PT-Symmetry of Multimode Waveguides: A Tool for Multichannel Communication

H. Benisty, Anatole Lupu, Aloyse Degiron

PT-Symmetry of Multimode Waveguides: A Tool for Multichannel Communication

Henri Benisty[1], *Member, IEEE* Anatole Lupu[2,3], and Aloyse Degiron[2,3]

[1]*Laboratoire Charles Fabry, Institut d'Optique, Univ. Paris-Sud, 2 Av. A. Fresnel, 91127 Palaiseau, France*

[2]*Univ. Paris-Sud, Institut d'Electronique Fondamentale, UMR 8622, 91405 Orsay Cedex, France*

[3]*CNRS, Orsay, F-91405, France*

Tel: (0033) 164533286, Fax: (0033) 164533318, e-mail: henri.benisty@institutoptique.fr

ABSTRACT

The idea of Parity-Time symmetry is to exploit the special eigenvalues of coupled modes experiencing a map of balanced gain and losses. We consider multimode waveguides with transverse PT-symmetry, hence we have N parallel stripe pairs (one gain stripe and one loss stripe) in the waveguide. The evolution of eigenmodes and eigenvalues in clusters of 2N modes that undergo N successive exceptional points is evidenced for realistic and idealised structures. Targeting a regime just above an exceptional point allows a pair of modes to be selected. We show the potential for selecting such modes with a good rejection against other modes, in comparison of non PT-symmetric schemes. This could become a tool for multichannel communication.

Keywords: parity-time symmetry, waveguide, transverse modes, exceptional point, multimode communication.

1. INTRODUCTION

To pack more bandwidth into a physical channel, an increasingly considered possibility is to exploit the multimode nature of a broad waveguide, in order to multiplex the bandwidth over several modes. Compared to a more incremental scheme with many single mode waveguides in parallel, there are a couple of advantages: There is less probability of failure, given the fact that the physical integrity of a broad waveguide is easier to guarantee through the device fabrication and lifetime than with a large set of narrow waveguides. There is more flexibility in architecture, with the possibility to spread the information over several modes of distinct dispersion, getting more immunity. However, there is no mainstream road to tap a given mode from a broad waveguide, or to demux modes in general. Modes differ by their transverse momentum, so in principle, a grating-like device could provide in-plane separation, at least in a more separated way than the diffraction at a plain cut.

Another possibility that recently appeared at the horizon of the integrated optics toolbox is a use of the so-called PT-symmetry, the parity-time symmetry and its symmetry-breaking characteristics. This is a concept originating from quantum mechanics, in order to obtain an operator having real eigenvalues while not being Hermitian. This happens very naturally in optics when a system of two elements, one with loss the other with gain, are coupled together. A basic case is a geometry of two parallel evanescently-coupled identical waveguides, but for the presence of gain in one of them and in equal amount of loss in the other. Their propagation constant are $\beta_1=\beta'+ig$ and $\beta_2=\beta'-ig=\beta'+i\,\chi$.

If the two guides are now coupled, in addition to these diagonal elements of the matrix depicting the spatial evolution, we have a non-diagonal element κ. Then, one has real eigenvalues with a splitting characteristic of coupling $|\Delta\beta|\neq 0$ as long as $g<\kappa$. But, at $g=|\chi|=\kappa$, an exceptional point (EP) occurs: there is a bifurcation, the two eigenmodes become complex conjugate $\beta_1=\beta'+i\beta''$ and $\beta_1=\beta'-i\beta''$ for $g>\kappa$, see [1]. There is a symmetry breaking since one of the modes now has gain and the other experiences losses.

This class of phenomenon has received a huge attention recently. Several phenomena such as "spatial" non-reciprocity [2-6], relation with nonlinear physics ("breathers", solitons [7-11]) and memory action [2-3] have

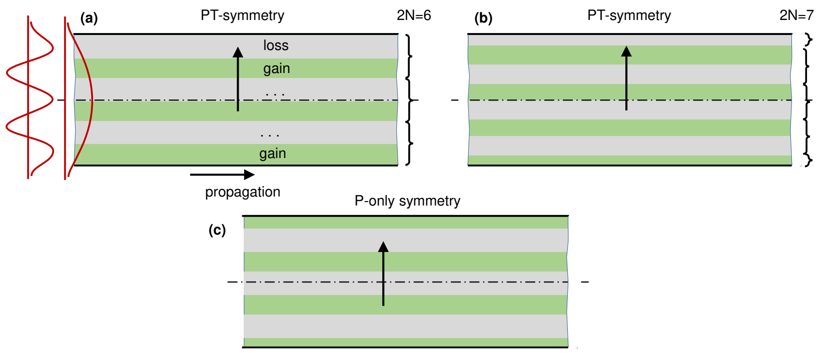

Figure 1. Waveguides with an inner periodic gain-loss pattern: (a) PT-symmetric pattern with 2N = 6 stripes; (b) with 2N = 7 stripes using two half-stripes; (c) P-only symmetric guide with 6 stripes using two half-stripes.

