Analysis of Hierarchy in Optical Near-Fields based on Angular Spectrum Representation

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Abstract: Optical near-fields exhibit different behavior at different scales, which allows designs of hierarchical systems. Based on the angular spectrum representation, hierarchy in optical near-fields is theoretically analyzed and its application to memory retrievals are demonstrated.

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1. Introduction

Recent advances in near-field optics and sub-wavelength-precision fabrication technology allow the design of optical devices and systems at densities beyond those conventionally limited by the diffraction limit of light [1, 2]. This higher integration density, however, is only one of the benefits of optical near-fields over electronics. Another aspect that could be exploited in devices and systems is the physical hierarchy of optical near-fields, in other words, the different physical behavior of the system at different scales. In our previous work [3], we theoretically and experimentally demonstrated hierarchical optical memory retrieval using scale-dependent hierarchy based on a simple dipole-dipole interaction. Suppose, for example, that we have several nanometer-size particles as a physical medium. Those nanometer-size particles can be nicely resolved by scanning a fiber probe with a size comparable to the size of particles to be observed. By using a larger-diameter fiber probe instead, we cannot resolve the detailed distribution of the particles, but we can extract certain features with a resolution comparable to the size of the probe, or the number of particles within the region-of-interest, as schematically shown in Fig. 1(a). Thus, we can see a scale-dependent physical hierarchy in this framework. Such early work, however, demonstrates only a part of the potential capability of optical near-fields. In fact, there is a serious limitation when we associate this physical hierarchy with an information hierarchy, as will be described below. In this paper, we take another approach; that is, we represent the hierarchy in optical near-fields with an angular spectrum, which allows more general treatment and enables functions that are not achievable under the simple dipole-dipole interaction scheme.

In the dipole-dipole interaction model, we can have a logical hierarchical architecture in the sense that the signal obtained in the "upper" layer is the sum of the signals obtained in the lower layer, as schematically shown in Fig. 1(b). Therefore, for example, it is impossible to have situations such as (1) retrieving a logical ONE in the first layer and a logical ZERO in the second layer (Fig. 1 (c)), or (2) retrieving a logical ZERO in the first layer and a logical ONE in the second layer, and so forth. In this paper, by employing angular spectrum representations, we also demonstrate how to arbitrarily associate the first and second layer information with the physical medium.

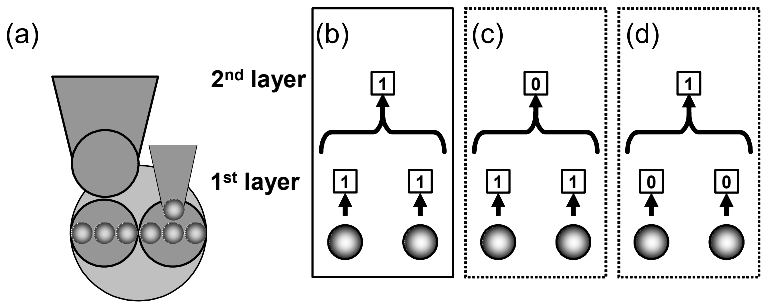

Fig. 1 (a) Scale-dependent hierarchy in optical near-fields. (b, c, d) Schematic diagrams of logical hierarchy. By using angular spectrum representation of optical near-fields, we can retrieve information, as shown in (b), (c), and (d).

2. Angular spectrum representation of optical near-fields

We use an angular spectrum representation of electromagnetic fields [4], which is useful to describe optical near-fields [5, 6]. One of the merits of the angular spectrum representation in analyzing hierarchy in optical near-fields is that it explicitly contains the physical parameters that are associated with the position or scale of the observation.

Suppose for example that we have an oscillating electric dipole, $\boldsymbol{d}^{(k)}$, on the xz plane. It is oriented with respect to the z axis by angle $\theta^{(k)}$, as shown in Fig. 2(a). We consider the electric field of radiation observed at position $\boldsymbol{R}$ which is displaced relative to the dipole, horizontally (along the x axis) by $r_{\parallel}^{(k)}$ and vertically (along the z axis) by $z^{(k)}$, as shown in Fig. 2(a). The angular spectrum representation of the electric field in the z direction is given by

$$E_0(r) = \left(\frac{iK^3}{4\pi\varepsilon_0}\right)\int_1^{\infty} ds_{\parallel} \frac{s_{\parallel}}{s_z} f(s_{\parallel}, \boldsymbol{d}^{(k)}) \tag{1}$$

where

$$f(s_{\parallel}, \boldsymbol{d}^{(k)}) = \left|\boldsymbol{d}^{(k)}\right| \left\{ s_{\parallel}\sqrt{s_{\parallel}^2 - 1}\, J_1(Kr_{\parallel}^{(k)} s_{\parallel}) \sin\theta^{(k)} + s_{\parallel}^2 J_0(Kr_{\parallel}^{(k)} s_{\parallel}) \cos\theta^{(k)} \right\} \exp\left(-Kz^{(k)}\sqrt{s_{\parallel}^2 - 1}\right) \tag{2}$$

where $s_{\parallel}$ 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. Here we call $f(s_{\parallel}, \boldsymbol{d}^{(k)})$ the angular spectrum of the electric field.

