Beaming of Millimeter Waves from Plasma Photonic Crystal Waveguides

Hitoshi HOJO, Naoto UCHIDA, Kunihiko HATTORI[1)] and Atsushi MASE[2)]

Plasma Research Center, University of Tsukuba, Tsukuba 305–8577, Japan
[1)]*Graduate School of Engineering, Tohoku University, Sendai 980–8579, Japan*
[2)]*Art, Science and Technology Center for Cooperative Research, Kyushu University, Kasuga 815–8160, Japan*

(Received 18 January 2006 / Accepted 24 February 2006)

The beaming of millimeter waves from two-dimensional plasma photonic crystal waveguides is studied numerically based on a finite difference time domain simulation. It is shown that the beaming of millimeter waves is due to coupling with surface lattice modulation in plasma photonic crystals having a glass-rod lattice in the background discharged plasma, while millimeter-wave beaming is due to the horn antenna of plasma rods in plasma photonic crystals having a plasma-rod lattice in a vacuum.

Keywords: plasma photonic crystal, millimeter wave, beaming, photonic crystal waveguide, horn antenna

DOI: 10.1585/pfr.1.021

The photonic crystal is a periodic array in which dielectric materials with different dielectric constants are arranged alternately one- two-, or three-dimensionally. As first proposed by H. Hojo *et al.* [1, 2], the plasma photonic crystal is thus defined as a periodic arrangement of discharged plasma and other dielectric materials, including a vacuum. There are two types of two- dimensional plasma photonic crystal [3]. The first type is a plasma photonic crystal in which cylindrical glass rods forming a crystal lattice are immersed in discharged background plasma (type-1), while the second type consists of cylindrical rods of discharged plasma that constitute a crystal lattice in a vacuum or air background (type-2). The type-2 plasma photonic crystal has been recently realized by O. Sakai *et al.* [4].

In the present study, we consider these two types of two-dimensional plasma photonic crystals, and study the beaming of millimeter waves from plasma photonic crystal waveguides. The beaming of light waves from photonic crystal waveguides has been primarily discussed in Refs. [5–7]. Here we assume square lattice rods with radius R and the lattice constant a. Our analysis is based on the finite difference time domain (FDTD) simulation of the Maxwell equations [8]. The basic equations are Maxwell equations for electromagnetic wave fields $\boldsymbol{E}$ and $\boldsymbol{B}$ and an equation of motion for the induced plasma current $\boldsymbol{J}$, which is approximately given by $\boldsymbol{J} = -en_0\boldsymbol{V}_{\mathrm{e}}$, as we are interested in the frequency region where ions can be assumed to be immobile. That is,

$$\frac{\partial}{\partial t}\boldsymbol{B} = -\nabla \times \boldsymbol{E}, \tag{1}$$

$$\frac{\partial}{\partial t}\boldsymbol{E} = \frac{1}{\varepsilon_{\mathrm{r}}}(\nabla \times \boldsymbol{B} - \boldsymbol{J}), \tag{2}$$

$$\frac{\partial}{\partial t}\boldsymbol{J} = f\boldsymbol{E}, \tag{3}$$

where each physical quantity is normalized as follows: $\omega_0 t \to t$, $\omega_0\boldsymbol{r}/\mathrm{c} \to \boldsymbol{r}$, $\boldsymbol{E}/E_0 \to \boldsymbol{E}$, $\mathrm{c}\boldsymbol{B}/E_0 \to \boldsymbol{B}$, $\boldsymbol{J}/(\varepsilon_0\omega_0 E_0) \to \boldsymbol{J}$, $f = (\omega_{\mathrm{pe}}/\omega_0)^2$, and $\omega_{\mathrm{pe}} = \sqrt{\mathrm{e}^2 n_0/(\varepsilon_0 m)}$ is the electron plasma frequency, and ω_0 is a reference frequency for normalization. For simplicity, we assume that plasma density is constant for both types. For the relative dielectric constant ε_{r}, we assume that $\varepsilon_{\mathrm{r}} = 7.0$ for the glass rods; otherwise, $\varepsilon_{\mathrm{r}} = 1.0$. We also assume $\boldsymbol{J} = 0$ except for plasmas. That is,

