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Directional field enhancement of dielectric nano optical disc antenna arrays

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ABSTRACT

This paper presents a discussion on the directive field enhancement of dielectric disc antenna arrays in optical band. The property of dielectric material is addressed, and field modes in a cylindrical resonator are discussed. It is identified that the fundamental mode of $HE_{11\delta}$ generates the far field with a higher directivity than other modes. More effective field enhancement in the radiation direction could be achieved by using multiple-disc antenna arrays. Simulation examples indicate that the directivity of a disc antenna array varies with the disc spacing. The maximum directivity is observed when the disc spacing is approximately equal to the half of the vacuum wavelength. The maximum directivity can be improved significantly when the disc number is increased.

1. Introduction

Recently nano antennas have received increasing attention in nanotechnology research. Such antennas can be applied in microscopy, spectroscopy, data-communication, and even solar energy harvesting [1–3]. It is known that antennas can be made with a metal or a dielectric material. In the upper microwave band dielectric antennas are favored as they have some advantages such as wider bandwidth, less loss and avoidance of surface waves, compared to metal antennas [4]. In optical band, both metallic and dielectric antennas are utilized practically as unique material properties exhibit in the metallic and dielectric materials [5–8]. The metal in optical frequency actually works as solid plasma, having its own plasma frequency, collision frequency, damping and so on, which result in a complex permittivity with a negative real part. The dielectric, which cannot be described by the Drude model [9], has a frequency-dependent complex permittivity in optical frequency.

Nano antennas can be analyzed using the classical electromagnetic (EM) theory with the parameters of permittivity, wave number and so on; the quantum theory is not used here. The EM equations are considered sufficient in the analysis of electromagnetic fields in nano-material which is characterized with the parameters mentioned previously. In [10], the dielectric waveguide theory was used to discuss the effective length of rod optical antennas. It was found that the effective length was shorter than the physical length of the rods. The equivalent circuit theory derived from the classic EM theory was also used to analyze the electromagnetic fields in nano devices [11–13].

In this paper, the electromagnetic property of dielectric materials in optical band is first described. Using the classical electromagnetic theory, the excited field modes in nano-optical disc antennas are then discussed. The mode with the maximal direct field enhancement is identified. Simulation examples are given to illustrate the coupling effect of discs in disc antenna arrays. An investigation into the effect of field enhancement in disc antenna arrays is presented. Optimal disc spacing for the maximal direct field enhancement in the disc antenna array is discussed.

2. Dielectric material in optical band

Dielectric materials show unique characteristics in optical band. Note that a dielectric material is characterized with relative permittivity $\varepsilon_r(\omega) = \varepsilon_{r1} + i\varepsilon_{r2}$. The real part ε_{r1} and the imaginary ε_{r2} are generally expressed by [6]

$$\varepsilon_{r1}(\omega) = 1 + \chi + K \cdot \frac{\omega_0^2 - \omega^2}{(\omega_0^2 - \omega^2)^2 + (\gamma\omega)^2} \quad (1)$$

$$\varepsilon_{r2}(\omega) = K \cdot \frac{\gamma\omega}{(\omega_0^2 - \omega^2)^2 + (\gamma\omega)^2} \quad (2)$$

where χ is electric susceptibility, K is a constant determined by physical parameters of atoms and electrons in the material, and γ is a damping rate. In (2) and (3) ω_0 is the resonant frequency of electrons within the material, and is generally greater than the frequency of visible light. It is noted from (2) and (3) that the relative permittivity in microwave band has an effective real part with a

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nearly zero imaginary part. When the frequency is increased to the infrared, optical or ultraviolet band, the imaginary part is non-trivial as the frequency is close to the resonant frequency of the material. The relative permittivity tends to be a frequency-dependent complex number with both real and imaginary parts being positive. This has been verified in the measurement [7],

It is known that the real part ε_{r1} represents the capability that of the material holds energy, and the imaginary part ε_{r2} represents the capability that of the material generates the loss of energy. Clearly a dielectric material in optical band loses some energy when it is excited by an EM field source. As the real part of relative permittivity is positive, the dielectric material in optical band can also be used as a resonator. In contrast, plasmonic material (metal in optical frequency) which is characterized by the Drude model has a negative real part. Therefore, an EM wave cannot penetrate into the metal. The following mode analysis for a dielectric waveguide is then inapplicable to metal in optical frequency. Note again that the real part ε_{r1} in optical frequency is larger than that in microwave frequency. The effective wavelength of a dielectric antenna is usually shorter in optical frequency.

3. Analysis of electric field distribution

In microwave band, antennas made of dielectric can effectively radiate EM waves [14]. These antennas work as a resonator. As a resonator is a section of a waveguide, the electromagnetic field around the resonator can be analyzed using the dielectric waveguide theory. Similarly, a dielectric disc antenna in optical band works as a radiative cylindrical dielectric resonator, as illustrated in Fig. 1. The wave propagation within a dielectric waveguide can be supported. The electric field distribution within the dielectric waveguide is determined by the boundary conditions. The equivalent magnetic current yields on the dielectric material as a result of the inner electric field. This current radiates the electromagnetic field from the disc antenna like a traditional metal antenna [11,12].

