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Effect of Photoinduced Plasma on Radiation Characteristics of a Vertical Electric Dipole

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***Abstract*—This paper theoretically describes effect of photoinduced plasma on radiation characteristics of a vertical electric dipole(VED) above a dielectric slab backed by a photonically plasma induced semiconductor. The radiation characteristics are analyzed by using spectral domainapproach(SDA) and stationary phase method. And, it is theoretically discussed about the beam steering of electromagetic wave radiated from the vertical electric dipole using photoinduced plasma, changing the strutural parameters, for application to phtonically controlled antennas.**

I. INTRODUCTION

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 The plasma works as loss medium at low density and functions as a good conductor at high density. [1]-[2]. The photoconductive switch has been applied to the high speed switch, the broad band electromagnetic wave generation using optical pulse and the broad band microwave measurement technology with transient radiation from optoelectronically pulsed antennas. Also, the optically controlled phase shifters, the photoinduced plasma gratings, the optoelectronically reconfigurable monopole antenna, and so on have been proposed and researhed so far as an optoelectronically reconfigurable high frequency circuits of which the material parameters and the structural parameters can be non-permanently changed using photoinduced plasma [1]-[5].

Most of theoretical researches on optically controlled microwave and millimeter wave circuis have been conducted for planar circuits [6]-[10]. So, they have been theoretically discussed using only analytical solutions to a horizontal current source. Also, these researches have done mainly for TE electromagnetic waves. The effects of the photoinduced plasma on radiation characteristics of a vertical current source have not been considered, as long as the author knows.

As described herein, using specral domain approach [7]-[10],[12], [13], [15]-[17] and method of stationary phase [12]-[14], radiation characteristics of a vertical electric dipole(VED) above a dielectric slab backed by a photnically plasma induced semiconductor slab are theoretically analyzed. And, the possibility of beam steering of radiated electromagentic waves from the vertical electric dipole is discussed theoretically, changing the structual paramers, for applicalion to photonically controlled antennas.

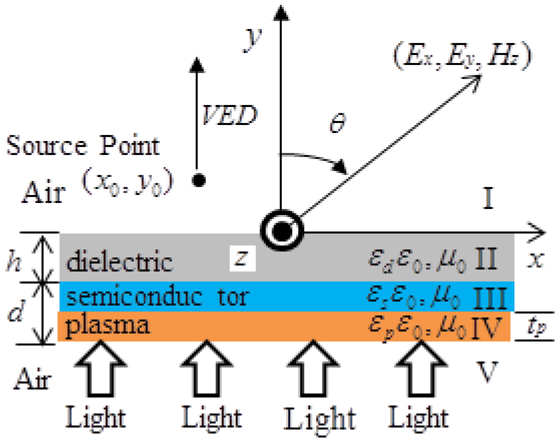


Fig. 1. Geometry of a vertical electric dipole above a dielectric slab backed by a photonically plasma-induced semiconductor slab

II. THEORETICAL ANALYSIS

A. Relative Complex Permittivity of the Photonically Controlled Semiconductor Plasma

The relative complex permittivity of the photoinduced 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 frequency 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] .

B. Theoretical Analysis using Spectral Domain Approach

A vertical electric dipole(VED) in y $(= I_0\delta(x - x_0)\delta(y - y_0)\hat{y})$ above a dielectric slab backed by a photonically plasma-induced semiconductor slab is assumed to be located at (x_0,y_0) as portrayed in Fig. 1. In Fig. 1, the plasma is assumed to be uniformly induced inside the semiconductor by the illuminated light. In Fig. 1, h, d and t_p respectively signify the thickness of the dielectric, the semiconductor without light illumination and the photoinduced plasma layer. The relative permittivity of the dielectric, the semiconductor and the photoinduced plasma are presented respectively ε_d, ε_s and ε_d. The electromagnetic field distribution is, by assumption, uniform in the z direction ($\frac{\partial}{\partial z} = 0$). Then, only the TM electromagnetic wave (E_x, E_y, H_z) is radiated by the vertical electric dipole. The componets of the electromagnetic wave are expressed by the Green's function in the spectral domain. The radiated far-zone fields are obtained by using the method of stationary phase. The stationary point is at $k_x = \sin\theta$ for both the upper space radiation and the lower space radiation. As a result, the far zone magnetic field is

$$H_z(R,\theta) = -\frac{1}{2}\sqrt{\frac{k_0}{2\pi R}}e^{-j(k_0R-\frac{\pi}{4})}F(\theta)e^{jk_x x_0}\sin\theta \qquad (2)$$

