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Using PT-Symmetry in Plasmonic Systems for Switching and Dynamic Memory Applications

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***Abstract* – We address the potential of a coupled plasmonic waveguides system with gain featuring a PT symmetry configuration for the realization of switching and dynamic memory applications based on a non-reciprocal modal behavior. The possibility for a perfect switching operation in such a non-conservative layout combining loss and gain is demonstrated. The positive role of losses allowing to lower the total amount of gain required for switching is particularly emphasized.**

I. INTRODUCTION

The interest generated by the recently emerged field of nanoplasmonic is strongly driven by the practical outcomes targeting light manipulation at nanoscale, allowing a further miniaturization of integrated optic circuits. The last years witnessed the demonstration of several key active devices incorporating plasmonics, such as “plasmon lasers” or “spasers” [1] or long-range plasmonic amplifiers [2,3]. Despite the undisputed potential of the plasmonic approach for miniaturization, its inherently high Joule losses remain a critical issue. The mitigation by gain to overcome metal related losses involve a rather high gain level, of the order of few hundred cm^{-1}.

In this contribution we aim to show that the combination of gain and plasmonic can also be used beyond the simple idea of loss compensation. It can be fruitfully exploited for the implementation of a switching operation in a PT-symmetry configuration that can be obtained by the association of a lossy plasmonic waveguide with a dielectric waveguide whose modes experience gain, either in core or in cladding.

Our interest is due to the fact that the implementation of the basic switching operation is otherwise quite challenging in plasmonics where electro-optical tuning of the refractive index is inefficient. Another contrast with most optical systems where propagation losses are primarily a plague is the possibility for losses to play a positive role in the case of PT symmetric couplers (PTSC), and specifically for their switching applications.

II. PT SYMMETRY SWITCHING OPERATION PRINCIPLE

A sketch of a PT symmetry directional coupler is shown in Fig. 1a. Gain in the top guide is denoted g_1 and losses in the bottom guide is denoted χ_2, although both can formally be positive or negative. Fig. 1b reminds the well-known eigenvalue evolution for a perfect case of balanced gain and losses as a function of the gain ($g_1 = \chi_2$). Positive imaginary parts are for losses.

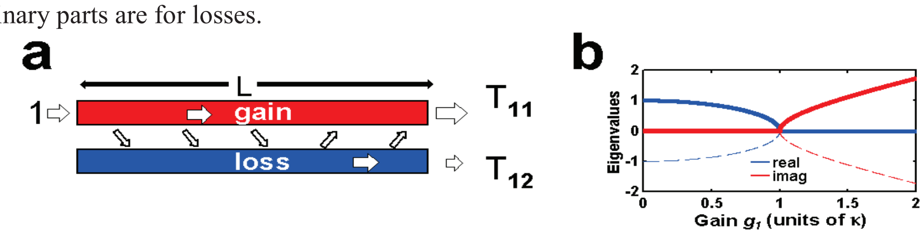

Fig. 1. a) Sketch of a PT symmetry directional coupler; b) Real parts (blue line) and Imaginary parts (red line) of the two eigenvalues β_{eff1} and β_{eff2} (solid and dashed lines) of a coupled system.

As it can be seen from Fig. 1b, the propagation constants (eigenvalues) in such a coupled waveguide system with combined gain and loss are real for $g_1<\kappa$, where $\kappa=\pi/2L_c$ is the coupling coefficient and L_c is the coupling length corresponding to a complete crossover from one guide to the other. The effective detuning of the propagation constants is gradually reduced with increasing the level of combined gain/loss in the system until they become imaginary for $g_1>\kappa$. The variation of the effective detuning below the critical point $g_1=\kappa$, can thus be exploited for the implementation of a switch or a modulator through the variation of the gain level in the system.

The most promising features of PTSC are to be sought in the singular nature of the critical point (also called exceptional point) whereby a small change of gain/loss causes a quick evolution of the eigenvalues from the real to the imaginary axis [4-9]. The generic possibility for achieving an abrupt switching with a modest variation of the combined gain/loss in the vicinity of the critical gain point was further substantiated in our recent work [10,11]. Little attention has been paid however to the total amount of gain required to perform switching. The analysis of the optimal conditions, allowing a switching operation with the lowest amount of gain by taking advantage from the presence of losses, is the subject of this work.

We show that it is possible to achieve a "perfect switching" where the light crosses over completely from one guide to the other. Furthermore, despite the presence of gain and loss in the system, the amount of cross coupled light is the same as that injected in the input waveguide only in specific designs. Therefore, the "bar" and "cross" states denominations that refer to passive waveguides should be generalized for PT symmetric systems.

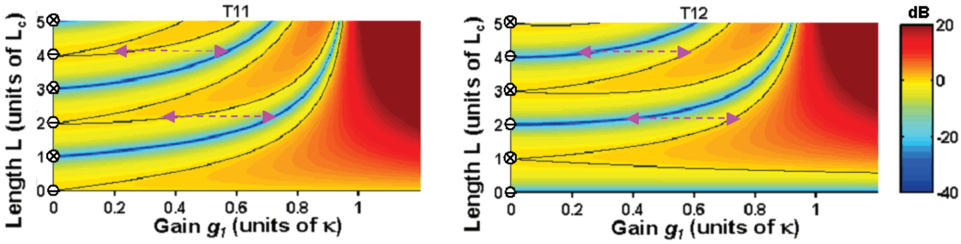

Fig. 2. Color map of a transmission $T^{ij}(L,g1)$ in a dB scale (colorbar). The thin black solid lines on the maps correspond to the iso-level curves $T^{ij}=1$. The ordinate axes points corresponding to a complete power crossover are marked by an Θ, and those indicating the bar state with zero net crossover are marked by a ⊗. The dashed line arrows correspond to a perfect switching operation from $T^{11}=1$, $T^{12}=0$ to $T^{11}=0$, $T^{12}=1$.

