SENSOR BASED ON AN EXCEPTIONAL POINT IN THE TE-TM OPTICAL COUPLER

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We investigate a gain–loss system of dielectric waveguides operating in the fundamental TE and TM modes, which are orthogonal and therefore exhibit no intrinsic coupling or exceptional points. This property is proposed for sensing applications. A system of coupled dielectric waveguides embedded in a medium with two- or three-dimensional random inhomogeneities is analyzed. We demonstrate that such inhomogeneities break the orthogonality of the TE and TM modes and restore coupling between their electromagnetic field components. As a result, the optical coupler transforms from a single-channel configuration into a dual-channel system, enabling enhanced sensitivity to external perturbations.

PACS: 42.25.Dd, 42.82.Et, 42.88.+h

INTRODUCTION

Optical sensing platforms have undergone significant development owing to their high sensitivity, compact form factor, and inherent immunity to electromagnetic interference [1], making them well suited for applications in environmental monitoring [2, 3], biomedical diagnostics [3, 4], and integrated photonic systems [5]. In particular, dielectric waveguide-based sensors provide precise control over modal properties and light–matter interaction, enabling scalable and high-performance sensing architectures [6].

Recent advances in non-Hermitian photonics [7] have introduced new mechanisms for sensitivity enhancement based on the existence of exceptional points (EPs), defined as degeneracies at which both eigenvalues and eigenvectors of a system simultaneously coalesce. Systems operating in the vicinity of an EP exhibit a nontrivial response to external perturbations, resulting in a characteristic nonlinear scaling of eigenvalue splitting and, consequently, enhanced sensitivity compared to conventional Hermitian systems [8].

In our previous work [9], we demonstrated the absence of a singularity in gain–loss configurations of dielectric waveguides supporting the fundamental transverse electric (TE) and transverse magnetic (TM) modes. Owing to their orthogonal polarization states, these modes do not share components of the electromagnetic field, leading to intrinsically decoupled modal dynamics. This property provides a favorable platform for controlled perturbation-induced coupling and can be effectively exploited in sensing applications.

In this work, we consider a system of coupled dielectric waveguides embedded in a medium characterized by two- and three-dimensional random inhomogeneities (Fig. 1).

The waveguide parameters are selected such that the TE and TM modes are phase-matched at the same operating frequency. The magnitude of the inhomogeneities is defined relative to the optical wavelength to ensure a measurable perturbative effect. In contrast to two-dimensional configurations, three-dimensional systems allow for inhomogeneities along the propagation direction (see as illustrated in Fig. 1), which give rise to radiation losses. These losses originate from the disruption of coherent wave propagation caused by spatial irregularities in the refractive index distribution.

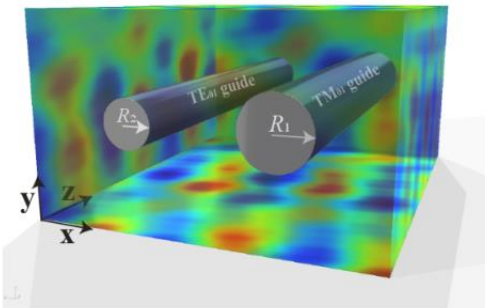

Fig. 1. Coupled dielectric waveguides in a medium with three-dimensional random inhomogeneity

Building upon these considerations, we investigate the emergence of an exceptional point in a TE–TM optical coupler under the influence of random inhomogeneities. The perturbations introduced by the inhomogeneous medium enable effective coupling between otherwise orthogonal modes and facilitate the realization of EP conditions. As a result, the system exhibits enhanced sensitivity to variations in environmental and structural parameters through pronounced changes in its spectral and modal characteristics. This work establishes a theoretical foundation for sensors based on exceptional-point physics in TE–TM coupled waveguide systems and demonstrates the potential of such configurations for high-precision optical sensing in realistic inhomogeneous environments.

RESULTS AND DISCUSSION

The investigated structure consists of coupled dielectric waveguides embedded in an inhomogeneous medium. The system parameters are selected to ensure phase matching between the fundamental transverse electric (TE) and transverse magnetic (TM) modes and to enable the formation of an exceptional point under