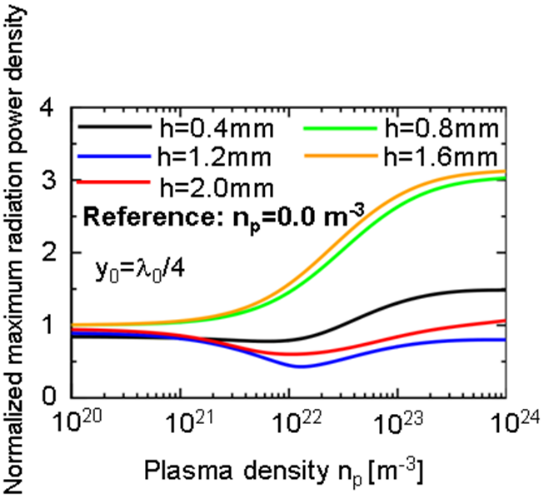
where $k_x = k_0\sin\theta$, $\gamma_I = \sqrt{k_0^2 - k_x^2}$, $R = \sqrt{x^2+y^2}$, $k_0R << 1$.The far zone average radiated power density is expressed by

$$p(R,\theta) = \frac{Z_0}{2}|H_y(R,\theta)|^2 \qquad (3)$$

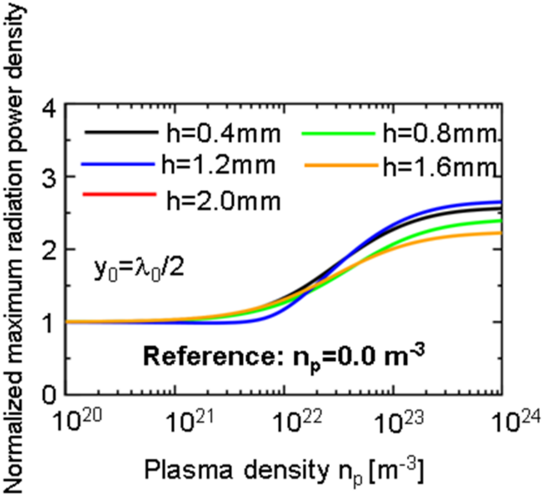
where $Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$.

III. NUMERICAL RESULTS

Numerical results of the characteristics of the vertical electric dipole above a photonically plasma induced semiconductor slab layered on the dielectric slab. In numerical calculations, the semiconductor and the dielectric are respectively assumed to be silicon and quartz. The materials of silicon are $\varepsilon_s = 11.8$, $m_e^* = 0.259m_0(kg)$,$m_h^* = 0.38m_0(kg)$, $m_0 = 9.11\times 10^{-31}(kg)$,$\nu_e = 4.52\times10^{12}(s^{-1})$, and $\nu_h = 7.71\times10^{12}(s^{-1})$ [1]–[2] and the relative permittivity of quartz is $\varepsilon_d = 3.8$ [11]. Also, photoinduced plasma is assumed to be uniformly induced in whole a silicon, and the thickness of silicon layer without light illumination d is chosen to be equal to the thickness of photoinduced plasma layer t_p($d = t_p = 20\mu m$ [2]). And, the numerical calculation results at 94GHz are shown under these assumptions. Then, The wavelength of electromagnetic waves in air λ_0 and The wavelength of electromagnetic waves in quartz λ_d are equal to $\lambda_0 \simeq 3.19mm$ and $\lambda_d \simeq 1.64mm$, respectively. Since photoinduced plasma is expected to make the electromagnetic wave radiated to the lower space only attenuate and the radiation pattern in the upper half space is expected to be symmetrical, the radiation characteristucs are discussed only for the electromagnetic wave radiated to the 1st qudrant ($x \geq 0$, $y \geq 0$, $0° \leq \theta \leq 90°$) in this work.



