The Absorbing Properties of Two-Dimensional Plasma Photonic Crystals

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Abstract Plasma photonic crystals composed of periodic plasma and dielectric materials have attracted considerable attention because of their tunable photonic band gaps, but only their band structures or negative refractive index properties have been addressed in previous works. In this paper, through studying the transmission and reflection characteristics of two types of two-dimensional plasma photonic crystals, it is found that plasma photonic crystals play an important role in absorbing waves, and they show broader band and higher amplitude absorption characteristics than bulk plasmas. Also, the absorption of plasma photonic crystals can be tuned via plasma parameters; varying the collision frequency can make the bandwidth and amplitude tunable, but cannot change the central frequency, whereas varying the plasma frequency would control both the location and the amplitude of the absorbers. These features of plasma photonic crystals have potential for terahertz tunable absorber applications.

Keywords: plasma photonic crystal, absorber, tunable, plasma frequency, collision frequency
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(Some figures may appear in colour only in the online journal)

1 Introduction

Plasmas can be controlled through their parameters, such as the applied voltage, gas pressure, gas temperature and external magnetic field. Plasma photonic crystals, which are composed of periodic plasma and dielectric materials, have attracted considerable attention because of their tunable photonic band gaps. For the one-dimensional (1D) plasma photonic crystals (PPC) that are formed by a periodic distribution of binary plasma and dielectric materials (including a vacuum), investigation of their dispersion and transmission characteristics showed that the photonic band gaps can be effectively tuned through the plasma frequency, plasma length, lattice constant [1,2] and incident angle [3]. For 1D magnetized plasma photonic crystals, the photonic band gaps can be controlled by an external magnetic field in addition to the plasma parameters [4,5]. When the periodicity of 1D plasma photonic crystals was broken by introducing appropriate layer defects, defect modes appeared, which led to applications in tunable filters [6–8].

There are two types of two-dimensional (2D) plasma photonic crystals. Type-I is a structure where plasma rods are arranged in the dielectric periodically, and type-II is a structure composed of dielectric rods in bulk plasma. Sakai et al. experimentally verified the photonic band gap for the millimeter wavelength range [9,10], and also studied the flat bands in transverse electric (TE) polarization using numerical methods [11]. Qi et al. studied the dispersion curves of non-magnetized [12,13] and magnetized [14] structures for both type-I and type-II crystals, and found that the photonic band gap and the flat bands of TE polarization can be tuned by the plasma density, dielectric materials and the external magnetic field. Kong et al. [15] and Zhang et al. [16] researched the band structures of the transverse magnetic (TM) polarization for two-dimensional honeycomb lattice and three-dimensional diamond lattice plasma photonic crystals by the modified plane wave method; the numerical results show that the band structures can be modulated by the plasma parameters.

Recently, the concept of plasma metamaterials, in which plasmas are included in the metamaterials, was proposed [17–19]. Unlike ordinary metamaterials, the dynamic permittivity of these materials can be manipulated by the external power supply used for plasma generation and the adjustable gas pressure and temperature. Besides, a negative refractive index can be obtained in plasma metamaterials [20,21], and electromagnetic waves propagating through these materials

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may suffer significant deformation.

In previous works on periodic structures containing plasmas, only the band structures of plasma photonic crystals or the negative refractive index of plasma metamaterials were studied. In fact, plasma plays an important role in absorption [22–24], the absorption is very poor when the electromagnetic wave frequency is below the plasma frequency, but the absorption can be efficient for higher frequencies through plasma collisions, and there is a maximum absorption value when the wave frequency is near the plasma frequency.

In the following, the absorbing properties of electromagnetic waves in the terahertz band are proposed for two types of 2D plasma photonic crystals. It is found that both structures show a broader band and a higher amplitude than bulk plasmas in terms of wave absorption, and their absorption can be tuned by plasma parameters. As we know, terahertz absorbers have attracted a great deal of interest worldwide during the past few years due to a host of potential applications including detectors, imaging [25], and sensing [26]. In this paper, investigation of the tunable absorbing properties of two-dimensional plasma photonic crystals in the terahertz band may provide a theoretical reference for the fabrication of terahertz absorbers in the future.

