Photonic-doped Zero-index Media as Coherent Perfect Absorbers

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***Abstract*—Defects usually play an important role in modifying the properties of electronic or electromagnetic materials. Very recently, photonic doping in zero-index media has been proposed by Nader Engheta's group (Science 355, 1058 (2017)), endowing the zero-index media with unprecedented properties of electromagnetic wave manipulation. Here, we theoretically and experimentally demonstrate the realization of coherent perfect absorption by using photonic doping of zero-index media with absorptive defects. Interestingly, such coherent perfect absorption is independent of the size and shape of this photonic-doped zero-index medium absorber, as well as the position of the doping defects. Moreover, such a doping scheme also enables novel ways to control absorption, such as multiple channels and multiple doping defects, etc.**

Keywords—Zero-index media; Photonic doping; Coherent perfect absorption

I. INTRODUCTION

Defects usually play an important role in modifying the properties of electronic or electromagnetic materials. Doping, i.e., intentionally introducing defects into a pure material, is of vital importance in the development of the semiconductor industry and electromagnetic materials. Very recently, the concept and theory of "photonic doping" of a single-zero zero-index medium (SZIM) with only permittivity near zero permittivity [1-2], was first proposed by Nader Engheta's group [1]. In their work, non-absorptive doping defects have been applied to tune the effective permeability of the SZIM as well as the transmission properties. Here, we extend the theory to consider the doping by absorptive defects in double-zero zero-index medium (DZIM) [3], whose permittivity and permeability are both near zero. We first theoretically demonstrate that photonic doping of DZIM can tune the absorption property efficiently and even lead to coherent perfect absorption (CPA), which is known as time-reversed lasing [4, 5]. Then, by constructing the DZIM using a photonic crystal (PhC) with Dirac-cone-like dispersion at the Brillouin zone center and embedding a proper doping defect, we have experimentally realized the CPA via doping of DZIM at microwave frequencies. We show that the doping scheme also enables novel ways to control absorption, such as multiple channels and multiple doping defects, etc. Our work proposes a unique doping approach for advanced coherent perfect absorption with versatile control functionalities.

II. THEORY OF CPA VIA A DOPED DZIM

A. *Effective parameters of doped DZIM*

Firstly, we consider DZIM with both permittivity and permeability near zero. By doping DZIM with several absorptive defects, we aim to realize the intriguing phenomenon of CPA, as illustrated in Fig. 1. The original doping theory was developed only for SZIM with near zero permittivity [1].

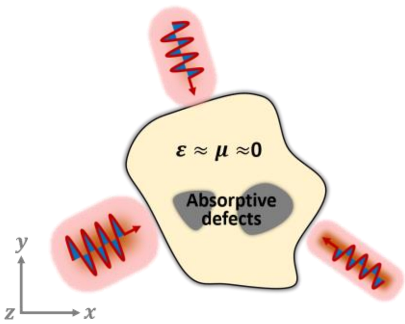

Fig. 1. Illustration of the CPA by using DZIM doped with absorptive defects.

Here, we extend the theory to the case of DZIM. We find that such doped DZIM can also be treated as effective media, whose effective parameters rely on the polarization of incident waves. For example, for the transverse magnetic (TM) polarization with the magnetic field polarized in the z direction, the magnetic field is uniform throughout the DZIM irrespective of the existence of defects, indicating a near-zero effective relative permittivity, i.e., $\varepsilon_{eff} \to 0$. Similarly, for transverse electric (TE) polarization with the electric field polarized in the z direction, the effective relative permeability is still near zero, i.e., $\mu_{eff} \to 0$ due to the constant electric field, while the effective relative permittivity ε_{eff} can be modified by the doping defects as,

$$\varepsilon_{eff} = -\frac{i}{\omega\varepsilon_0 E_0 S}\oint \mathbf{H}_d \cdot d\mathbf{l}\,, \qquad (1)$$

where ε_0 and ω are the permittivity of vacuum and the angular frequency, respectively. E_0 is the uniform electric field within the DZIM. S is the area of the DZIM together with all defects. The term $\oint \mathbf{H}_d \cdot d\mathbf{l}$ denotes the line integral of magnetic fields along the boundaries of all defects.