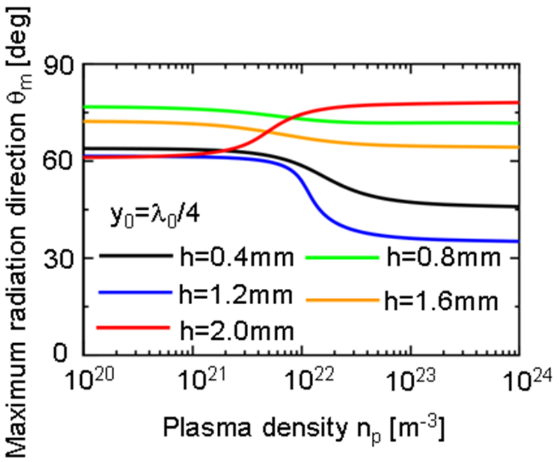
(a) $y_0 = \lambda_0/4$



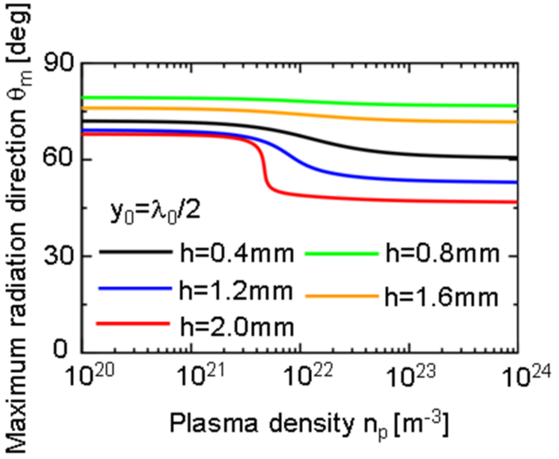
(b) $y_0 = \lambda_0/2$

Fig. 2. Plasma density dependence of the normalized maximum radiation power density $p(R,\theta)$ of a vertical electric dipole above a photonically plasma-induced semiconductor layer superimposed on a dielectric slab as a function of the thickness of the dielectric slab h. ($f = 94GHz$,$\varepsilon_d = 3.8$, $d = t_p = 20\mu m$, $x_0 = 0.0$.)

Figs. 2(a) and (b) show plasma density n_p dependence of the normalized maximum radiation-power density from VED as a function of the thickness of the dielectric h for two values of the source point of VED y_0, fixing $f = 94GHz$,$\varepsilon_d = 3.8$, $d = t_p = 20\mu m$ and $x_0 = 0.0$. Figs. 2 (a) and (b) were calculated for $y_0 = \lambda_0/4$ and $y_0 = \lambda_0/2$. Plasma density dependence of the maximum radiation power seems to be larger in case that VED is located at $y_0 = \lambda_0/4$ than $y_0 = \lambda_0/2$. Specially, it is remarkable when the thickness of the dielectric h is chosen to be an odd multiple of the quarter wavelength in the dielectric $\lambda_d/4$ ($h = (2n+1)\lambda_d/4$,$n = 0, 1, 2, \cdots$). Figs. 3 (a) and (b) show that plasma density n_p dependence of the maximum radiation angle θ_m of the VED as a function of the thickness of the dielectric h for two values of the source point of the VED y_0, fixing $f = 94GHx$, $\varepsilon_d = 3.8$, $d = t_p = 20\mu m$ and $x_0 = 0.0$. Figs. 3 (a) and (b) were calculated for $y_0 = \lambda_0/4$ and $y_0 = \lambda_0/2$, respectively. Plasma density dependence of the maximum radiation angle seem to be larger in case that VED is located at $y_0 = \lambda_0/4$ than