2 Design of two-dimensional plasma photonic crystal absorbers

In our calculation, the two-dimensional plasma photonic crystal is simulated by the commercial program HFSS (High Frequency Structure Simulator) [27]. For normal incidence, the electromagnetic wave can be divided into TE polarization, where the electric field is perpendicular to the rod, and TM polarization, where the electric field is parallel to the rod. Fig. 1 shows a schematic view of TE polarization for type-I plasma photonic crystals, the HFSS model refers to a box composed of nine plasma rods, the waveguide ports for transmitting modeling are placed in the front and back of the box. For TE polarization, to obtain a periodic structure based on the image theory [28], perfect magnetic conductor (PMC) boundaries on the top and bottom of the box are set to image plasma rods infinitely in height, and perfect electric conductor (PEC) boundaries on both sides to image the rods infinitely in width. By exchanging the PMC conditions with the PEC conditions, the HFSS model for TM polarization can be obtained. It should be noticed that PEC is an idealization of a good conductor, the PEC boundary can be defined by the conditions \( \mathbf{n} \times \mathbf{E} = 0, \mathbf{n} \cdot \mathbf{B} = 0 \), and PMC is a medium which has no simple physical counterpart but can be used as an idealization of a hole in a dielectric of high permittivity or a body with high permeability. The PMC boundary can be defined by the conditions \( \mathbf{n} \times \mathbf{H} = 0, \mathbf{n} \cdot \mathbf{D} = 0 \), where \( \mathbf{n} \) denotes the unit vector normal to the boundary surface.

![Fig.1 A schematic view of TE polarization for type-I plasma photonic crystals](image)

By obtaining the transmission \( T(\omega) \) and reflection \( R(\omega) \), the absorption \( A(\omega) \) can be calculated from \( A(\omega) = 1 - R(\omega) - T(\omega) = 1 - |S_{11}|^2 - |S_{21}|^2 \). In the following, the effects on the absorptions of the periodic numbers, plasma frequency and collision frequency are analyzed for both type-I and type-II structures. If not otherwise specified, both structures have dimensions given by period \( a = 0.1 \text{ mm} \), radius \( r = 0.2a \), and height \( h = a \), and the plasma frequency and the collision frequency of the plasma are assumed to be \( f_p = 0.6 \text{ THz} \) and \( \nu = 0.2 \text{ THz} \), respectively, where the dielectric is air.

3 Numerical results and discussion

3.1 Type-I structure

Fig. 2 shows the transmission and reflection of two polarizations for (a) type-I, and (b) bulk plasma, where the box shown in Fig. 1 is filled with plasma. The horizontal axis shows the frequency (in terahertz) and the vertical axis denotes the magnitude. The solid and dotted lines denote the transmission and reflection of the TE polarization, respectively, and the dashed and dotted lines denote the transmission and reflection of the TM polarization, respectively. For the TE polarization of the type-I structure, it is found that there is no transmission around 0.4 THz when the reflection magnitude is lower than 0.55, while for the TM polarization, there is a little transmission, with most waves reflected below the cut-off frequency of 0.2 THz. For the bulk plasma shown in Fig. 2(b), there is no difference between the TE and TM polarizations in their reflection and transmission curves, and it can be seen that most transmission takes place above the plasma frequency of 0.6 THz. In fact, the cut-off phenomena of electromagnetic wave transmissions in plasma can easily be seen from the relative dielectric function of
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Therefore, when compared with the TM polarization of type-I structures and that of the bulk plasma, the absorption of the TE polarization for type-I structure has obvious advantages in terms of both the bandwidth and the magnitude.

Physical insights into the absorption in plasma have been offered in several references \[22-24\], where it was reported that the absorption is mainly attributed to the plasma collision processes. To understand the origin of different absorption characteristics between the TE and TM polarizations of type-I structures, their dispersion curves are calculated in Fig. 4 using the modified plane wave method \[12,14\]. The horizontal axis shows the wave vector \(k\) varying along the first irreducible Brillouin zone M-G-X-M, and the vertical axis denotes the frequency in THz. For the TE polarization
in Fig. 4(a), the electric field component normal to the plasma surface excites the surface plasma waves [10]; then, flat bands with near-zero group velocity appear from 0.3 THz to 0.6 THz, and these flat bands excite electromagnetic wave resonance; then, most of the waves around 0.4 THz are absorbed by the plasma collision. For the TM polarization, the electric fields are presented only along the plasma rods, and no surface plasma wave can be excited, but there is a cut-off frequency at 0.2 THz, which is consistent with the transmission and reflection curves shown in Fig. 2(a).

