PT symmetry in a side-coupled resonator structure for broadband unidirectional invisibility

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We analyze the scattering properties of a Parity-Time (PT) symmetric structure made of a waveguide and a finite chain of side-coupled resonators. 1D PT-structures exhibit unidirectional invisibility, meaning unit-transmission and zero-reflection for incidence from one direction. The side-coupled nature of our structure provides for different features than the traditional PT Bragg grating, which we explore rigorously. For example, we can achieve a broadband unidirectional invisibility with only two resonators, and we observe rich dispersions for the unidirectional invisibility with four resonators.

Introduction

Originating from fundamental studies of parity-time (PT) symmetric Hamiltonians in quantum mechanics [1], PT symmetric photonic structures have now been investigated for a decade, exploiting the combination of balanced gain and loss to achieve particular properties. Usually in optics loss is an unwanted feature that limits many applications. But in the framework of PT-symmetry, it becomes a key element.

We particularly focus on an important behavior of one-dimensional PT-structures, the anisotropic transmission resonances (ATRs) or unidirectional invisibility [2,3]. This means that one obtains unity transmission and zero reflection for incidence from one side, and a different reflection from the other side.

Structures

We study the various effects of PT symmetry in a finite chain of resonators next to a waveguide (see Fig. 1). We use numerical and analytical calculations with coupled-mode-theory in a transfer and scattering matrix approach to analyze in detail various geometries with multiple cavities.

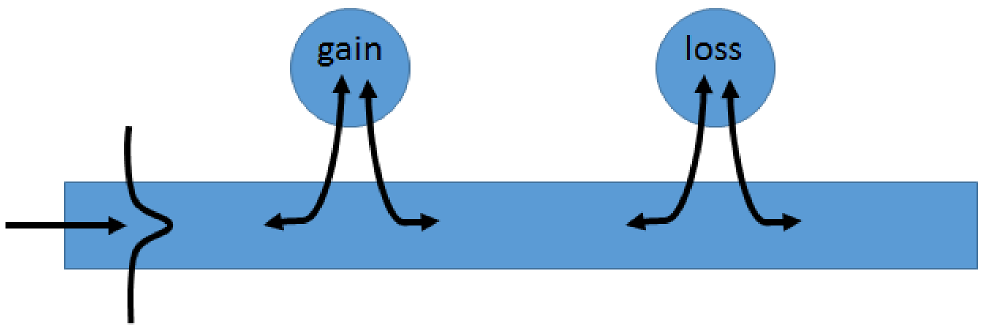

Figure 1: Scheme of a two resonator chain.

An important parameter for these coherently interacting cavities is the length of the intermediate waveguide, which can be tuned to change the phase ϕ and interference properties.

Two resonator chain

The spectrum of two side-coupled resonators (without gain or loss) can exhibit a very narrow transmission peak (see Fig. 2). We exploit this peak with PT symmetry to demonstrate broadband ATRs.

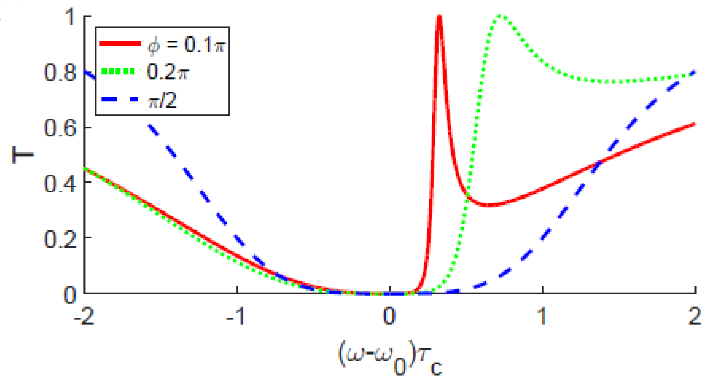

Figure 2: Transmission of a two resonator structure without gain or loss as a function of the detuning $(\omega - \omega_0)\,\tau_c$

With balanced gain and loss (which are quantified by $\tau_c\gamma$), we can see in Fig. 3 that left and right reflections are not equal. A line of ATRs emerges from the previous peak of transmission (deep blue zone). The theoretical equation of this ATRs is given by: $(\omega - \omega_0)\,\tau_c = (1 - \tau_c\gamma)\tan\phi$ (green dashed lines in Fig. 3). We observe that for the special value of $\phi = \pi/2$, the slope become infinity and the ATRs are present at any detuning values and are broadband.

In addition, we address the stability limit (dotted black lines in Fig. 3) of this kind of system, as the presence of gain can readily make them unstable. Moreover, study of the scattering matrix provides us detailed info on lasing states (red stars), and on exceptional points (magenta ovoid).