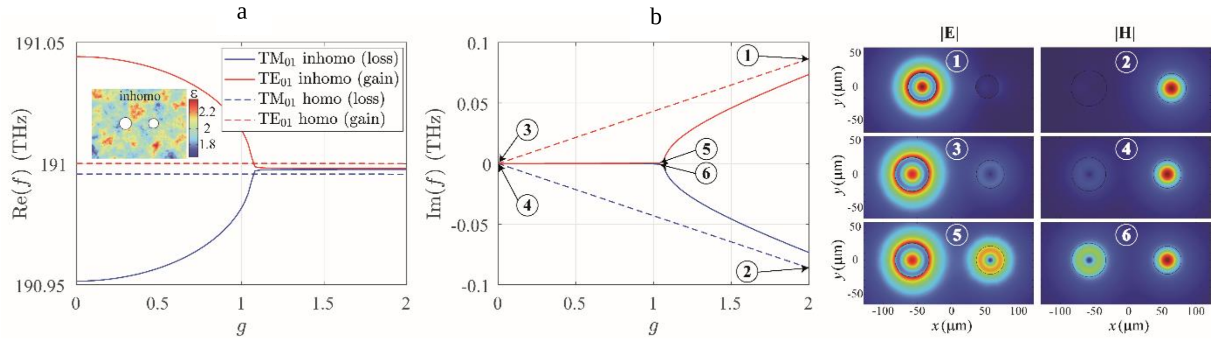

Fig. 2. The real (a) and imaginary (b) parts of the eigenvalues f for the TE_{01} and TM_{01} modes as a function of the gain-loss parameter g between the coupled waveguides. Panels (1)–(6) show the magnitudes of the electric $|\boldsymbol{E}|$ and magnetic $|\boldsymbol{H}|$ fields for the points marked in (b)

perturbation. The waveguide radii are $R_1 = 250$ nm and $R_2 = 207$ nm, while the separation between the waveguides is $d = 700$ nm. The propagation constant is $k_z = 6.374 \cdot 10^6$ m^{-1}. The dielectric permittivities of waveguides are defined as $\varepsilon_1 = 12 - i\,0.01\,g$, $\varepsilon_2 = 12 + i\,0.0065\,g$, where g is the gain-loss parameter. To describe the spatial inhomogeneity of the medium, the Weierstrass-Mandelbrot (W-M) function $W(\boldsymbol{r})$ is employed. The random inhomogeneity of the media $\varepsilon_m(\boldsymbol{r})$ is incorporated into the relative permittivity as

$$\varepsilon_m(r) = a_0 + a_m\,W(\boldsymbol{r}),\ \langle W(\boldsymbol{r})\rangle = 0,\ \sigma\big(W(\boldsymbol{r})\big) = 1.$$

Here the value $a_0 = 2$ is the average of medium inhomogeneity. The value $a_m = 0.1$ is the amplitude of inhomogeneity. The profile of the medium inhomogeneity is shown in the inset of Fig. 2,a. All numerical simulations were performed using the finite-element method implemented in COMSOL Multiphysics, enabling accurate modeling of modal coupling and radiation losses in inhomogeneous media.

Fig. 2,a,b demonstrate the presence of an exceptional point in the TE–TM optical coupler when embedded in an inhomogeneous ambient medium. In contrast, in a homogeneous medium, the waveguides do not interact in the selected fundamental modes. The electric and magnetic field profiles, shown for characteristic points 1–6, reveal a qualitative transition from single- to dual-channel operation. This approach is scalable: by reducing the waveguide size, the operational wavelength can also be scaled down to match the characteristic scale of the medium inhomogeneities. Additionally, increasing the amplitude of the inhomogeneities results in a shift of the EP toward larger gain–loss parameters g. Unlike two-dimensional configurations, three-dimensional systems allow inhomogeneities along the propagation direction (see as illustrated in Fig. 1), which gives rise to radiation losses. These losses originate from the disruption of coherent wave propagation caused by spatial irregularities in the refractive index distribution. This effect must be considered in the design of such systems.

CONCLUSIONS

A system of coupled dielectric waveguides embedded in a medium with two- and three-dimensional random inhomogeneities has been investigated. It has been shown that the presence of such inhomogeneities can break the intrinsic orthogonality between TE and TM modes, thereby enabling coupling between their electromagnetic field components. Furthermore, the introduction of random inhomogeneities modifies the modal interaction dynamics, effectively transforming the system from single-channel to dual-channel operation. This transition arises from perturbation-induced coupling mechanisms.

The obtained results indicate that controlled or intrinsic disorder in the surrounding medium can be utilized as a functional mechanism for mode coupling and sensitivity enhancement. This demonstrates the potential of the proposed system for application in optical sensing technologies, particularly in configurations where high sensitivity to environmental perturbations is required.

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СЕНСОР НА ОСНОВІ ВИНЯТКОВОЇ ТОЧКИ В СИСТЕМІ ТЕ–ТМ-ЗВ'ЯЗАНИХ ХВИЛЕВОДІВ

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Ми досліджуємо систему діелектричних хвилеводів із підсиленням і втратами, що працюють на основних модах ТЕ і ТМ. Ці моди є ортогональними та тому не виявляють внутрішнього зв'язку або виняткових точок. Дану особливість пропонується використати для сенсорних застосувань. Вивчено систему зв'язаних діелектричних хвилеводів, вбудованих у середовище з дво- або тривимірними випадковими неоднорідностями. Показано, що такі неоднорідності порушують ортогональність мод ТЕ і ТМ та відновлюють зв'язок між компонентами їхніх електромагнітних полів. У результаті оптична система переходить від одноканальної до двоканальної конфігурації, що забезпечує підвищену чутливість до зовнішніх збурень.