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Scattering of Electromagnetic Waves by an Optically Controlled Subwavelength Slot Grating on a Dielectric Slab

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1. Intruduction

The light illumination to a semiconductor with photon energy greater than the semiconductor's band gap energy make semiconductor plasma induced in the semiconductor and the complex permittivity of the semiconductor change as a function of the plasma density [1]- [2]. Phase shifter , high speed switch, photo-induced plasma grating(PIPG) , broad band electromagnetic wave generating, broad band microwave measurement technology with transient radiation from optoelectronically pulsed antenna, optoelectronically reconfigurable monopole antenna, and so on, have been proposed and researched as microwave and millimeter wave applications of this phenomenon so far [1]- [11].

Especially, researches on Bragg reflction filters, leaky wave antennas, and refletarray antennas using PIPG have been paid attention to [1], [4]- [9]. However, it has been said the carrier diffusion in the semiconductor would make it difficult to design the PIPGs [1], [4], [5]. To resolve this problem, electromagnetic wave scatteing characteristics of an optically controlled infinite periodic slot array on a dielectric slab have been theoretically studied [12]. But the scattering characteristics could be only broadly controlled using photoinduced plasma because the scattering characteristics have been considered only for the period of the order of the wavelength of electromagnetic waves. The author considers electromagnetic wave scattering characteristics of a semiconductor filled periodic slot array with much smaller period than the wavelength of electromagnetic waves could be controlled more flexibly using photoinduced plasma.

In this study, using mode matching technique [13], [12], the author theoretically analyzed electromagnetic wave scattering characteristics of an optically controlled subwavelength infinite periodic slot array on a dielectric slab. And it is discussed about the possibility of the application of the slot array to the optically controlled reconfigurable quasi-optical circuits at millimeter wave frequency band.

2. Theory

2.1 Relative Complex Permittivity of Photoinduced Plasma

The relative complex permittivity of the optically induced plasma region in the semiconductor is given as

$$\varepsilon_p = \varepsilon_s - \sum_{i=e,h} \frac{\omega_{pi}^2}{\omega^2 + \nu_i^2}(1 + j\frac{\nu_i}{\omega}) \tag{1}$$

where ε_s is the relative permittivity of the semiconductor without the plasma and $\nu_e(\nu_h)$ is the collision angular frequnency for electrons(holes). ω is the angular frequnecy of millimeter waves and ω_{pi} is the plasma frequency. The plasma frequency can be expressed as $\omega_{pi}^2 = \frac{n_p e^2}{m_i^* \varepsilon_0}$ $(i = e, h)$ where n_p is the plasma density, e is the electronic charge, $m_i^*(i = e, h)$ is the effective mass of electrons/holes, and ε_0 is the free-space permittivity [1]- [2] .

2.2 Analysis Using Mode Matching Method [13], [12]

A dielectric slab with an infinite periodic slot array filled with a semconductor illuminated with light at L time the interval of the original period of the periodic slot array P is portrayed in Fig. 1. In Fig. 1,

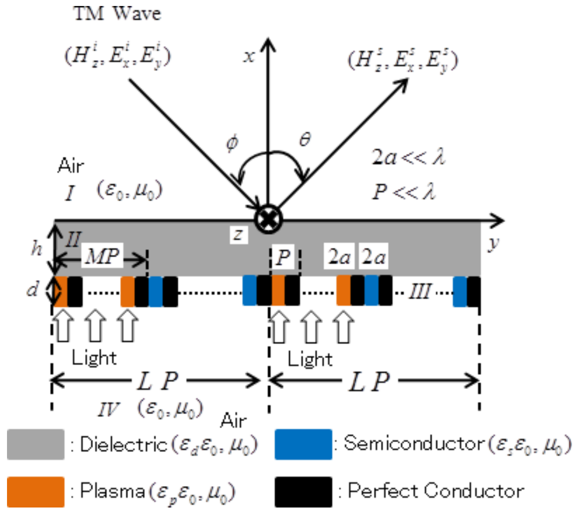

Figure 1: Geometry of an optically controlled subwavelength slot grating on a dielectric slab and TM plane electromagnetic wave incidence.

