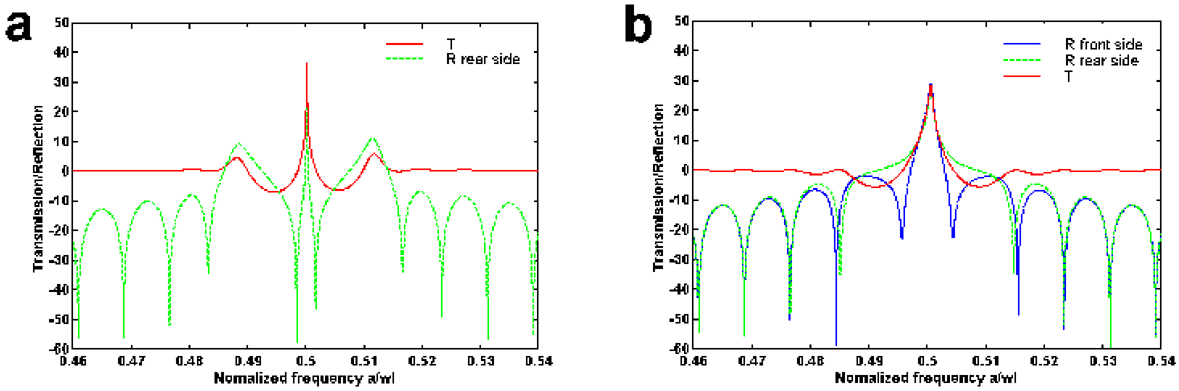

Figure 2. Reflection and transmission spectra of nonuniform PT-symmetric Bragg gratings. a) A_R=-A_I=-0.95; b) A_R=-A_I=0.95.

3. TOWARD A NEW PLATFORM OF GAIN-LOSS MODULATED ACTIVE OPTICAL DEVICES

The examples provided above show that the principle of gain-loss modulation lying in the heart of PT-symmetry optics enables a range of innovative solutions in the field of integrated optics at 1.5µm. For instance one major bottleneck of the III-V/Si hybrid integration approach is that each type of active devices (laser, modulator, etc) requires a specific composition of III-V semiconductor alloy, involving a variety of (re)growth challenges. The PT-symmetry principle provides an alternative way for the realization of active devices that could become functional in a new platform for integrated optics. By using PT-symmetric coupled waveguides and Bragg reflectors as fundamental building blocks, it is possible to build a wide variety of functional optical devices such as dynamic buffer memories [9,10], switches and reconfigurable spatial [13] or wavelength [14] add-drop demultiplexers, highly narrow band single longitudinal mode modulators exploiting the principle of coherent perfect absorption [15,16] etc… The advantage of the PT-symmetry solution is that the fabrication of all these devices can be done with a single stack of III-V semiconductor alloys that greatly simplifies the technological process. Combinations of III-V and silicon photonics could also be exploited in this way, to reduce the number of transitions between passive and active layers in complex circuits. The disruptive paradigm of the PT-symmetry could thus provide a major boost to integrated optics and is expected to foster a new generation of tunable, reconfigurable and non-reciprocal devices. A collection of examples illustrating the practical implementation of such PT-symmetric devices is shown in Fig. 3, with avenues either in pure III-V (Fig. 3a,c) or in hybrid silicon photonics (Fig.3b).

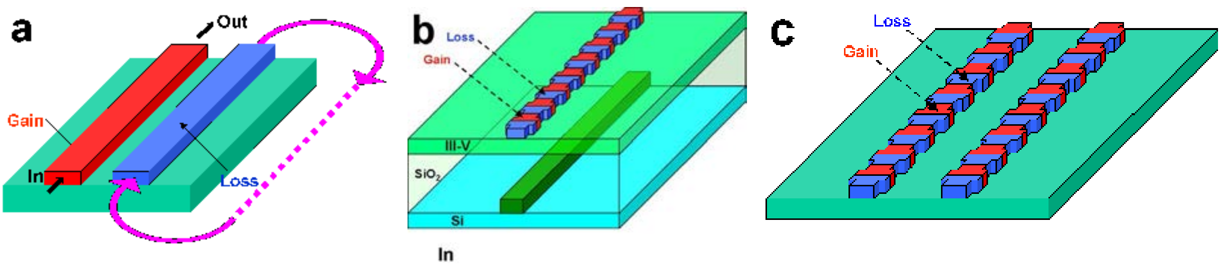

Figure 3. Sketch of: a) Dynamic buffer memory using PT-symmetric directional coupler switch and feedback loop; b) Reconfigurable add-drop demultiplexer; c) Coherent absorption modulator.

The principle of the local variation of the complex index profile can be implemented through the control of the PTTS geometry parameters such as waveguides interdistance separation, waveguide width, grating duty ratio etc…Preliminary results (illustrated in Fig. 4) on the experimental realization of PT symmetric structures based on such III-V's will be presented.

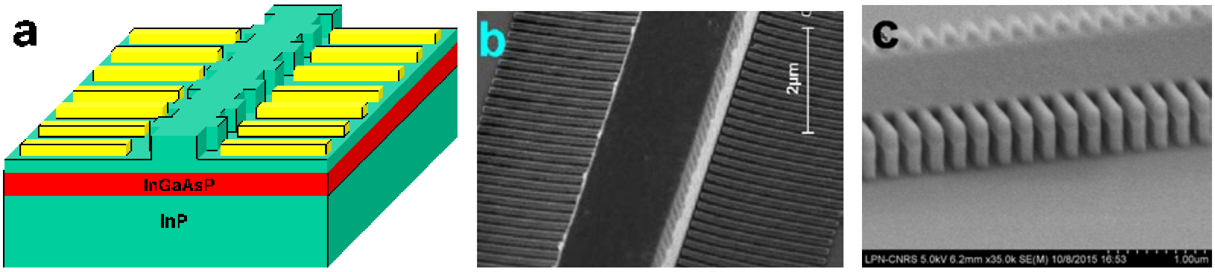

Figure 4: a) Sketch of a PT-symmetric Bragg grating with complex index profile; b) SEM view of the metallic wires Bragg grating providing modulation for the imaginary part of the complex index profile; c) SEM view of the laterally corrugated dielectric Bragg grating (modulation of the real part of the complex index profile).

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