attracted the attention in optics (on waveguides and their arrays [8,10,11]) and metamaterials. Also remarkable is that fact that the exact parity-time symmetry can be relaxed and fixed losses can be used with variable gain, open the possibility to combine PT-symmetry with plasmonics [12] with adequate care [13]. The operation as a switch has already been considered in some details [6,14], including the fact that more losses can mean less gain modulation to bring the required switching event. Switching with gain modulation is useful in materials whose electro-optics modulation is awkward, e.g., metal (plasmonics) and optical fibers.

The question we address in our paper is the use of PT-symmetry to provide mode selection in a broad, largely multimode waveguide. We study a pattern of *transverse* PT symmetry illustrated in Fig. 1, here (a,b) cases, whereby we anticipate that only modes whose transverse structure fits the gain/loss pattern could be selected (we allow half-stripes to fine tune periodicity and selectivity, and allow also zero mean gain for the P-symmetric case). We also hope that the abrupt bifurcation of eigenvalues at exceptional points can help improving the rejection of unwanted modes, since only one ("dressed") mode has gain if we select gain values that are somewhat beyond that of the first exceptional point. This feature should deprive P-symmetric (Fig.1c) solution from a similar advantage.

2. CLUSTERING OF MODES AND SEQUENCE OF EXCEPTIONAL POINTS

Our first stack was to take a model slab waveguide of constant index n = 2.8 and width W = 6λ at wavelength λ =1.55µm, surrounded: it could correspond to a simplified SoI (silicon-on-insulator) waveguide value, that we picture in Fig.2b, although, for simplicity, we freeze the vertical dimension, so that we can apply a slab ("1D") model. To add gain or loss to such a system, one could recourse to hybrid oxyde-free bonded silicon/3-5 structures [15,16] operating with gain from the InP-based 3-5 for instance. We use 2N = 6 stripes as in Fig. 1a. The dielectric map takes the form: $\varepsilon(x) = \varepsilon_R(x) + i\,\Delta\varepsilon_I f(x)$, with f=+1 or f= -1 according to the stripe gain or loss nature at transverse position x (and of course $\Delta\varepsilon_I = g$). We find by a matrix method the set of clustering eigenvalues and exceptional point sequence obvious in Fig. 2a. The two central elements of each cluster merge first into a first exceptional point EP1, then two surrounding modes meet at EP2, the outermost at EP3.

