Electromagnetic-Wave Transmittance Characteristics in One-Dimensional Plasma Photonic Crystals

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Transmittance of electromagnetic waves with normal incidence in one-dimensional plasma photonic crystals is studied numerically based on the invariant imbedding method. Wave transmittance as a function of wave frequency shows the appearance of forbidden band gaps, which are conspicuous in photonic crystals. We also demonstrate that the small modification of plasma photonic crystal leads to different transmittance profile with discrete transmission line such as TAE mode in magnetically confined plasmas, which depends on plasma density.

Keywords: plasma photonic crystal, electromagnetic wave, transmission rate, microplasma, forbidden band gap

1. Introduction

Plasma photonic crystal is defined as a periodic array in which discharged plasma and other dielectric material are arranged alternately one-, two-, or three-dimensionally[1-4]. Plasma photonic crystal composed of microplasmas is proposed as a near-coming optical device for controlling electromagnetic waves in millimeter or submillimeter frequency range. Several experimental works on two-dimensional plasma photonic crystals are recently reported[5]. In the present paper, we consider one-dimensional plasma photonic crystals, and study numerically the propagation characteristics of electromagnetic wave in them. We here calculate numerically the transmittance of electromagnetic wave in one-dimensional plasma photonic crystals by using the invariant imbedding method[6]. We find out the forbidden frequency band-gap in the wave dispersion relation and then demonstrate the relationship between the photonic crystal structure and the frequency band-gap structure. The plasma photonic crystals with the frequency band gap can be utilized as frequency filters in millimeter or submillimeter frequency range.

2. Plasma Photonic Crystal Model

In this section, we first consider the modeling of one-dimensional plasma photonic crystals. In Figure 1, we show a model of one-dimensional plasma photonic crystal, which is composed of ten sheet plasma layers and eleven quartz glass layers. We may imagine that plasma is contained in quartz glass box. However, electrodes for plasma production are neglected here. We assume that the thickness of plasma layer is d, and that of quartz glass layer is h, and the plasma is uniform. We also assume that ε_g = 4 as the dielectric constant of quartz glass. The dielectric constant of plasma is the Drude model defined by $\varepsilon = \varepsilon_0 \tilde{\varepsilon}$, where ε_0 is the permittivity of vacuum and $\tilde{\varepsilon}$ is given by eq.(3).

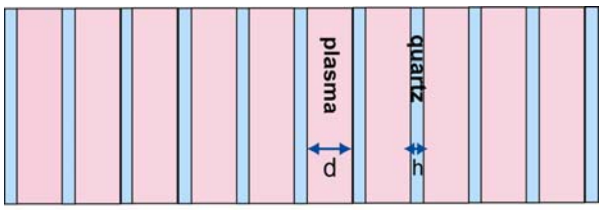

Fig.1 the modeled plasma photonic crystal, where d is the plasma thickness and h the quartz glass thickness.

3. Electromagnetic Wave Transmission Rate

In this section, we calculate numerically the transmission rate of electromagnetic waves in one-dimensional plasma photonic crystals based on the invariant imbedding method[6]. Following to the invariant imbedding method, the wave transmission coefficient a and reflection coefficient b are described by the following equations:

$$\frac{\mathrm{d}}{\mathrm{d}z} a = ik_0 a + \frac{1}{2} ik_0 \left[\tilde{\varepsilon}(z,\omega) - 1\right] a(1+b) , \quad (1)$$

$$\frac{\mathrm{d}}{\mathrm{d}z} b = 2ik_0 b + \frac{1}{2} ik_0 \left[\tilde{\varepsilon}(z,\omega) - 1\right] (1+b)^2 , \quad (2)$$

with

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$$\tilde{\varepsilon}(z,\omega) = 1 - \frac{\omega_{pe}^2}{\omega(\omega + i\nu)}, \qquad (3)$$

where $k_0 = \omega/c$, and ω is the wave frequency, c the light speed, ω_{pe} is the electron plasma frequency and ν the collision frequency. We solve eqs.(1)-(3) with the initial condition at the left-hand side (z = 0) of the one-dimensional plasma photonic crystal:

$$a = 0, \quad b = 1 \quad \text{at} \quad z = 0. \qquad (4)$$

In this case, the wave transmission rate T is given by

$$T = \left| a(z = z_f) \right|^2, \qquad (5)$$

where z_f is the position of the right-hand side of the one-dimensional plasma photonic crystal.