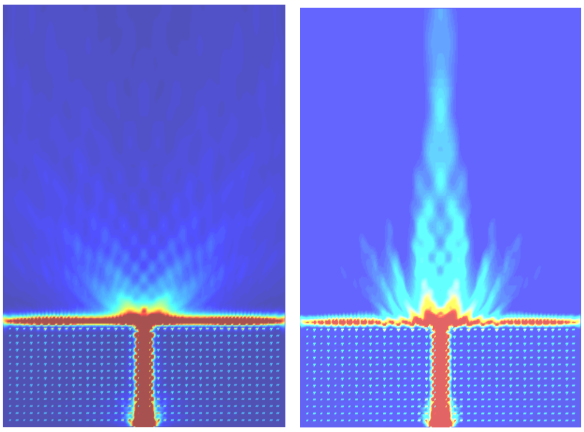
$\varepsilon_{\mathrm{r}} = 1.0$ and $\boldsymbol{J} \neq 0$ for plasma,
$\varepsilon_{\mathrm{r}} = 7.0$ and $\boldsymbol{J} = 0$ for glass,
$\varepsilon_{\mathrm{r}} = 1.0$ and $\boldsymbol{J} = 0$ for vacuum (or, air).

The simulation is performed in the x-z plane, where the waveguide is formed by a line defect, and the wave-guided mode is excited on the lower boundary of x. We impose the out-going wave condition for other three boundaries. We assume a transverse-electric mode (E_{y}) for the excited wave-guided mode.

Hereafter, we show the simulation results. Figure 1 shows a snapshot of the magnitude $|\boldsymbol{S}|$ of the Poynting vector $\boldsymbol{S} = (\boldsymbol{E} \times \boldsymbol{B})/\mu_0$ of a millimeter wave emitted from a type-1 plasma photonic crystal waveguide, with parameters $a = 3\,\mathrm{mm}$, $R = 0.6\,\mathrm{mm}$, $n = 2 \times 10^{12}\,\mathrm{cm}^{-3}$, $\omega/(2\pi) = 45.2\,\mathrm{GHz}$, and $R = 0.3\,\mathrm{mm}$ assumed for the rods of the last layer. As the plasma is underdense ($\omega > \omega_{\mathrm{pe}}$) for wave propagation, the type-1 plasma photonic crystal here corresponds to the conventional photonic crystal composed of glass rods. The surface lattice lies on the straight line in

---

author's e-mail: hojo@prc.tsukuba.ac.jp



(a) Without modulation. (b) With modulation.

Fig. 1 Snapshots of the Poynting vector magnitude $|\boldsymbol{S}|$ of a millimeter wave from a type-1 plasma photonic crystal waveguide without (a) and with (b) surface lattice modulation.

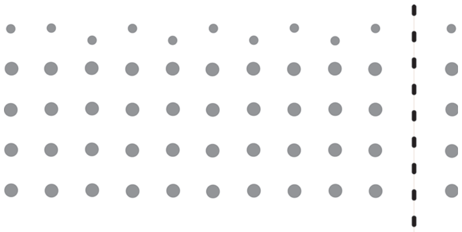
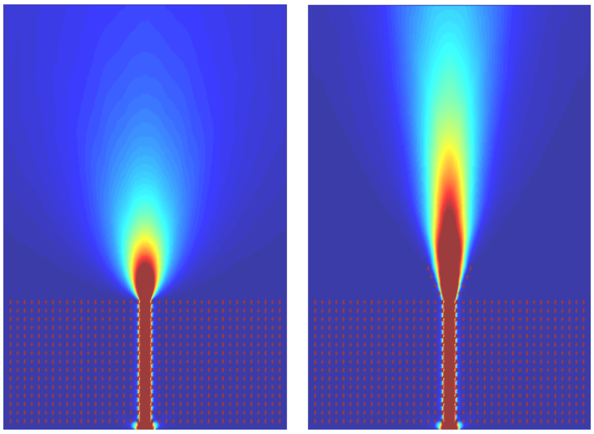


Fig. 2 Structure of the surface lattice modulation shown in Fig. 1. The dashed line shows the waveguide center, and the photonic crystal is symmetrical with respect to the dashed line.