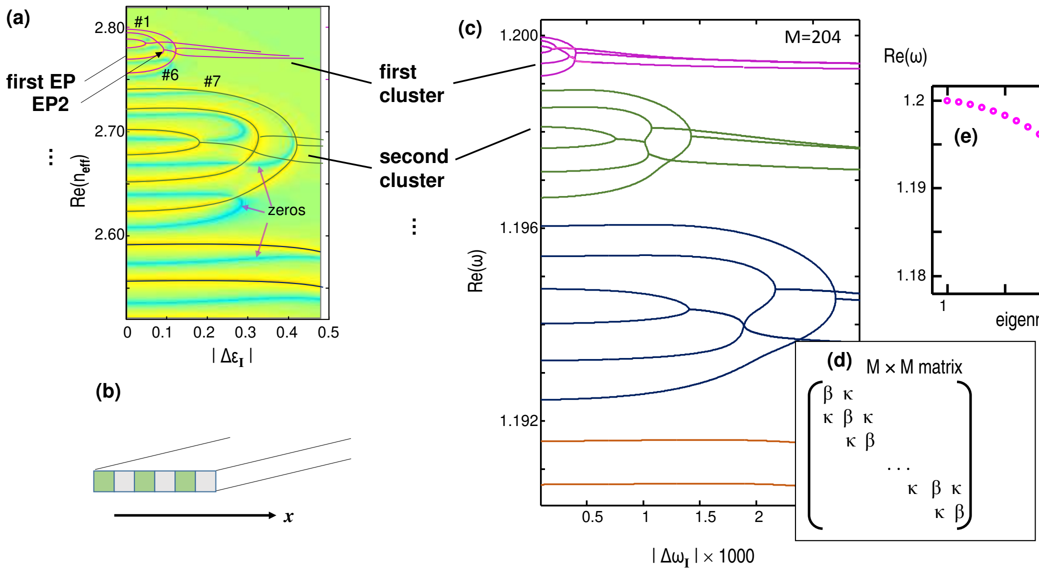

Figure 2. (a) map of eigenvalues (poles of M_{11} matrix element) and zeros of T matrix for the real waveguide sketched below in (b)(modelled with a frozen third dimension); (c) Similar result from the model of M coupled elementary waveguides whose evolution matrix at g=0 is given in (d), with eigenvalues in (e) for the 20 topmost of them (centre frequency $\omega_0 \equiv 1$, total bandwidth 0.4, from Re(ω) 0.8 to 1.2)

Faced to such a complexity, and to the length of pole hunting in complex plane, we tried to devise a more basic model accounting for the same physics. In Fig.2(d,e) we show the ingredients : a set of M=204 coupled identical waveguides coupled to their neighbour only, that form the well-known band shown in Fig.2e. We add diagonal gain and loss imaginary elements so as to fully mimic the six stripes of Fig.2b, and we find the result of Fig.2c. It is essentially similar to Fig.2a, allowing the exploration of the main trends (e.g. mode selection and sensitivity to imperfection) with this simplified model.

We have developed elsewhere [17] a perturbation theory using the PT-symmetric potential matrix elements to second order in g. This theory shows that the strongest coupling are indeed associated in the sequence that we evidenced in Fig.2, namely modes 3 and 4, modes 2 and 5 and modes 1 and 6, and so on for the next cluster of 6. We note some more complexity is possible. For instance, EP2 in cluster 2 is split into two close EP's.

3. USE FOR SELECTION IN MULTIMODE WAVEGUIDE MULTICHANNEL COMMUNICATION.

If we can, by selecting a gain/loss pattern at the surface of a broad waveguide, get a selection of a given mode presented at the entrance, with good rejection from other modes, we could use such a system to capture signals sent on a selected mode in such waveguides. Let us make it clear that we consider here at the entrance modes $m = 1,2,\ldots$, of the pure passive dielectric waveguide without gain or loss, similar to the modes m of Fig.2e, with a typical profile $E \propto sin(\pi m x/W)$. And what we get is not a full demux or add/drop, whereby all non-selected modes would survive. But it can serve as a first step to implement a selective device no larger than the guide itself.

We want to take benefit of the situation in the domain between EP1 and EP2, where the only gain mode should beat all the others, and hoping that the pattern selectivity works. An exploration of a situation with 2N = 9 stripes with half-stripes similar to Fig. 1(b) is given below in Figs. 3(a), 3(b).