Hereafter, we show the numerical results on the wave transmission rate T. In Fig.2, we show the wave transmittance T as a function of ω for d = 5mm, h = 0.5mm and $n = 10^{11}$cm^{-3}. We find four forbidden band gaps in Fig.2. We show the wave transmittance T in the case of no plasma in Fig.3, where other used parameters are same as those in Fig.2. From the comparison of Figs.2 and 3, we find that the wave transmittance profile in Fig.2 almost overlaps to that in Fig.3 except for the appearance of cutoff due to a plasma effect in Fig.2. The wave transmittance in Fig.2 goes up abruptly from ω = 2~3GHz, while the electron plasma frequencies ω_{pe} being the uniform-plasma cutoff is 2.84GHz for $n = 10^{11}$cm^{-3}. We next show the wave transmittance as a function of ω in the case of $n = 10^{13}$cm^{-3} in Fig.4, where d and h are same as those in Fig.2. We find four forbidden band gaps, however, the band gap frequencies are different from those in Fig.2, and also the band gap widths become larger than those in Fig.2. The cutoff frequency in Fig.4 is about 23.2GHz, while the electron plasma frequency ω_{pe} is 28.4GHz for $n = 10^{13}$cm^{-3}. These discrepancies in Figs.2 and 4 are considered to be due to the actual plasma effect, while a low-density plasma of $n = 10^{11}$cm^{-3} is only contributing to the appearance of cutoff as shown in Fig.3.

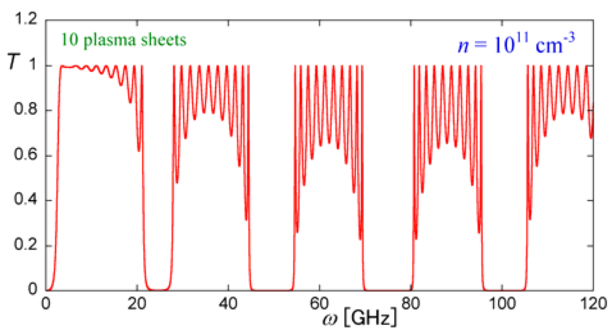

Fig.2 Wave transmittance T as a function of ω, where d = 5mm, h = 0.5mm and $n = 10^{11}$cm^{-3}.

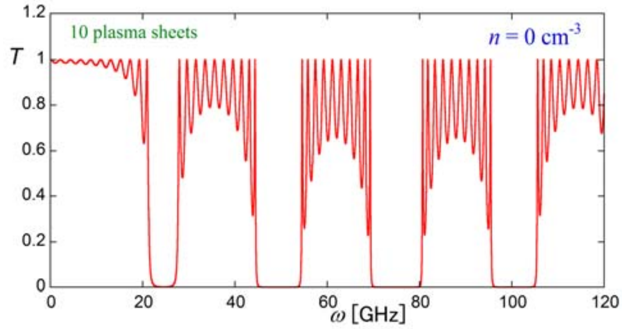

Fig.3 Wave transmittance T without plasma (n = 0) as a function of ω, where d = 5mm and h = 0.5mm.

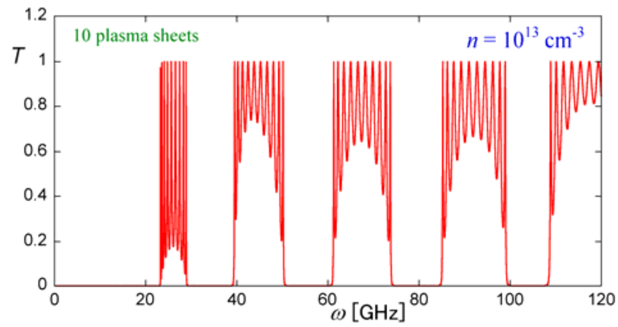

Fig.4 Wave transmittance T as a function of ω, where d = 5mm and h = 0.5mm.

In Figure 5, we show the wave transmittance T as a function of w in a case of 15 plasma layers (and 16 quartz glass layers) for d = 5mm and h = 0.5mm. From the comparison with Fig.2 and Fig.4, the values of forbidden band gaps for 10 plasma layers almost coincide with those for 15 plasma layers, while the fine structure of T in the propagation region are different each other. Therefore, we note that a system of 10 plasma layers is well simulating a realistic photonic crystal, while an ideal photonic crystal has infinite periodicity.

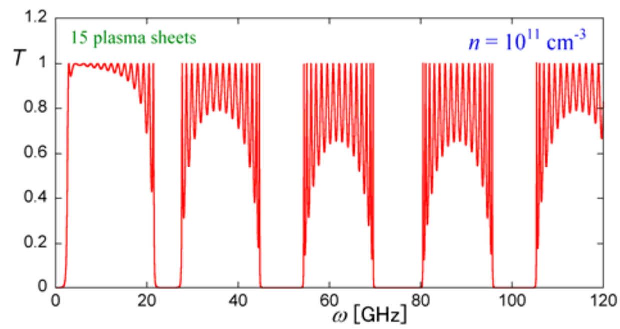

Fig.5 Wave transmittance T as a function of ω in a case of 15 plasma layers, where d = 5mm and h = 0.5mm.

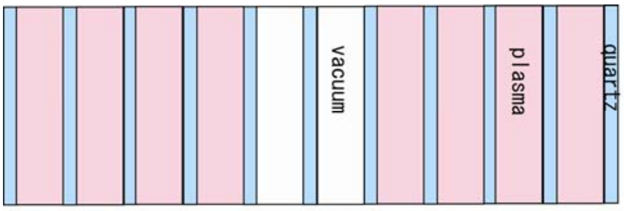

Fig.6 A modified plasma photonic crystal, where the central two plasma layers are replaced by vacuum.