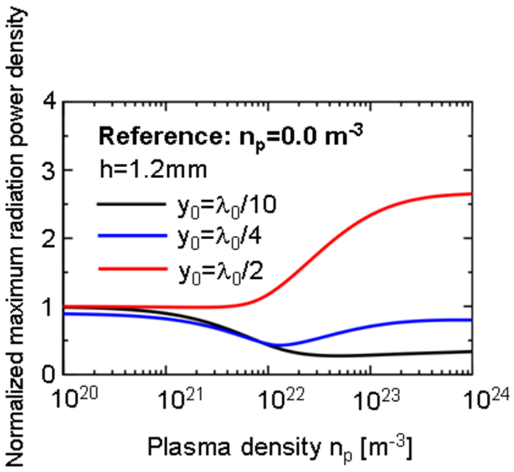


(a) $y_0 = \lambda_0/4$

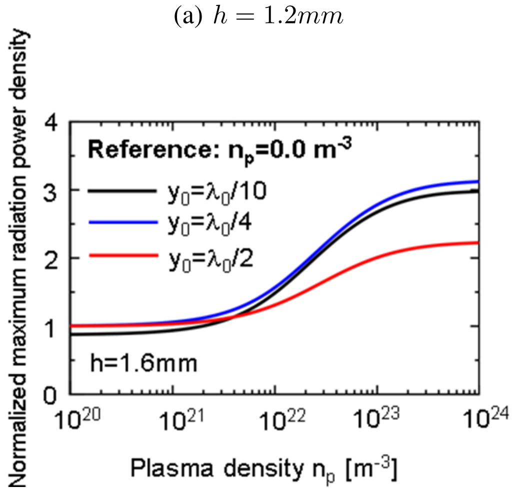


(b) $y_0 = \lambda_0/2$

Fig. 3. Plasma density denpendence of the maximum radiation angle θ_m of a vertical electric dipole above a photonically plasma-induced semiconductor layer superimposed on a dielectric slab as a function of the thickness of the dielectric slab h ($f = 94GHx$, $\varepsilon_d = 3.8$, $d = t_p = 20\mu m$, $x_0 = 0.0$.



(a) $h = 1.2mm$

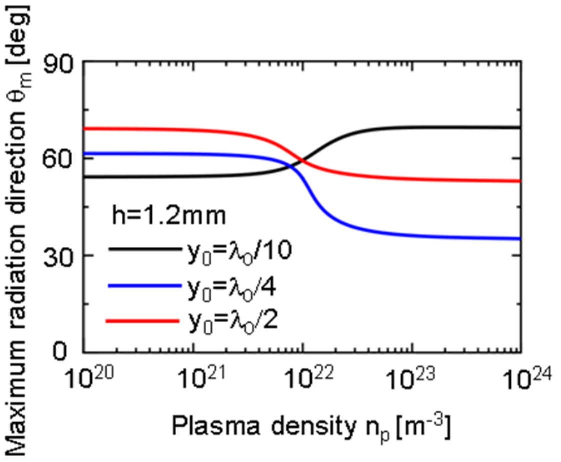


(b) $h = 1.6mm$

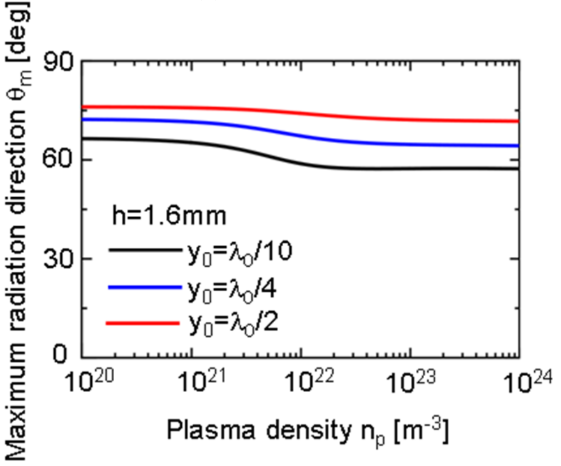
Fig. 4. Plasma density dependence of the normalized maxium radiation power density $p(R, \theta)$ of a vertical electric dipole above a photonically plasma-induced semiconductor layer superimposed on a dielectric slab as a function of the position of the vertical electric dipole y_0 ($f = 94GHz$, $\varepsilon_d = 3.8$,$d = t_p = 20\mu m$, $x_0 = 0.0$).