B. Condition of CPA

Next, we study the CPA condition with TE-polarization using DZIM doped with absorptive defects. From the above analysis, we can see that the doped DZIM can be regarded as an effective medium with effective parameters $\mu_{eff} \to 0$ and ε_{eff} given by Eq. (1). We assume that electromagnetic waves are normally incident onto DZIM from N ($N \geq 1$) different channels with different orientations. The n-th channel has a width of w_n, and is filled with a medium of relative permittivity $\varepsilon_{c,n}$ and relative permeability $\mu_{c,n}$. The amplitudes of the incident waves in difference channels are the same, i.e. E_0, while their phases can be different, as characterized by φ_n in the n-th channel. Then, the condition of CPA can be derived as [6],

$$\sum_{n=1}^{N}\frac{\sqrt{\varepsilon_0\varepsilon_{c,n}}}{\sqrt{\mu_0\mu_{c,n}}}w_n = -\frac{1}{E_0}\oint \mathbf{H}_d \cdot d\mathbf{l}\,, \qquad (2)$$

where μ_0 is the permeability of vacuum. The integral $\oint \mathbf{H}_d \cdot d\mathbf{l}$ represents the line integration along the boundaries of all defects. In the realization of CPA, the geometrical and electromagnetic parameters of the defects such as the size, shape and permittivity can be tuned so that the integral $\oint \mathbf{H}_d \cdot d\mathbf{l}$ satisfies Eq. (2).

III. Simulation and Experimental Results

In the following, we have performed numerical simulations by using software COMSOL Multiphysics to verify the CPA phenomenon. Figure 2 presents the distribution of the electric fields in a three-channel configuration under the incidence of TE polarization. The widths of the two channels are $w_1 = 0.8\lambda_0$ (left) and $w_2 = w_3 = 0.4\lambda_0$ (right). The radius of the defect is $R_d = 0.4\lambda_0$. The permittivity of the defect is obtained based on Eq. (2). From Fig. 2, we can see that all the incident waves are perfectly absorbed by the absorptive defect inside DZIM, demonstrating the behavior of CPA.

Moreover, we have also performed microwave experiments to demonstrate the CPA phenomenon. A dielectric photonic crystal (PhC) with Dirac-cone-like dispersion at the Brillouin zone center is designed to realize the DZIM at the frequency 11.17GHz. In the experiments, we measured the electric field distribution inside the absorptive defect embedded in the center of the PhC array, as shown by the lower inset in Fig. 3, which is almost identical with the simulation results (upper inset in Fig. 3). These results clearly verifies the realization of CPA via the photonic-doped DZIM.

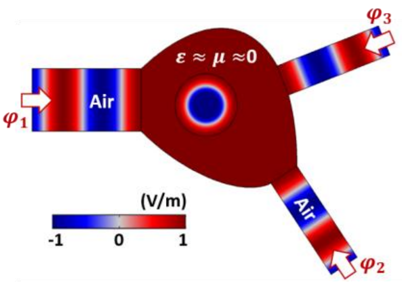

Fig. 2. Electric field-distribution when CPA is achieved within a three-channel model of DZIM with an absorptive defect.

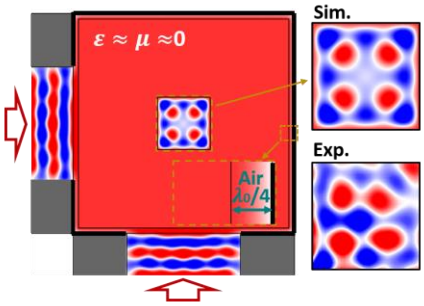

Fig. 3. The simulated electric field distribution in a two-channel model. The right upper and lower panels are the simulated and experimentally measured electric field distribution inside the defect, respectively.

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