It is noted that in a dielectric waveguide propagation constant γ is determined from [6],

$$\gamma^2 = k_c^2 - k^2 \tag{3}$$

where wavenumber $k = \sqrt{2\pi f \mu_0 \varepsilon_r \varepsilon_0}$ and cutoff wavenumber $k_c = (\lambda/\lambda_c)k$. Cutoff wavelength λ_c can be computed by enforcing the boundary conditions on the waveguide surface [16]. It is determined by geometry and material properties of the waveguide, and field mode in the waveguide. The complex propagation constant can be expressed by $\gamma = \alpha + j\beta$. Both wave attenuation constant α and wave phase constant β are given by

$$\beta = (2\pi f)\sqrt{\mu\varepsilon_0\varepsilon_{r1}}\sqrt{1-(\lambda/\lambda_c)^2} \tag{4}$$

$$\alpha = -\pi(\varepsilon_{r2}/\varepsilon_{r1})/\left(\lambda\sqrt{1-(\lambda/\lambda_c)^2}\right) \tag{5}$$

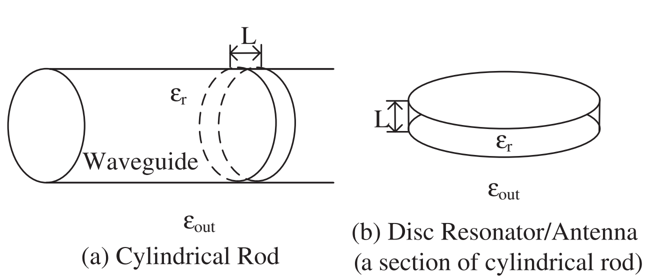

Fig. 1. Cylindrical rod and disc resonator/antenna.

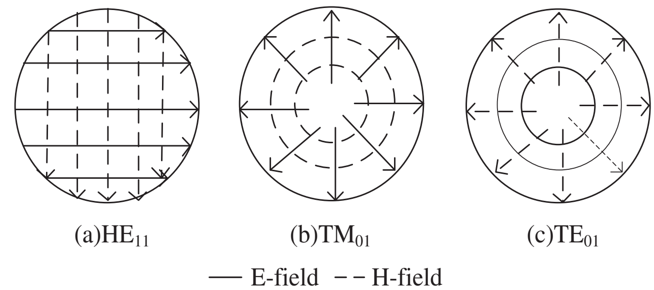

Fig. 2. EM field distributions on the cross-section area of a cylindrical dielectric waveguide or resonator: (a) the fondamental mode of HE_{11} (b) the 2nd mode of TM_{01}, and (c) the 3rd mode of TE_{01}.

For the dielectric material in optical band, both real part ε_{r1} and imaginary part ε_{r2} are positive. Wave propagation in the dielectric waveguide is supported if the wavelength of the electromagnetic (EM) field is less than the cutoff wavelength of the waveguide, as shown in (4). The fundamental field mode in a cylindrical dielectric waveguide is found to be the HE_{11} mode, not the TM_{01} mode appearing in a traditional metallic waveguide in microwave band. Fig. 2 illustrates the field distributions of first three field modes in the cross-section area of a cylindrical waveguide or resonator, which are also applicable to a dielectric circular rod [15]. The numerical analysis in [15] indicates that E-field lines for the mode HE_{11} run in parallel on the cross-section area. The field reaches the maximum value at the central point of the cross-section, and declines when moving away from the central point. For the mode TM_{01} or TE_{01}, the E-field distribution is rotationally symmetric on the cross-section area.

In a circular dielectric waveguide [16], if the attenuation constant of a cladding medium $q = \sqrt{\beta^2 - (2\pi f)^2 \mu\varepsilon_{out}}$ has a complex value (ε_{out} is the permittivity of the medium cladding around the dielectric material, Fig. 1), the EM field can be effectively radiated from the dielectric material to the outer medium. When parameter q has a positive value, the EM wave is confined within the waveguide. No radiation is generated from the waveguide or resonator in this case.

Normally, a cylindrical resonator is considered as a segment of the cylindrical waveguide with the length of $\lambda/2$, as illustrated in Fig. 1. When the cylindrical resonator works as a disc antenna for radiating an EM wave, segment length, which is often defined as δ, is much smaller than $\lambda/2$. The E-field distribution on the cross section area is similar to those given in Fig. 2. The field distribution determines the equivalent magnetic current $M = E \times \hat{n}$ on the surface of a disc antenna [4], which is treated as the radiating source. The disc antenna made of a dielectric material may support the mode $HE_{11\delta}$ [16] while the other modes ($TE_{01\delta}$ and $TM_{01\delta}$) may also be generated. As seen in Fig. 2, the E field has quasi-straight parallel field lines for the mode $HE_{11\delta}$, radial field lines for the mode $TM_{01\delta}$, or circular field lines for the mode $TE_{01\delta}$. The field peak appears in the center for the mode $HE_{11\delta}$, and appears at

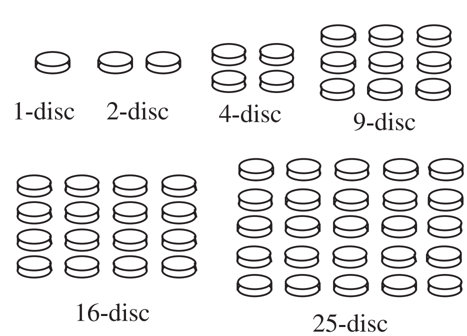

Fig. 3. Configurations of dielectric nano optical disc antennas arrays.