Nonreciprocal Perfect Absorber Consisting of Nonlinear Plasma and Matching Metamaterials

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Abstract— A novel, compact and multichannel nonreciprocal absorber through a wave tunneling mechanism in epsilon-negative and matching metamaterials is theoretically proposed. Nonreciprocal absorption properties are acquired via the coupling together of evanescent and propagation waves in an asymmetric configuration, constituted of nonlinear plasma alternated with matching metamaterial. The absorption channel number can be adjusted by changing the periodic number. Due to the positive feedback between nonlinear permittivity of plasma and the inner electric field, bistable absorption and reflection are achieved. Moreover, compared with some designs proposed before, our design is more compact and independent of incident angle or polarization. This kind of multilayer structure offers additional opportunities to design novel ormidirectional EM wave absorbers.

1. INTRODUCTION

The metamaterial perfect absorber has been wildly explored due to the fact that it can achieve unity absorptivity of electromagnetic (EM) waves. The motivation for studying metamaterial perfect absorbers comes mainly from their potential applications in emitters, sensors, spatial light modulators, spectroscopic detectors and wireless communications. The concept of perfect absorber was first proposed by Landy et al. [1] who had explored the electromagnetic response-tailorable ability of metamaterials. As a kind of metamaterials [2], plasma can have a tunable negative permittivity controlled by external parameters. Moreover, nonlinearity takes place easily in plasma metamaterials when the incident wave has a relatively high input intensity [3].

Up to now, some nonreciprocal devices have been investigated using unidirectional transmission or absorption. However, a tunable multichannel nonreciprocal perfect absorber which is insensitive to the incident angle is rare reported. In this paper, an incident angle independent unidirectional absorber with nonlinear plasma and matching double negative material is theoretically proposed. Distinct from the Tamm plasmon-polaritons, our proposed device is composed of nonlinear transparent structure with lossy double negative (DNG) substrate, which is also compact and efficient.

2. STRUCTURE MODEL AND PERFECT ABSORPTION CONDITION

In order to make the EM wave perfect transmit through one dimensional layered device without loss, we chose the plasma-DNG structure (AB^N), where A denotes the plasma, B denotes the matching metamaterial, and N represents the periodic number. The relative permittivity and permeability of layers are assumed to be

$$\varepsilon_A^L = 1 - \frac{\omega_{peA}^2}{\omega(\omega - i\nu_A)}, \quad \mu_A = 1 \tag{1}$$

and

$$\varepsilon_B = 1 - \frac{\omega_{peB}^2}{\omega(\omega - i\nu_B)}, \quad \mu_B = 1 - \frac{\omega_{meB}^2}{\omega(\omega - i\nu_B)} \tag{2}$$

where ω_{peA}, ω_{peB}, and ω_{meB} were assigned as the electronic plasma frequency and magnetic plasma frequency, respectively. ν_A and ν_B are collision frequencies for layers A and B, respectively. The working frequencies were selected to fulfill $\omega < \omega_{peA},\ \omega_{peB}$, and $\omega < \omega_{meB}$. Plasma is assumed to be nonmagnetic ($\mu_A = 1$) and is chosen as a material with a nonlinear Kerr effect. Considering the most powerful $|E|^2$ nonlinear dependence [2], the whole permittivity of the nonlinearity of field-dependent plasma metamaterials is expressed as

$$\varepsilon_A^{NL} = \varepsilon_A^L + \varepsilon_A^{NL} = \varepsilon_A^L + \varepsilon_0 \chi \left|E\right|^2, \tag{3}$$

where χ is the nonlinear coefficient. According to the theory in nonlinear optics [4], the value of χ for gas discharge was was selected at $7.7 \times 10^{-13}\,\mathrm{m^2V^{-2}}$ in the following calculation, which is within the range of $10^{-4} \sim 10^{-5}$ esu ($1\,\mathrm{m^2V^{-2}} \approx 9 \times 10^8$ esu), where $|E|$ is the intensity of the electric field.