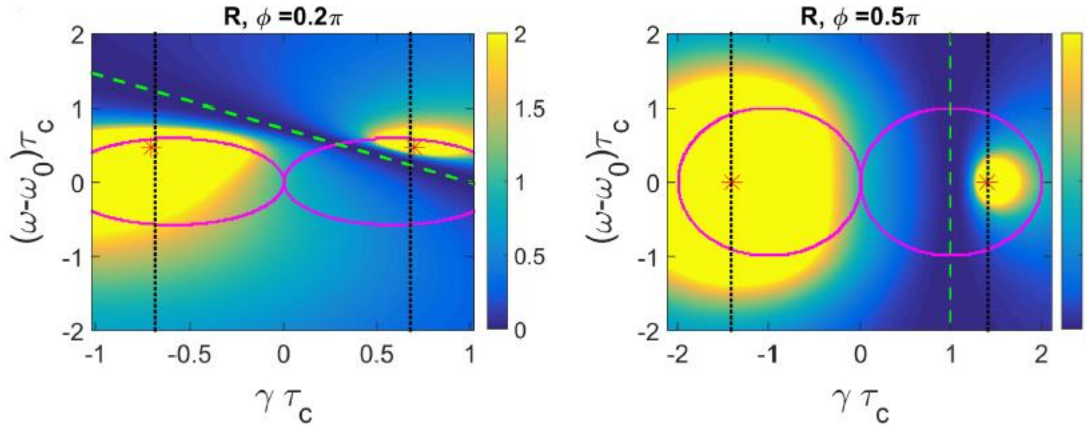

Figure 3: Left ($\tau_c\gamma$ < 0) and right ($\tau_c\gamma$ > 0) reflection as a function of the gain/loss amount $\tau_c\gamma$ and the detuning for two different two resonator structures. Graphs are saturated to two. Green dashed lines indicate the ATRs.

Four resonator chain

For a chain of four resonators the possible configurations are numerous, as we can choose between a Gain-Gain-Loss-Loss or Gain-Loss-Gain-Loss profile, and we can even symmetrically modify the frequencies of the resonators and the amount of gain and loss. Each of these configurations gives rise to a unidirectional invisibility scheme with complex behavior as a function of the frequencies (see Fig. 4): a rich, tunable dispersion with multiple, crossing ATRs (the green lines) is obtained, offering possibilities for "ATR engineering".

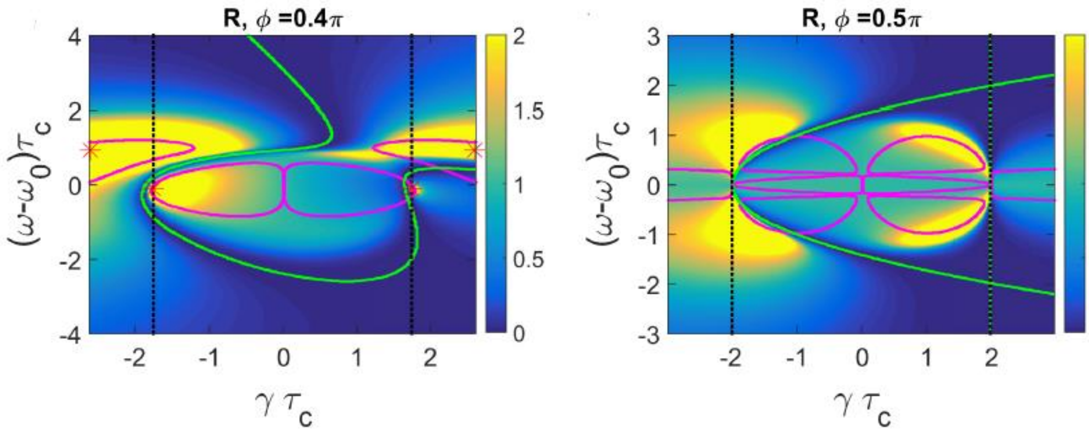

Figure 4: Left ($\tau_c\gamma$ < 0) and right ($\tau_c\gamma$ > 0) reflection as a function of the gain/loss amount $\tau_c\gamma$ and the detuning for two different four resonator structures. Graphs are saturated to two. Green lines indicate the ATRs.

Conclusion

We introduce a new PT geometry consisting of side coupled cavities with interesting unidirectional characteristics. In these systems we show that the bandwidth can be uniquely tuned to be particularly broad or narrow, via a simple structural parameter (the length of waveguide between the cavities). The unidirectional effect is one of the most salient features in the PT-field; it is strongly researched nowadays for potential applications.

Acknowledgements

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