Both the slot width $2a$and the period of the periodic slot array without light illumination P are assumed to be much smaller than wavelegth of incident electromagnetic wave $\lambda(2a << \lambda, P << \lambda)$. Then, the light illumination makes the total period of the periodic slot array change from $P_{tot} = P$ to $P_{tot} = L \times P$. Photoinduced semiconductor plasma is assumued to be induced to adjacent K slots out of total L slots in the unit cell. In Fig. 1, $2a$, h, d, and P respectively signify the slot width, the dielectric slab thickness, and the slot thickness (or that of the semiconductor, the optically induced plasma), and the period of the infinite periodic slot array without light illumination. Additionaly, ε_s, ε_p, and ε_d respectively signify the relative permittivity of the semiconductor, the plasma, and the dielectric. The author uses a simple model in which the plasma distributes itself uniformly in region $\mathrm{III}^{(l)}$ $(l = 1, \cdots, K)$. The electromagnetic field distribution is, by assumpition, uniform in the z direction, as $(\frac{\partial}{\partial z}=0)$. The time dependence $e^{j\omega t}$ is assumed and suppressed. As described in this paper, the scattering characteristics are analyzed when TM electromagnetic plane wave $(H_{zI}^i, E_{xI}^i, E_{yI}^i)$ with an angle of incidence ϕ illuminates the periodic slot array. The scattered electromagnetic field in Region I $(H_{zI}^s, E_{xI}^s, E_{yI}^s)$, the scattered electromagnetic field in Region II $(H_{z\mathrm{II}}^s, E_{x\mathrm{II}}^s, E_{y\mathrm{II}}^s)$, and the electromagnetic field in Region IV $(H_{z\mathrm{IV}}^s, E_{x\mathrm{IV}}^s, E_{y\mathrm{IV}}^s)$ are given as a summation of space harmonics. The electromagnetic fields in Region $\mathrm{III}^{(l)}$ $(l = 1, \cdots, L)$ are given as a superposition of the modes of the parallel plate waveguide formed between the strips. The matrix equations are obtained by applying the boudary conditions to the tangential components of these electromagnetic fields. These electromagenetic fields are determined by solving the matrix equation. The power reflection coefficients R_n and the power transmission coefficients T_n for the individual modes are defined, respectively, by

$$R_n = \frac{\frac{1}{2P_{tot}} Re\{\int_0^{P_{tot}} (\boldsymbol{E}_n^r \times \boldsymbol{H}_n^{r*}) \cdot \boldsymbol{x}\, dy\}}{\frac{1}{2P_{tot}} Re\{\int_0^{P_{tot}} (\boldsymbol{E}^i \times \boldsymbol{H}^{i*}) \cdot (-\boldsymbol{x})\, dy\}} \quad T_n = \frac{\frac{1}{2P_{tot}} Re\{\int_0^{P_{tot}} (\boldsymbol{E}_n^t \times \boldsymbol{H}_n^{t*}) \cdot (-\boldsymbol{x})\, dy\}}{\frac{1}{2P_{tot}} Re\{\int_0^{P_{tot}} (\boldsymbol{E}^i \times \boldsymbol{H}^{i*}) \cdot (-\boldsymbol{x})\, dy\}} \tag{2}$$

where $\boldsymbol{E}_n^r$, $\boldsymbol{H}_n^r$, $\boldsymbol{E}_n^t$, and $\boldsymbol{H}_n^t$ are the reflected and transmitted fields for mode n. $\boldsymbol{E}^i$, $\boldsymbol{H}^i$ are the incident fields and $\boldsymbol{x}$ is the unit vector along the x axis [14].

3. Numerical Results

The numerical results of the scattering characteristics of a TM electromagnetic plane wave by the optically controlled infinite periodic slot array presented in Figure 1 are discussed in this section In numerical calculations, the semiconductor and the dielectric are assumed respectively to be silicon and quartz.