The variation with propagation distance L and gain g_1 of the intensity at the PTSC output for basic quantities (T^{11}, T^{12}) are depicted in Fig. 2. The introduction of the balanced gain/loss in the system leads to the splitting of the bar (respectively cross) states and the birth of two branches where $T^{ii}=1$ (resp. $T^{ij}=1$ where i≠j,) originating from the initial states. These branches are drawn as black thin solid lines on Fig. 2.

From Fig. 2, the lowest amount of gain for switching occurs for a coupling length $L=2L_c$ in the case of the gain input waveguide (T^{11}). In the initial state (no gain), transfer to the 2nd waveguide is null, $T^{12}=0$, while $T^{11}=1$ (usual "bar" state). A perfect switching operation consists of cross-coupling all the power to the second waveguide having losses ($T^{12}=1$ and $T^{11}=0$). We determined that the condition for perfect switching is given by:

$$(g_1+\chi_2)L_c=0.676\pi=2.125 \qquad (1)$$

which is controlled by the "imaginary detuning" $(g_1+\chi_2)$. This fixed amount necessary to perform switching does not depend on the physical implementation of the PT symmetry coupler. For the considered case when $g_1=\chi_2$ this corresponds to an amplification level of 18.6dB [related to $\exp(2g_1L_c)$] in the waveguide with gain in isolation (Fig. 3b, dashed line and arrow).

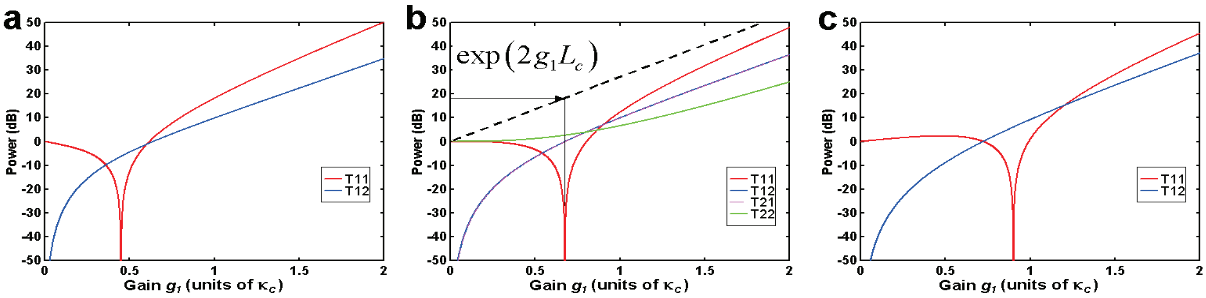

Fig. 3. Cross and bar states intensity variation with gain g_1 : a) $\chi_2=3g_1$; b) $\chi_2=g_1$; c) $\chi_2=0.5g_1$.

One interesting feature that can be observed from Fig. 3b is that when light is injected in the loss waveguide (green and magenta curves), an asymmetrical operation is obtained. This kind of asymmetric operation, different from [12], can be used for the implementation of a buffer memory function.

Another remarkable feature, genuinely connected to the underlying PT-symmetric layout, is that the gain level g_1 required for switching can be reduced by *increasing* the loss contribution $\chi_{2,}$ at the price of a penalty on the transmission level that turns out to be quite affordable (Fig. 3a). Conversely, decreasing loss contribution leads to the increase of the gain g_1 required for switching (Fig. 3c).

Essentially similar results hold for the case with fixed losses and variable gain accounting for plasmonic systems. The design of a PT symmetry switch using long range surface plasmon polariton waveguides (LRSPP) is depicted in Fig. 4a. The commutation behavior from a preliminary calculation of eigenmodes is displayed Fig. 4b as a function of length for zero gain and then for still small gain in figure 4c. We anticipate that the smoothing of the zero that becomes stronger with gain beyond g_1=0.002 has to be corrected by a "healing" procedure [11].

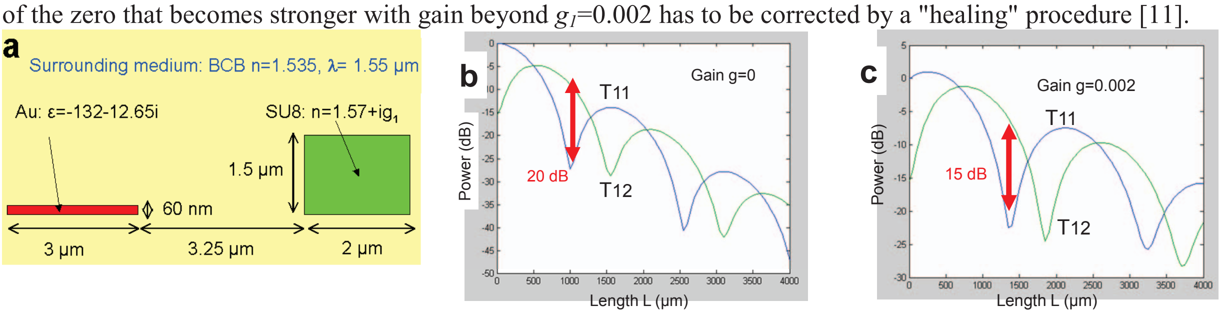

Fig. 4. a) LRSPP design for a switch using PT symmetric couplers. b) Behavior deduced from numerical modeling of eigenmodes at g_1=0 as a function of length. c) Same for a small gain g_1=0.002.

III. Conclusion

We have outlined how to consider PT-symmetry with plasmonics for switching systems, in a generic setting of coupled mode theory, providing design rules. We also hinted at an actual PTSC switch based on LRSPP.

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