Fig. 5 shows the absorption as a function of the periodic number \( N \) in the transmission direction, where the solid, dot-dashed and dashed lines represent \( N=5, 9 \) and 13, respectively. It is found that there is no shift in either the absorption location or the dips, while the absorption peak increases with increasing periodic number, because more plasma rods are then added to the structure. Fig. 6 shows the absorption varying with the plasma frequency for the TE polarization, where the dot-dashed, dashed and solid lines correspond to the plasma frequencies \( f_p = 0.4 \) THz, 0.5 THz and 0.6 THz, respectively. It is found that with increasing plasma frequency, the absorption shifts towards higher frequencies with broader bandwidths; this tendency can be explained based on the locations of the flat bands relative to the plasma frequency. As shown in Fig. 7, the locations of the flat bands shift towards higher frequencies and the bandwidths increase with increasing plasma frequency.

3.2 Type-II structure

Fig. 8 shows the absorption as a function of the collision frequency for \( R=0.015 \) mm, where the dot-dashed, solid and dashed lines correspond to the collision frequencies \( \nu = 0.05 \) THz, 0.1 THz and 0.6 THz, respectively. As the collision frequency has little effect on the dispersion relations of the structure [3,5], there is no shift in the central absorption frequency when the collision frequency increases from 0.05 THz to 0.6 THz. Because plasma collisions are predominant in the energy absorption of electromagnetic waves, the absorption clearly increases with increasing collision frequency, and the absorption tends to become flat, e.g., the relative bandwidth reaches 27% with absorption above 90% for \( \nu = 0.6 \) THz.
that of the bulk plasma, which is probably caused by the filled plasma in the background. In the first region, the relative bandwidth achieved is 22% for an absorption magnitude over 90%, with a peak larger than 94%, while for type-I structures, the peak is at only 80%, with a wide dip of 50%. For the second region of type-II structures, the peaks and the dip are higher than the corresponding values of the plasma. Therefore, when using the same parameters, type-II structures provide more efficient absorption.

Fig. 9 Absorption of type-I, type-II structures and bulk plasma

Fig. 10 shows the effect of the plasma frequency on the absorption of type-II structures for $R=0.03$ mm, where the dot-dashed, dashed and solid lines correspond to plasma frequencies $f_p=0.4$ THz, 0.5 THz and 0.6 THz, respectively. It can be seen that with increasing the plasma frequency, the absorption shifts to higher frequencies with the two bandwidth regions enlarging. Fig. 11 shows the absorption versus the collision frequency characteristics, where the dot-dashed, solid and dashed lines represent the collision frequencies of 0.2 THz, 0.4 THz and 0.6 THz, respectively. It is clear that with increasing collision frequency, there is little shift in the two absorption regions, but the bandwidth increases, particularly for the second region, which indicates that the plasma collisions cause high absorption.

Fig. 10 Influence of plasma frequency on absorption

Fig. 11 Influence of collision frequency on absorption

4 Conclusion

In conclusion, the absorption characteristics of two types of two-dimensional plasma photonic crystals were studied by using the HFSS software. Compared with bulk plasmas with the same size and plasma parameters, the two types of plasma photonic crystals show much more efficient absorption and the characteristics of type-II structures are superior to those of type-I structures for certain plasma parameters. There is only one absorption region for type-I structures, while there are two regions for type-II structures; the first region has the same location as that of type-I structures but shows wider absorption; the second region has nearly the same location as that of the bulk plasma, but shows a higher amplitude. For both types, variation of the collision frequency can make the bandwidth and the amplitude tunable, but cannot change the central absorption frequency; however, changing the plasma frequency would vary the absorption locations. The two types of plasma photonic crystal studied here would have potential applications in tunable terahertz absorbers.

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