We next consider a modification of one-dimensional plasma photonic crystal shown in Fig.1. In Fig.6, we show one of modified plasma photonic crystals, where the central two plasma layers are replaced by vacuum. Such a configuration can be realized by switching off electrodes for producing the central two plasma layers. In Fig.7, we show the wave transmittance T as a function of ω for the model of Fig.6, where d = 5mm, h = 0.5mm and $n = 10^{11}$cm^{-3}. We see that in this case the transmittance profile (solid line) almost overlaps to that (dashed line) of the model shown in Fig.1. This reason is clear, because a plasma of $n = 10^{11}$cm^{-3} is actually only contributing to the appearance of cutoff in the one-dimensional plasma photonic crystal, as discussed previously in connection with Figs.2 and 3. The actual plasma effect is expected in case of $n = 10^{13}$cm^{-3}. In Fig.8, we show the wave transmittance T (solid line) as a function of ω for the same modified model of Fig.6, where d = 5mm, h = 0.5mm, $n = 10^{13}$cm^{-3}, and the dashed line is for the model shown in Fig.1. In this case, we have a transmittance profile with discrete transmission lines. We find that the discrete transmission lines appear in the forbidden bang gaps generated in the model shown in Fig.1, and also that the fine structure of the transmittance in the model of Fig.6 is rather different from that in the model of Fig.1. The appearance of the discrete transmission line might look like the TAE (Toroidicity-induced Alfven Eigenmode) [7], which is an eigenmode existing in the Alfven continuum spectrum gaps in tokamak plasmas. More actually, this discrete transmission line might be analogous to a localized mode existing in the band gap of two-dimensional photonic crystal with point defect, or, a guided mode existing in the band gap of two-dimensional photonic crystal with line defect. Finally, we note that the plasma photonic crystals with the frequency band gap can be utilized as frequency filters in micro and millimeter frequency range.

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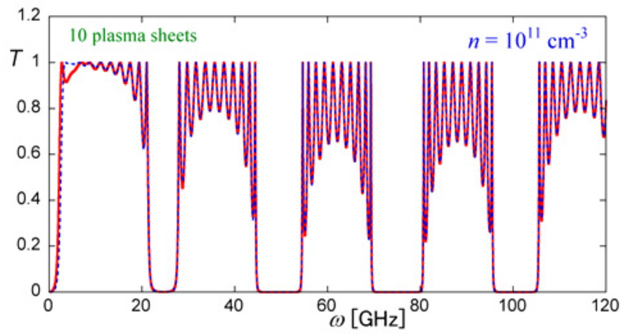

Fig.7 Wave transmittance T (solid line) as a function of ω in the model of Fig.5, where d = 5mm, h = 0.5mm, and $n = 10^{11}$cm^{-3}. The dashed line denotes that for the model of Fig.1.

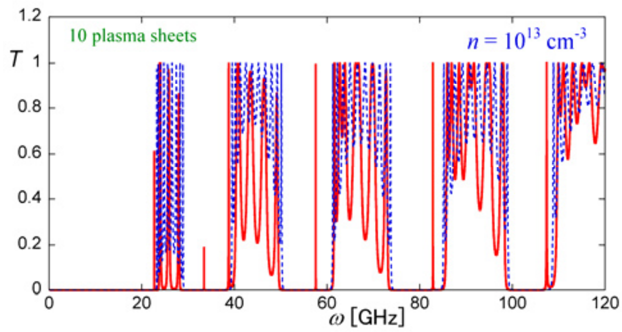

Fig.8 Wave transmittance T (solid line) as a function of ω in the model of Fig.5, where d = 5mm, h = 0.5mm, and $n = 10^{13}$cm^{-3}. The dashed line denotes that for the model of Fig.1.

References

[1] H. Hojo, K. Akimoto and A. Mase, Conference Digest on 28th Int. Conf. Infrared and Millimeter Waves (Otsu, Japan, Sept.28-Oct.2, 2003), 347-348.
[2] H. Hojo and A. Mase, J. Plasma Fusion Res. **80**, 89 (2004).
[3] H. Hojo, N. Uchida, A. Mase, Proc. Joint 30th Int. Conf. Infrared and Millimeter Wave, and 13th Int. Conf. Terahertz Electronics (Williamsburg, USA, 2005), 117-118.
[4] H. Hojo, N. Uchida, K. Hattori and A. Mase, Plasma and Fusion Research **1**, 021-1-2 (2006).
[5] O. Sakai et al., Plasma Phys. Control. Fusion **47**, B617 (2005).
[6] R. Bellman and G. M. Wing, *An Introduction to Invariant Imbedding* (John Wiley & Sons, Inc. 1975).
[7] C.Z. Cheng and M.S. Chance, Phys. Fluids **29**, 3659 (1986).