3. Theory and simulation of hierarchy in optical near-fields

Suppose that two closely separated dipole moments, $\boldsymbol{d}^{(k)}$ (k=1,2), whose orientation, $\theta^{(k)}$, is either $\pi/2$ or $-\pi/2$, are located on the x axis. We consider the electric field at a position equidistant to $\boldsymbol{d}^{(k)}$ (k=1,2). When those dipoles have the same orientation, namely $\theta^{(1)} = \theta^{(2)}$, the sum of the angular spectrum will be zero since $f(s_{\parallel}, \boldsymbol{d}^{(1)}) = -f(s_{\parallel}, \boldsymbol{d}^{(2)})$. On the other hand, the sum of the angular spectrum will be non-zero if $\theta^{(1)} = -\theta^{(2)}$. Therefore, we can associate those two cases with information retrieval of a logical ZERO level and a logical ONE level, respectively. In the case of $\theta^{(1)} = -\theta^{(2)}$, we should also note that the electric field intensity will be maximized at a certain distance from the x axis. As shown in Fig. 2(b), the distance from the x axis, denoted by z, at which the electric field intensity is maximum increases as the separation between the two dipoles, $2\times r$, increases. This is one of the physical manifestations of a physical hierarchy of optical near-fields.

Furthermore, such an approach suggests an application to hierarchical memory systems where we can retrieve information depending on the physical scale of the observation. We begin with an example of retrieving a logical ZERO by observing very close to the dipoles (we call this "first layer" retrieval), and retrieving a logical ONE by observing relatively far from the dipoles ("second layer" retrieval). Suppose that we have closely separated dipoles, $\boldsymbol{d}^{(1)}$ and $\boldsymbol{d}^{(2)}$, whose orientations are given by $\theta^{(1)} = \theta^{(2)} = \pi/2$, and another dipole pair, $\boldsymbol{d}^{(3)}$ and $\boldsymbol{d}^{(4)}$, having orientations opposite to $\boldsymbol{d}^{(1)}$ and $\boldsymbol{d}^{(2)}$, or $\theta^{(3)} = \theta^{(4)} = -\pi/2$. Now, at a position close to the x axis equidistant from $\boldsymbol{d}^{(1)}$ and $\boldsymbol{d}^{(2)}$, such as at the position **A** in Fig. 2(d), the total electric field is ZERO since the sum of the angular spectrum vanishes because $\theta^{(1)} = \theta^{(2)} = \pi/2$ and the electric field originating from $\boldsymbol{d}^{(3)}$ and $\boldsymbol{d}^{(4)}$ is small. In fact, as shown in Fig. 2(c), when the angular spectrum at position **A** oscillates, the integral of the angular spectrum, which is correlated to the field intensity at that point, will be low. We then consider the second layer retrieval, which is the observation at the intermediate position between those dipole pairs, such as at the position **B** in Fig. 2(d). From this position, the four dipoles effectively appear to be two dipoles that are oriented in opposite directions to each other. Therefore, we can

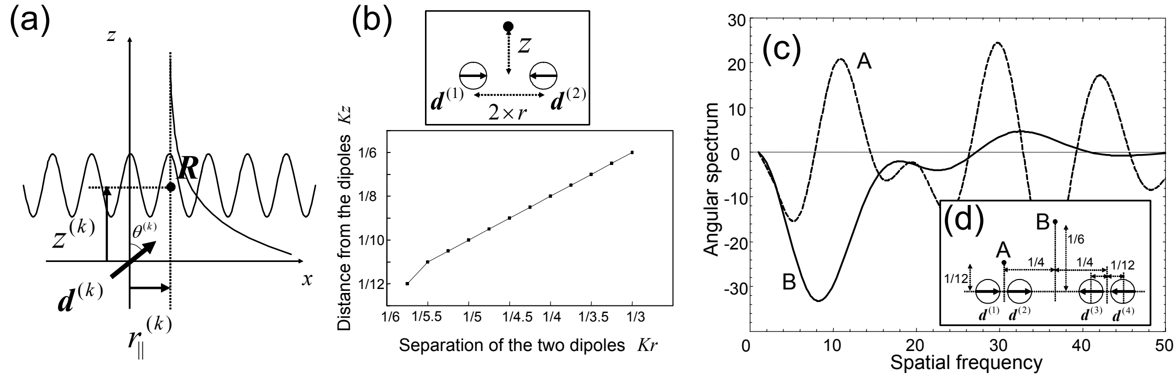

Fig. 2 (a) Angular spectrum representation of optical near-fields. (b) The position at which the electric field is maximized depends on the separation of the two dipoles. (c) Angular spectrum obtained at positions **A** and **B** in (d).

retrieve a logical ONE level at this position **B**. In fact, as shown in Fig. 2(c), the angular spectrum shows a peak value, meaning that the electric field is localized to some degree [5]. To summarize the above mechanisms, we can retrieve a logical level of ONE in the second layer, even though the pieces of information retrieved in the first layer are two ZEROs.

