Analysis of Modulation of Optical Near-Fields by Positioning Nanoparticles Based on Angular Spectrum Representation

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Abstract: Optical near-fields can be modulated by engineering the surrounding electromagnetic environment. We theoretically and numerically analyze the modulation of optical near-fields by positioning an embedded nanoparticle using an angular spectrum representation and finite-difference time-domain simulations.

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1. Introduction

Recent advances in optical near-fields have allowed the design of optical devices and systems at densities beyond those conventionally limited by the diffraction of light [1-3]. Basic fundamental processes such as signal transfer via optical near-fields between quantum dots [1] or metal nanoparticles [2] have been studied in detail. Such local interactions of optical near-fields can, however, be altered by controlling the surrounding environment, such as placing metal nanoparticles in the vicinity of the near field, which allows the possibility a system where the electric field can be made to propagate from an electric dipole exclusively to a certain position in space, as schematically shown in Fig. 1(a). In this paper, in order to suitably design the correlation distance of the near field, we analyze the basic system shown in Fig. 1(b) to determine how the electric field at the position P will be affected by positioning a particle M in the system. We use the angular spectrum to represent the optical near-field [4,5] since it allows the spatial positions of the scatterers in the system to be treated explicitly, as well as giving an intuitive picture of how the electric field behaves [5]. Also, since it requires less computational load, it is useful for finding optimum parameters among large parameter sets.

2. Modulating an optical near field by positioning a nanoparticle: Analysis and simulation based on angular spectrum representation

We assume a dipole, $\boldsymbol{d}^{(0)}$, oscillating at a frequency K on an xz plane and oriented parallel to the z axis, as shown in Fig. 1(b). We consider the electric field at position $\boldsymbol{r}_0$ and how it is modulated by changing the position of a particle centered at $\boldsymbol{R}$. The electric field induced by $\boldsymbol{d}^{(0)}$ at position $\boldsymbol{R}$ is given by

$$\boldsymbol{E}^{(0)}(\boldsymbol{R}) = \left(\frac{iK^3}{4\pi\varepsilon_0}\right)\left\{-\frac{1}{3}\left[\boldsymbol{d}^{(0)} - 3\left(\boldsymbol{n}_0 \bullet \boldsymbol{d}^{(0)}\right)\boldsymbol{n}_0\right]h_2^{(1)}(KR) + \frac{2}{3}\boldsymbol{d}^{(0)}h_0^{(1)}(KR)\right\} \tag{1}$$

where $h_n^{(1)}$ represents spherical Hankel functions of the first kind and $\boldsymbol{n}_0$ is a unit vector from the position of dipole $\boldsymbol{d}^{(0)}$ to $\boldsymbol{R}$ [5]. An electric dipole is induced in the particle M, which is given by

$$\boldsymbol{d}^{(S)} = \chi^{(S)}\varepsilon_0\boldsymbol{E}^{(0)}(\boldsymbol{R}) \tag{2}$$

where $\chi^{(S)}$ is the electric susceptibility of the particle, which can be determined by Mie scattering theory, and

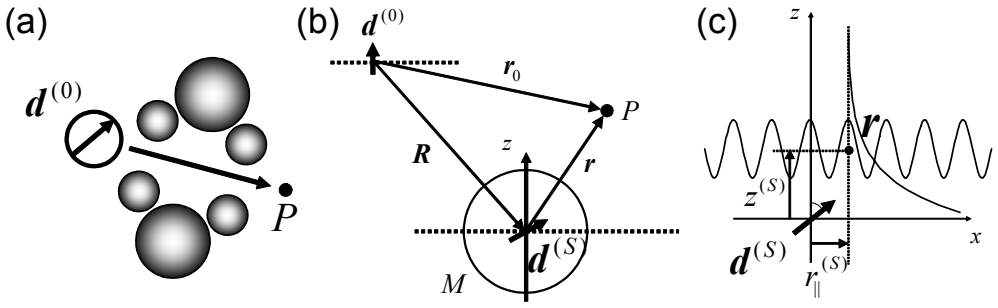

Fig. 1 (a, b) Engineering correlation distances through optical near field interactions by engineering environment. (b) The system of interests to see how the positioning of nanoparticle (M) affects the interaction between the source dipole $\boldsymbol{d}^{(S)}$ and the point P. (c) Angular spectrum representation of optical near-field.