$y_0 = \lambda_0/2$, too. Specially, it is remarkable when the thickness of the dielectric h is chosen to be an odd multiple of a quarter wavelength in a dielectric. From figure 2 and figure 3, it is expected that the electromagnetic wave radiated from the VED would be remarkly scanned, if the VED is located near a quarter wavelength in air $\lambda_0/4$ ($y_0 = \lambda_0/4$)and the thick of the dielectric h is about odd multiple of a quarter of the wavelength in the dielectric $\lambda_d/4$ ($h \simeq (2n+1)\lambda_d/4$, $n = 0, 1, 2, \cdots$).

Figs .4 (a) and (b) show plasma density dependence of the normalized maximum radiation-power density from VED as a function of the source point of VED y_0 for two values of the thickness of the dielectric, fixing $f = 94GHz$,$\varepsilon_d = 3.8$,$d = t_p = 20\mu m$ and $x_0 = 0$. Figs. 4 (a) and (b) were calculated, repectively for $h = 1.2mm \simeq 3\lambda_d/4$ and $h = 1.6mm \simeq \lambda_d$. In the case of $h = 1.6mm$, the more the photoinduced plasma density increase, the more the radiation power density increase. But in case of $h = 1.2mm$, the more closely the VED approaches to the boundary between air and the dielectric, the more effect the photoinduced plasma comes to have on the maximum radiation power. Probably, the reflection of the electromagnetic wave radiated from the VED would be easily small since $h = 1.2mm$ is close to an odd multiple of a quarter wavelength in the dielectric $\lambda_d/4$ ($h = (2n+1)\lambda_d/4$, $n = 0, 1, 2, cdots$). Figs. 5 (a) and (b) show plasma density dependence of the maximum radiation angle θ_m of the VED as a function of the source point of the VED for two values of the thickness of the dielectric fixing $f = 94GHz$,$\varepsilon_d = 3.8$,$d = t_p = 20\mu m$ and $x_0 = 0.0$. Figs. 5(a) and (b) were calculated, respectively for $h = 1.2mm \simeq 3\lambda_d/4$ and $h = 1.6mm \simeq \lambda_d$. As found from these figures, the maximum radiation direction θ_m is expected to be scanned more by plasma induction in case of $h = 1.2mm$ than $h = 1.6mm$. Also, in case of $y_0 = \lambda_0/4$ of (a) of figure 5, the maximum radiation direction θ_m is scanned most widely. From the numerical-calculation result shown until now, it is expected that the maximum radiation



(a) $h = 1.2mm$



(b) $h = 1.6mm$

Fig. 5. Plasma density dependence of the maximum radiation angle θ_m of a vertical electric dipole above a photonically plasma-induced semiconductor layer superimposed on a dielectric slab as a function of the position of the vertical electric dipole y_0 ($f = 94GHz$,$\varepsilon_d = 3.8$,$d = t_p = 20\mu m$,$x_0 = 0.0$)

direction θ_m could be scanned more widely by choosing the thickness of the dielectric slab h to an odd multiple of a quarter wavelength in the dielectric $\lambda_d/4$ ($h = (2n+1)\lambda_d/4$, $n = 0, 1, 2, \cdots$) and optimizing the source point of the VED y_0.

IV. CONCLUSION

In this paper, radiation characteristics of a vertical electric dipole(VED) above a photonically plasma induced semiconductor layered on a dielectric slab have been theoretically analyzed using specral domain approach (SDA) and method of stationary phase. And, the possibility of beam steering of radiated electromagentic waves from the vertical electric dipole has been theoretically discussed. As the result,it was expected that the maximum radiation direction could be scanned more widely by choosing the thickness of the dielectric slab to an odd multiple of the quarter wavelength in the dielectric and optimizing the source point of the VED.

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