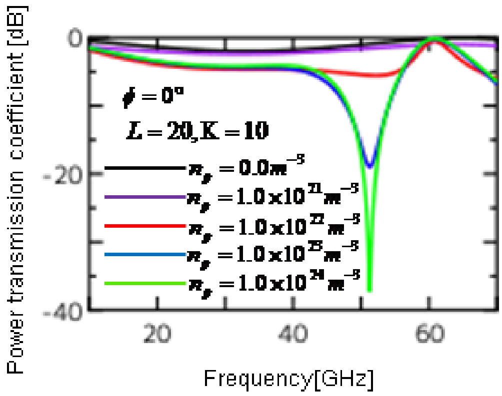

Figure 2: Frequecny dependence of the power transmission coefficient T_0 as a function of plasma density n_p : $h = 1.0mm$, $d = 20\mu m$, $2a = 100\mu m$, $P = 200\mu m$, $\phi = 0°$, $L = 20$, $K = 10$

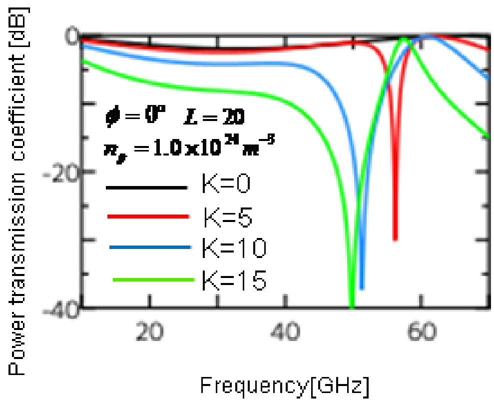

Figure 3: Frequency dependence of the power transmission coefficients T_0 as a function of the number of the slots filled with photoinduced semiconductor plasma K : $h = 1.0mm$, $d = 20\mu m$, $2a = 100\mu m$, $P = 200\mu m$, $L = 20$, $\phi = 0^{circ}$ $n_p = 1.0 \times 10^{24} m^{-3}$

Numerical calculations show the material constants of silicon as $\varepsilon_s = 11.8$, $m_e^* = 0.259m_0(kg)$,$m_h^* = 0.38m_0(kg)$, $m_0 = 9.11 \times 10^{-31}(kg)$,$\nu_e = 4.52 \times 10^{12}(s^{-1})$, and $\nu_h = 7.71 \times 10^{12}(s^{-1})$ [1]- [2] and the relative permittivity of quartz as $\varepsilon_d = 3.8$ [11]. The photoinduced plasma thickness (=silicon thickness=slot thickness) is chosen as $d = 20\mu m$ [2]. In addition, the dielectric slab thickness, the slot width, and the period of the slot array without light illumination are $h = 1.0mm$, $2a = 100\mu m$, $P = 200\mu m$.

Figure 2 portrays the the frequency dependence of the power transmission coefficients T_0 as a function of the plasma density n_p for $L = 20$, $K = 10$. In Figure 2, the notch caused by the resonance anomaly come to be clearly appeared as the plasma density increases. Also, figure 3 portrays the frequency dependence of the transmission coefficient T_0 as a function of the number of the slots filled with photoinduced semiconductor plasma K for $\phi = 0$, $L = 20$, $n_p = 1.0 \times 10^{24} m^{-3}$. In Fig. 3, the frequency band of the notch caused by the resonance anomaly were shited to lower frequency band, as the number of the slots filled with photoinduced semiconductor plasma M increases. These results suggests the periodic slot array could be applied to an optically controlled reconfigurable periodic array.

4. Conclusion

In this study, using mode matching technique, the author theoretical analyzed electromagnetic wave scattering characteristics from a dielectric slab with an infinite periodic slot array filled with a semiconductor in which semiconductor plasma are induced every the interval of the integer time the original period of the slot array on the assumption that the period of the slot array without light illumination would be much smaller than the wavelength of the incident electromagnetic wave . And it was discussed about the possibility of the application of the slot array to the optically controlled reconfigurable circuits at millimeter wave frequency band. It was found that the frequency band at which the resonance anomaly was caused would be controlled by changing the plasma density and the equivalent number of the slots.

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