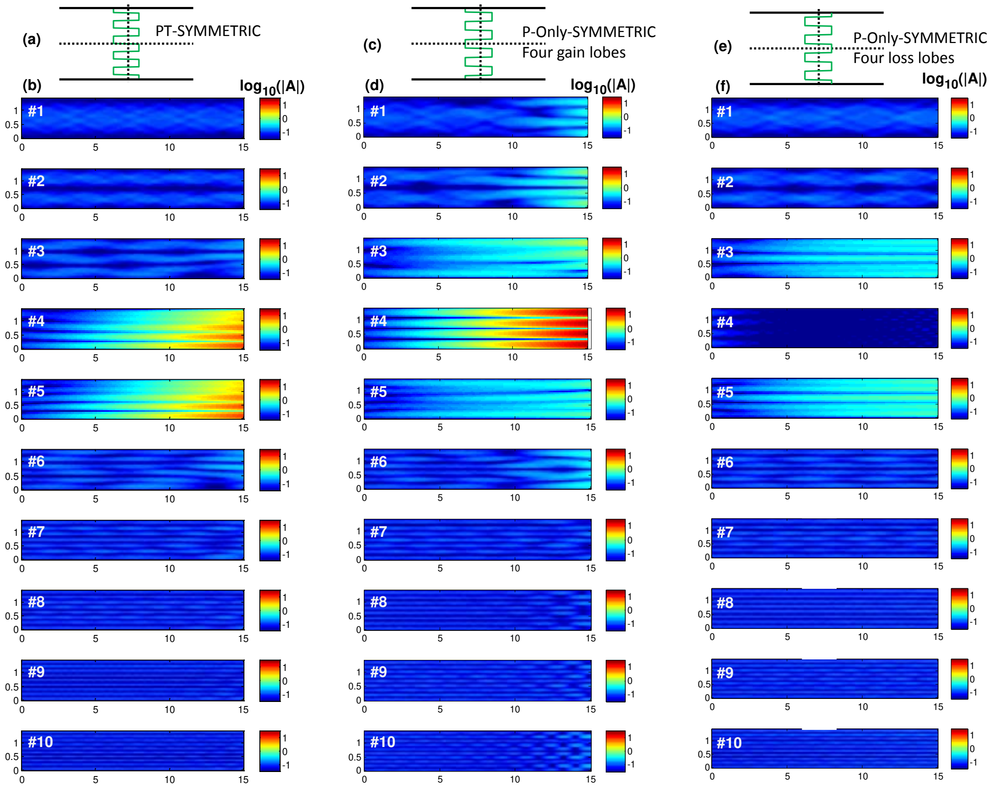

Figure 3. (a,c,e) gain/loss profiles for different PT- or P- symmetry as indicated ; (b,d,f) corresponding maps of intensity in the broad waveguide for 15 unit lengths and the same absolute gain, for injected modes #1 to #10 of the passive (no gain, no loss) waveguide. Color map is log of intensity. Only the PT-symmetric case (a,b) neatly rejects modes other than #4 and #5. P-symmetric configurations with four gain lobes (c,d) do select mode four – or anti-select in cases(e,f) with four loss lobes– but have important secondary modes : the SMSR – Secondary Mode suppression Ratio – is poor.

We show in Fig. 3 the test of the fate of modes #1 to #10 in a model waveguide using M = 144. For the first row, Figs. 3(a), 3(b), the PT-symmetric case, we choose a gain value where the first EP (EP1) has just been crossed. So, out of the many modes, only two modes have a complex part in the eigenvalue. Here, these modes have merged from #4 and #5, the first EP of the first cluster. Only one of the merged mode has gain (propagation constant $\beta_{PT,1} = \beta' - i\,\beta''$), the other has losses ($\beta_{PT,2} = \beta' + i\,\beta''$). We see that all but two modes #4 and #5 are essentially unaffected in intensity. The fact that we pick up and amplify two modes is natural if we think that the gain mode was built from these two modes (we are not in a perturbative regime, though, and the profiles are heavily affected). We see twice the same mode and we do not see the loss mode. For this latter, we checked that its profile is symmetric to the observed gain mode, not surprisingly: its stronger lobes are on the more lossy side of the profile (the top in Fig. 3a) instead of the bottom (the "more gainy" side of the profile) as appears on #4 and #5 maps when the amplifying mode grows at the expense of the other ones.

In Figs. 3(c), 3(d) we compare to a case where we attempt to pick-up mode #4, thanks to a P-symmetric gain/loss pattern having slightly larger stripes to fit this purpose within the P-symmetry constraint and the Dirichlet-like profile boundary condition. With the same gain, the process is undoubtedly successful for mode #4. But we see that the SMSR (Secondary Mode Suppression Ratio, here in a modal sense instead of the usual frequency meaning for laser spectral purity) is not very good, with modes #2, #3 and #4 being also sizably amplified.

We advocate that this is a consequence of the presence of several modes with nonzero gain instead of a single one in the PT-symmetric case. Such modes can pick up some power from unwanted modes. We anticipate that, applying a Fourier analysis, the selectivity vs. mode could be akin to a sinc function with centre shifted at mode #4, and not able to provide the same single-mode selectivity as the blaze condition of gratings that singles out a given order, but we have to work out this tentative claim.

The last case, Figs. 3(d), 3(e), shows the application of a similar P-symmetric gain-loss profile, albeit with sign reversal, swapping gain and loss. The striking feature is now the almost perfect silencing of mode #4, a feature that might be helpful in some conditions, with the fate of noise to be assessed, notably. Still, side modes #3 and #4 are picked up and amplified. This would deserve more analysis as well.