Fig. 1 (a) and in Fig. 1 (b) is modulated as shown in Fig. 2. The magnitude of the modulation is $0.3a$. A comparison of Figs. 1 (a) and (b) shows the effective beaming of the millimeter wave emitted from the plasma photonic crystal waveguide. The effectiveness of the performance is due to the coupling with the surface lattice modulation, as pointed out in Ref. [5].

We next show the simulation results for type-2 plasma photonic crystals. Figure 3 shows snapshots of the Poynting vector magnitude $|\boldsymbol{S}|$ of millimeter waves emitted from the type-2 plasma photonic crystal waveguide, with the parameters $a = 3\,\mathrm{mm}$, $R = 0.6\,\mathrm{mm}$, $n = 1 \times 10^{15}\,\mathrm{cm}^{-3}$, and $\omega/(2\pi) = 43\,\mathrm{GHz}$. In this case, the plasma is overdense ($\omega < \omega_{\mathrm{pe}}$) in order to adjust the permittivity of the plasma to the quite different value of that of a vacuum. Thus, the type-2 plasma photonic crystal here is similar to the photonic crystal composed of metallic rods. However, we have to note that in this case the wave electric field does not vanish on the plasma-rod surface, but partly penetrates into the plasma rods. In Fig. 3, from the comparison of without (a) and with (b) a horn antenna described in Fig. 4, we see that the beaming of emitted millimeter waves becomes possible by the installation of a horn antenna composed of plasma rods. Unfortunately, in this case, the surface lattice modulation seen in Fig. 2 was not effective for beaming a millimeter wave from a type-2 photonic crystal waveguide. Finally, though a photonic crystal with a horn antenna is described in Ref. [6], we should note that there exists a significant difference between this photonic crystal and the present type-2 plasma photonic crystal with regard to the composition of a horn antenna. In the photonic crystal described in Ref. [6], many layers of semiconductor lattice rods are required to form the horn antenna, on the other hand, only one layer of plasma rods is sufficient to form the horn antenna in the type-2 plasma photonic crystal described in the present study.



(a) Without horn antenna. (b) With horn antenna.

Fig. 3 Snapshots of the Poynting vector magnitude $|\boldsymbol{S}|$ of a millimeter wave from a type-2 plasma photonic crystal waveguide without (a) and with (b) a horn antenna composed of plasma rods.

Fig. 4 Structure of horn antenna shown in Fig. 3, where the horn angle is 53.1 degrees. The photonic crystal is symmetrical with respect to the dashed line showing the waveguide center.

[1] H. Hojo, K. Akimoto and A. Mase, *28th Int. Conf. Infrared and Millimeter Waves* (Otsu, 2003) p.347.
[2] H. Hojo and A. Mase, J. Plasma Fusion Res. **80**, 89 (2004).
[3] H. Hojo, N. Uchida and A. Mase, *Joint 30th Int. Conf. Infrared and Millimeter Waves & 13th Int. Conf. Terahertz Electronics* (Williamsburg, USA, 2005) p.117.
[4] O. Sakai *et al.*, Plasma Phys. Control. Fusion **47**, B617 (2005).
[5] E. Moreno *et al.*, Phys. Rev. B **69**, 121402 (2004).
[6] A.R. Weily *et al.*, Phys. Rev. E **68**, 016609 (2003).
[7] A.R. Weily *et al.*, Phys. Rev. E **70**, 037602 (2004).
[8] Q. Chen *et al.*, IEEE Trans. Antennas Propagation **46**, 1739 (1998).