In such logical two-layer signal retrieval, there are a total of six different signal combinations, as summarized in Fig. 3(a). One of the two first-layer signals depends on the dipole pair $\boldsymbol{d}^{(1)}$ and $\boldsymbol{d}^{(2)}$, and the other depends on the dipole pair $\boldsymbol{d}^{(3)}$ and $\boldsymbol{d}^{(4)}$. The signal in the second layer depends on combinations of those four dipoles. We have a logical ONE in the second layer because $\theta^{(1)}=-\theta^{(4)}$ and $\theta^{(2)}=-\theta^{(3)}$ (Case 1 and 3). Retrieving a logical ZERO in the second layer corresponds to $\theta^{(1)}=\theta^{(4)}$ and $\theta^{(2)}=\theta^{(3)}$, as summarized in Cases 2 and 4. Distinguishing the signals between Case 5 and Case 6 is not explained by the above rule, but we can distinguish them based on the fact the electric field originating from closely positioned dipoles, namely $\boldsymbol{d}^{(2)}$ and $\boldsymbol{d}^{(3)}$, is larger than that from $\boldsymbol{d}^{(1)}$ and $\boldsymbol{d}^{(4)}$, as summarized in Cases 5 and 6 in Fig. 3(a).

We also performed numerical simulations based on finite-difference time-domain methods to see how they agree with theoretical angular spectrum representations. We sassumed four metal nanoparticles (diameter of 10 nm) in the system in order to simulate dipoles. Their positions are shown in Fig. 3 (b). The operating wavelength was 488 nm. The distributions of the electric field intensity along the *z* axis are shown for Cases 2 and 3, where the expected intensity profiles are observed when retrieving both the first and the second layer signals. The electric field amplitude at the position indicated by a circular mark in Fig. 3(b) was evaluated for each of the six cases. They show good agreement with the values derived from the theory, as summarized in Fig. 3(a).

4. Conclusion

We show an analysis of hierarchy in optical near-fields based on an angular spectrum representation of electric fields and demonstrate its application to hierarchical memory retrieval. We are currently performing further theoretical analyses of the hierarchical properties of optical near-fields as well as experimental demonstrations using semiconductor quantum wires.

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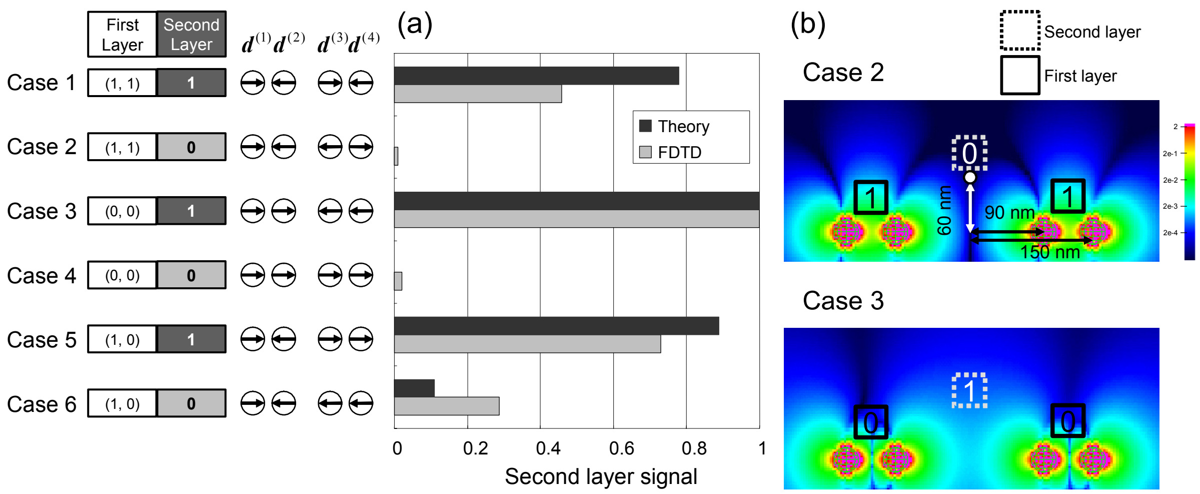

Fig. 3 Hierarchical retrieval of signals from an array of electric dipoles. (a) Theoretical analysis based on angular spectrum representation and FDTD simulations agrees well. (b) Examples of intensity distributions obtained by FDTD simulations.