depends on the radius and the refractive index of the particle. Here, we consider the electric field of radiation observed at position $\boldsymbol{r}$ which is displaced relative to the dipole $\boldsymbol{d}^{(S)}$ horizontally (along the x axis) by $r_{\|}^{(S)}$ and vertically (along the z axis) by $z^{(S)}$, as shown in Fig. 1(c). The angular spectrum representation of the electric field in the z direction is given by

$$E_z(\boldsymbol{r}) = \left(\frac{iK^3}{4\pi\varepsilon_0}\right)\int_1^\infty ds_{\|}\frac{s_{\|}}{s_z} f(s_{\|}, \boldsymbol{d}^{(S)}) \tag{3}$$

where

$$f(s_{\|}, \boldsymbol{d}^{(S)}) = \left\{\sqrt{2}d_1^{(S)} s_{\|}\sqrt{s_{\|}^2 - 1}J_1(Kr_{\|}^{(S)}s_{\|}) + d_0^{(S)}s_{\|}^2 J_0(Kr_{\|}^{(S)}s_{\|})\right\}\exp\left(-Kz^{(S)}\sqrt{s_{\|}^2 - 1}\right) \tag{4}$$

where $s_{\|}$ is the spatial frequency of an evanescent wave propagating parallel to the x axis, and $J_n(x)$ represents Bessel functions of the first kind. The coefficients $d_1^{(S)}$ and $d_0^{(S)}$ are given by the inner product of the electric dipole given by eq. (2) and the spherical bases, which are respectively given by $\boldsymbol{e}_1 = -1/\sqrt{2}(1, i, 0)$ and $\boldsymbol{e}_0 = (0,0,1)$. Here we call $f(s_{\|}, \boldsymbol{d}^{(S)})$ the angular spectrum of the electric field.

Now, let the point of interest P be separated from the electric dipole, $\boldsymbol{d}^{(0)}$, by a distance L. The center of the particle, $\boldsymbol{R}$, is separated from the electric dipole $\boldsymbol{d}^{(0)}$ by a distance A horizontally (along the x axis) and a distance B vertically (along the z axis), as shown in the inset of Fig. 2(a). We consider a case KL = 1/2 where K is the wave number. Fig. 2(b) shows the amplitude of the angular spectrum of the electric field as the center of the particle is displaced orthogonally to the x axis by (i) KB = 1/6 and (ii) KB = 1/4, while KA is kept constant at 1/4. We can see that the angular spectrum in case (i) is larger than that in case (ii). Integration of the angular spectrum yields the electric field amplitude. The solid curve in Fig. 2(b) shows the electric field amplitude at point P as the position of the particle is displaced orthogonally to the x axis; it is apparent that the electric field is maximized when the particle is shifted slightly away from the x axis. We also performed numerical calculations based on finite-difference time-domain (FDTD) methods to see how the calculation results agreed with those obtained through the angular spectrum analysis. The operating wavelength used in FDTD simulations was 488 nm, and an Ag nanoparticle was assumed for the particle M. L was 40 nm. The square marks in Fig. 2(b) show the amplitude of the electric field at point P calculated by FDTD, which shows the same behavior as the angular spectrum method.

Since the angular spectrum method has much lower computational demands compared to the FDTD simulations as well as giving an intuitive physical picture, it may be useful in finding optimum values from a large number of parameters for designing a nanophotonic system; an example of this is illustrated in Fig. 2(c), where the electric field amplitude at the point P is evaluated as the position of the particle is displaced both vertically and horizontally.

In summary, we have shown an analysis of an optical near field based on the angular spectrum representation to determine how the near field is affected by the position of a nearby nanoparticle. Based on this analysis, we are now considering a method which will allows us to engineer correlation distances by suitably arranging multiple metal nanoparticles.

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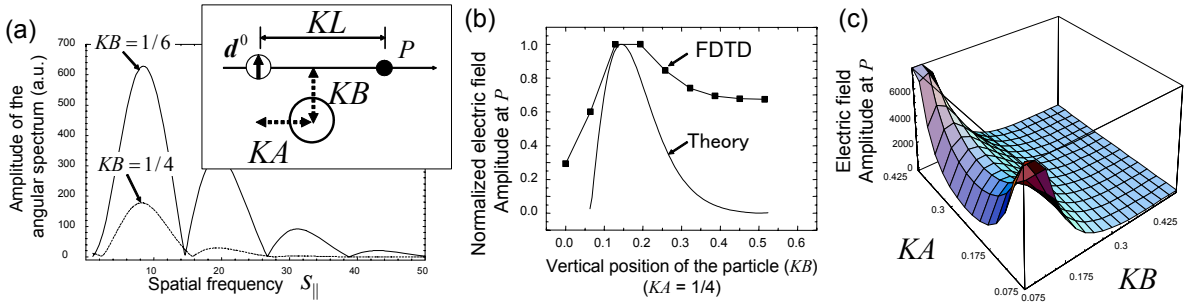

Fig. 2 (a) Parameters for the position of the particle and angular spectrum examples. (b) Amplitude of the electric field at P. (d) Calculated electric field amplitude based on angular spectrum as the position of the particle is displaced both horizontally and vertically.