Tailoring of electric dipoles for highly directional propagation in parity-time symmetric waveguides

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Abstract: Electric dipoles are often used as accurate models for electromagnetic sources in integrated photonic structures. We tailor an electric dipole source to create a contrast between wave propagation on both sides of the dipole in parity-time-symmetric waveguides. The unique features of parity-time symmetry enable the creation of various types of contrasting behavior, which can be exploited in integrated photonics applications.

Electric dipole sources have been used for several years in integrated photonics as compact electromagnetic sources, due to their efficient coupling to photonic guided modes [1,2]. The near-field directionality of circularly polarized electric dipoles has recently been demonstrated, by taking advantage of constructive or destructive interference of different evanescent waves. [3,4] Coupling dielectric or plasmonic waveguides to these circular or elliptical dipoles can lead to directional excitation of the waveguide modes, an interesting feature for integrated photonic structures. However, the near field of these elliptical electric dipoles still exhibits an inversion symmetry, which removes the directionality if the dipole is at the center of an inversion-symmetric photonic structure. In order to restore the contrasting properties between two sides, we take advantage of the unique characteristics of parity-time-symmetric coupled waveguides. Parity-time (PT) symmetry can be realized in coupled waveguides by using a balanced profile of the imaginary part of the refractive index, such as one waveguide made of a gain material and the other with an equal amount of loss. [5] The uniqueness of these structures stems from the two regimes in which they can operate depending on the value of the gain/loss parameter γ, that defines the absolute imaginary part of the refractive index in the waveguides. The transition between these two regimes occurs at the exceptional point (EP), which is located at a certain value of γ dependent on the structure geometry. In the PT-symmetric regime ($\gamma < \gamma_{EP}$), both supermodes of the structure propagate without any gain or loss, whereas in the PT-broken regime ($\gamma > \gamma_{EP}$) one supermode benefits from the gain and explodes in amplitude while the other experiences losses and exponentially decreases.

In our structure, the electric dipole is placed in the center of the air layer separating two PT-symmetric slab waveguides, spaced so that the dipole field couples equally to both waveguides. The waveguide made of the gain material is at the top, and the lossy guide is at the bottom (see fig. 1(a)). The value of the gain/loss parameter at the EP for our structure is $\gamma_{EP} = 0.123$. We use the CAMFR eigenmode expansion Maxwell equations' solver to numerically simulate our setup for different values of γ.

In order to create a contrast between the electromagnetic waves propagating on the left and right sides of the source, for each γ, we search for the electric dipole that gives an excitation amplitude closest to zero for the mode 2 on the left side of the dipole. In the PT-broken regime ($\gamma > 0.123$ – fig. 1(b,c)), the mode 2 is the gain mode. Removing it on the left makes the field considerably smaller than on the right side, as the gain mode remains on the right making the field explode. In the PT-symmetric regime ($\gamma \leq 0.12$ – fig. 1(d-f)), the mode 2 is one of the two propagating supermodes of the structure. Removing this mode on the left produces a uniform field profile, while exciting both modes on the right causes a beating, thus creating a contrast in the wave propagation between the two sides of the dipole.

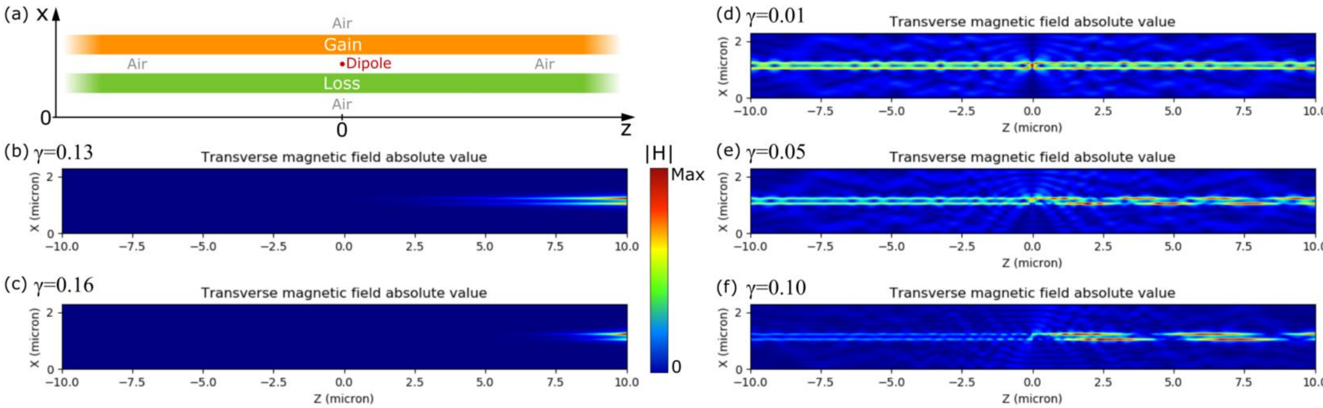

Figure 1 - (a) Schema of the photonic structure used in the simulations. The dielectric gain and loss materials are represented in orange and green respectively and the air in white. The location of the dipole is marked by a red dot. (b-f) Magnetic field absolute value in the structure for γ = 0.13, 0.16, 0.01, 0.05 and 0.10 respectively.

Figures 1(d-f) also show that in the PT-symmetric regime ($\gamma < 0.123$), the field profile in the structure is different when the gain/loss parameter γ varies. For small values of γ, the symmetric mode 1 is as strongly excited on the left as on the right (Fig. 1(d) – γ = 0.01), resulting in similar field strengths on both sides. Then, when γ gets closer to the EP (Fig.1(e,f) – γ = 0.05 & 0.10), the mode 1 strength on the left decreases; the field thus becomes significantly larger on the right side.

In the end, we demonstrate that by using an adequate electric dipole coupled to PT-symmetric waveguides, a contrast in the mode excitation can be obtained between both sides of the dipole. This contrast can be exploited in integrated photonic structures, for example to excite specific waveguides in a directional coupler arrangement: due to the presence of beating on only one side of the dipole, one of the waveguides could be excited on this side, while the waveguides on the non-beating side could be strongly (Fig. 1(d)) or barely (Fig. 1(f)) excited.

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