4. CONCLUSIONS

We studied the potential of various gain/loss profiles for treatment of multimode transmission signals in a broad multimode waveguide. We explained how PT-symmetric configurations gave rise to clusters, with ordered sequence of exceptional points (EPs) in these clusters. We have used this understanding to analyse the high quality of modal selection with good "SMSR" (Secondary Mode Suppression Ratio), although modal selection then merges the two modes that formed the EP. We have checked on simple simulations that geometries with similar stripe but with only P-symmetry do leave higher secondary modes when they select (or "anti-select") a given mode with the number of lobes matching the number of gain(or loss) lobes of their gain/loss profile.

These possibilities open new perspectives for the management of multimode transmission on-chip or on-board data communication exploiting all physical limits.

REFERENCES

[1] J. Ctyroky, V. Kuzmiak, and S. Eyderman, "Waveguide structures with antisymmetric gain/loss profile," Opt. Express **18,** 21585-21593 (2010).

[2] M. Kulishov, J. M. Laniel, N. Bélanger, J. Azaña, and D. V. Plant, "Nonreciprocal waveguide Bragg gratings," Opt. Express **13,** 3068-3078, (2005).

[3] M. Kulishov, J. M. Laniel, N. Bélanger, and D. V. Plant, "Trapping light in a ring resonator using a grating-assisted coupler with asymmetric transmission," Opt. Express **13,** 3567-3578 (2005).

[4] Z. Lin, H. Ramezani, T. Eichelkraut, T. Kottos, H. Cao, and D. N. Christodoulides, "Unidirectional invisibility induced by PT-symmetric periodic structures," Phys. Rev. Lett. **106,** 213901 (2011).

[5] L. Feng, M. Ayache, J. Huang, Y.-L. XU, M.-H. Lu, Y.-F. Chen, Y. Fainman, and A. Scherer, "Nonreciprocal light propagation in a silicon photonic circuit," Science **333**, 729-733 (2011).

[6] A. Lupu, H. Benisty, and A. Degiron, "Using optical PT-symmetry for switching applications," Photon. Nanostruct. Fund. Appl. **12,** 305-311 (2014).

[7] V. V. Konotop, V. S. Shchesnovich, and D. A. Zezyulin, "Giant amplification of modes in parity–time symmetric waveguides," Phys. Lett. A **376,** 2750-2753 (2012).

[8] M. C. Zheng, D. N. Christodoulides, R. Fleischmann, and T. Kottos, "PT optical lattices and universality in beam dynamics," Phys. Rev. A **82**, 010103 (2010).

[9] G. P. Tsironis and N. Lazarides, "PT-symmetric nonlinear metamaterials and zero-dimensional systems," Appl. Phys. A **115**, 449-458 (2014).

[10] Y. N. Joglekar, C. Thompson, D. D. Scott, and G. Vemuri, "Optical waveguide arrays: quantum effects and PT symmetry breaking," Eur. Phys. J. Appl. Phys. **63**, 30001 (2013).

[11] I. V. Barashenkov, L. Baker, and N. V. Alexeeva, "PT-symmetry breaking in a necklace of coupled optical waveguides," Phys. Rev. A **87**, 033819 (2013).

[12] H. Benisty, A. Degiron, A. Lupu, A. De Lustrac, S. Chenais, S. Forget, M. Besbes, G. Barbillon, A. Bruyant, S. Blaize, and G. Lerondel, "Implementation of PT symmetric devices using plasmonics: Principle and applications," Opt. Express **19,** 18004-18019 (2011).

[13] H. Benisty, C.Yan, A. Degiron and A. Lupu, "Healing near-PT-symmetric structures to restore their characteristics ingularities: analysis and examples," J. Lightwave Technol. **30,** 2675-2683 (2012).

[14] A. Lupu, H. Benisty, and A. Degiron, "Switching using PT-symmetry in plasmonic systems: positive role of the losses," Opt.Express **21,** 21651-21668 (2013).

[15] K. Bougot-Robin, A. Talneau, and H. Benisty, "Low-index nanopatterned barrier for hybrid oxide-free III-V silicon conductive bonding," Optics Express **22**, 23333-23338 (2014).

[16] K. Bougot-Robin, C. Pang, X. Pommarede, A. Itawi, A. Talneau, J. P. Hugonin, and H. Benisty, "Embedded Effective-Index-Material in Oxide-Free Hybrid Silicon Photonics Characterized by Prism Deviation," Journal of Lightwave Technology **32**, 3283-3289 (2014).

[17] H. Benisty, A. Degiron, A. Lupu, Phys Rev A, " Transverse periodic PT-symmetry for modal demultiplexing in optical waveguides", submitted.