In order to absorb most of the EM wave energy transmitted from the above structure, we need to adjust the structure parameters for the last layer. The structure of the nonreciprocal absorber is designed as AB^NA'. Here, layer A' has the same refractive index as A but with different thickness and collision frequency. In the subsequent calculations based on the nonlinear transfer matrix method [5, 6], A and A' are nonlinear plasma layers with $\omega_{peA} = \omega_{peA'} = 100\,\mathrm{GHz}$, $\nu_A = 0$ and $\nu_{A'} = 2.5\,\mathrm{GHz}$. B is matching metamaterial with $\omega_{peB} = \omega_{meB} = \omega_{peA}$, $\nu_B = \nu_A$. The thicknesses $d_A = d_B = 0.5\,\mathrm{mm}$, and $d_{A'} = 2\,\mathrm{mm}$ are selected to study the device performance in the region from microwave to millimeter wave.

3. NONRECIPROCAL ABSORPTION PROPERTIES IN INCIDENT ANGLE INSENSITIVE PLASMA-DNG STRUCTURES

First, we demonstrate the characteristic of the perfect absorption. Without loss of generality, Fig. 1(a) shows the linear reflection, transmission and absorption of the structure ABA' as a function of the incident wave frequency. Obviously, there is a perfect absorption peak with zero transmission and zero reflection at frequency $\omega = 15.42\,\mathrm{GHz}$. This phenomenon is attributed to the effect of the first two transparent layers [7] and the last dissipative layer. To confirm this assumption, the field distributions at $\omega = 15.42\,\mathrm{GHz}$ are calculated and shown in Fig. 1(b). Antisymmetric electric field distribution of the propagation mode is observed in the proposed structure, and they gradually decrease within the last lossy metamaterial.

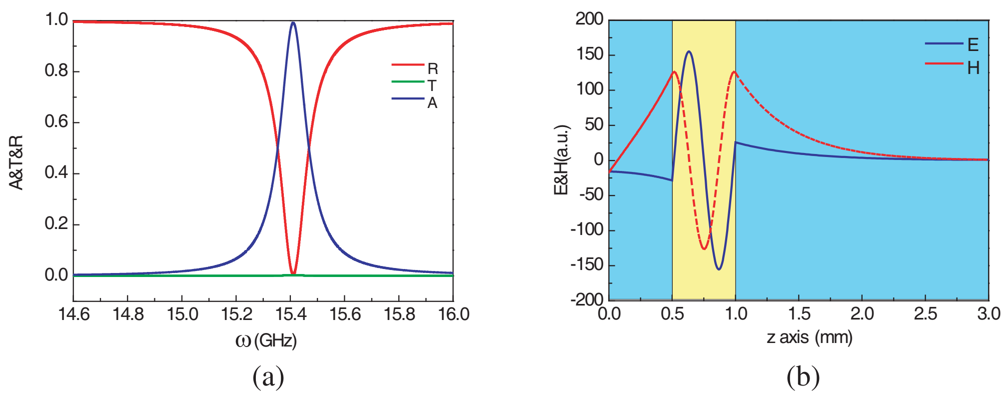
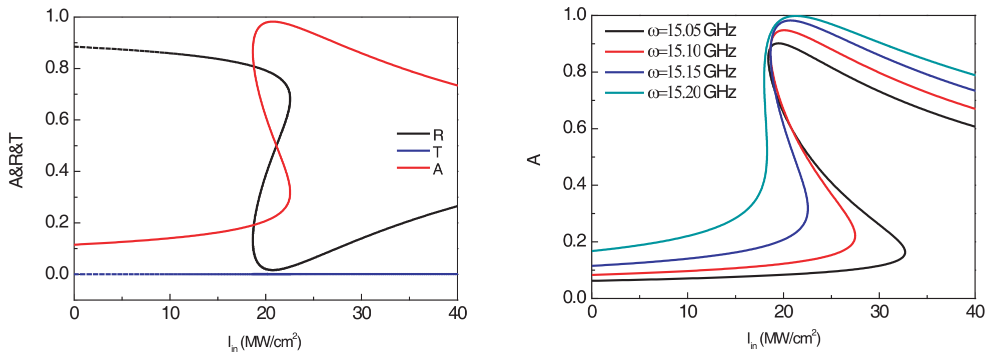


Figure 1: (a) Linear absorption (A), reflection (R), and transmission (T) spectrum of the absorber. (b) Electric (E) and magnetic (H) field distributions in the absorber at $\omega = 15.42\,\mathrm{GHz}$.

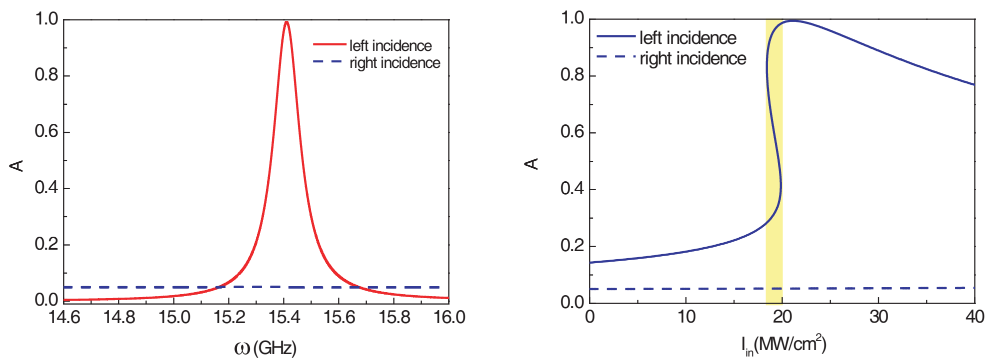
Then we explore the nonlinear performance of the absorber to illustrate its active property since nonlinearity takes place easily in plasma. Fig. 2(a) shows the dependence of the nonlinear performance on the left side wave intensity at $\omega = 15.15\,\mathrm{GHz}$. Not only the nonlinear absorption but also reflection are seen to exhibit bistable behaviors. Because of the nonlinearity of plasma and its loss properties, electromagnetic nonlinearity enhancement in the asymmetric structure will result in nonreciprocal transmission of EM waves. The effect of the incident wave frequency on the bistable absorption behavior is shown in Fig. 2(b). It is found that the critical frequency is 15.18 GHz, and the lower input wave frequency, the higher the critical threshold intensity.

Because of the nonlinearity traits in plasma and its loss characteristics, electromagnetic nonlinearity enhancement in the asymmetric structure leads to nonreciprocal absorption of EM waves. Fig. 3(a) shows the linear absorption spectra of the structure ABA' for both the left and right hand side incident EM waves. Near perfect absorption is observed under left incidence, but little absorption under right incidence. The maximum absorption contrast is 90.5% at $\omega = 15.18\,\mathrm{GHz}$. In Fig. 3(b), as shown from the yellow region of the nonlinear absorption spectra, the absorption under left incidence is at the upper branch, owing to its intensity being beyond the bistable threshold, whereas the absorption under right is at the lower branche because the bistable threshold is not reached.



(a) (b)

Figure 2: (a) Nonlinear absorption (A), reflection (R), and transmission (T) spectra of the absorber with structure ABA' at $\omega = 15.42\,\mathrm{GHz}$. (b) Influence of the input wave frequency to the nonlinear absorption of the absorber.



(a) (b)

Figure 3: (a) Linear and (b) nonlinear absorption of the absorber with structure ABA' for the left and right incidence, respectively.

4. CONCLUSIONS

In this paper, a compact asymmetric nonreciprocal perfect absorber consisting of nonlinear plasma and matching metamaterials has been proposed. The linear and nonlinear absorption, reflection, and the transmission performances of the absorber have been investigated numerically, and exhibit the tunable multichannel nonreciprocal perfect absorption characteristics.

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