Subwavelength Optical Imaging through a Metallic Nanorod Array

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(Received 19 July 2005; published 28 December 2005)

We propose a subwavelength imaging system without a lens or a mirror but with an array of metallic nanorods. The near-field components of dipole sources were plasmonically transferred through the rod array to reproduce the source distribution in the other side. We calculated the field distribution at the different planes of imaging process using the finite-difference time-domain algorithm and found that the spatial resolution was 40 nm given by the rod size and spacing. A typical configuration is a hexagonal arrangement of silver rods of 50 nm height and 20 nm diameter. We also show that the image formation highly depends on the coherence and the polarization of the source distribution and the source-array distance.

DOI: 10.1103/PhysRevLett.95.267407
PACS numbers: 78.20.Bh, 78.66.Bz, 42.25.Bs, 42.82.Et

A metallic nanostructure with a distinct shape and arrangement exhibits interesting optical properties and has potential for a variety of applications in imaging, lithography, optoelectronic devices, and biosensors [1,2]. It is well known that gold nanoparticles in glass exhibit a reddish color and their mechanism and spectral response were thoroughly studied by Maxwell-Garnett in 1904 [3]. In 1994, Kawata and Inouye proposed the use of a sharpened metallic tip as a probe in near-field scanning optical microscopy [4]. This configuration has been applied to nanoimaging and analysis, including infrared absorption [5], spontaneous Raman scattering [6], and coherent anti-Stokes Raman scattering [7]. Nie and Emory reported the detection of Raman scattering signal from a single molecule adsorbed on a metal particle or aggregated with an enhancement factor of $10^{14}–15$ [8]. Halas and her group showed that a concentric metallic nanoshell strongly couples with resonant surface plasmons at the near-infrared spectra and applied this technology to biological sensors and labels [9]. Ebbesen’s group discovered that periodically arranged nanodisks or nanoholes in metal film beam anomalous light as a collection of surface plasmon polaritons (SPPs) [10–12]. In this Letter, we report subwavelength image transfer, which is another interesting property of metallic nanostructures. The structure we propose is a metallic nanorod array. The function of this structure is similar to that of Pendry’s superlens silver film [13,14], but the mechanism is different as discussed later.

Figure 1(a) shows the configuration of a silver nanorod array structure. The typical array arrangement is hexagonal. We define diameter $d$, height $h$, and pitch $a$ as the structural values of the array. The rod diameter and the pitch are much shorter than the wavelength, while the height can be longer than the wavelength. We numerically investigated the mechanism of plasmonic image transfer with the finite-difference time-domain (FDTD) calculation in three dimensions. In the calculation, structural values $d$, $h$, and $a$ are set to 20, 50, and 40 nm, respectively. The rod axis is parallel to $z$ axis. The calculation volume is $200 \times 200 \times 130$ nm$^3$ for $x$, $y$, and $z$ directions, and the unit cell size is $1 \times 1 \times 1$ nm$^3$. We iterate 5400 steps of the field calculations to achieve convergence. The permittivity of silver is set as $\varepsilon = -9.121 + 0.304$ at 488 nm [15].

In the simulation, we use point sources shaped as the letter “Λ” as an object [Fig. 1(b)]. The point sources are all $z$ polarized but incoherently oscillating as fluorescent intensity distribution. These images show clearly that a superlens can be created with a metallic nanorod array. The results are consistent with the FDTD calculation.

Metallic Nanolens ~Plasmonic Nanodevice for Optical Nano-Imaging~

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Introduction

Nanoplasmonics is recent active research field because of the abilities manipulating light in a nanometer world through the field confinement and enhancement by surface plasmon. Localized surface plasmon resonances(LSPR) excited on metal nanoparticles are widely accepted to be the basis for enhancing light field intensity and have been applied to spectroscopic research fields such as surface enhanced Raman scattering (SERS) and surface enhanced infrared absorption(SEIRA). Especially, well-designed metallic nanostructures exhibit unique optical properties. For example, sharpened metallic nanoprobe provides nanosized spot with strong field confinement at the tip apex[1]. Ebbesen’s group discovered that a single aperture, even a subwavelength sized one, surrounded by a periodic corrugation on the metal surface emits the enhanced light in certain angles due to the surface plasmons[2]. Moreover, subdiffraction plasmonic lithography with 60 nm resolution is experimentally demonstrated by using silver thin film with the thickness of 35 nm[3]. This concept is called “superlens” and based on the excitation of the slow lateral propagation of surface plasmon on the entrance and exit surfaces of the quite thin metallic film, which gives rise to the imaging of subwavelength field distribution [4].

In this work, we propose a metallic nanolens, which is a novel plasmonic nano-imaging device constructed by the arrays of metallic nanorods[Fig. 1]. This nanolens provides the spatial resolution exceeds much beyond the diffraction limit of light. Light emitted from the object closely placed at the input surface excites the surface plasmon resonance on the adjacent metal rods. The nano-imaging feature looks similar to superlens, but the resolution is not limited for the longer distance image transfer, because the physical mechanism is much different.

Spectroscopic features, influence of the source coherence, and optimization of the structure are discussed based on finite-difference time-domain(FDTD) simulations.

40nm resolutive imaging

Figure 2(a) shows the configuration of a silver nanorod array structure. The typical array arrangement is hexagonal. We defined diameter \(d\), height \(h\), and pitch \(a\) as the structural values of the array. The rod diameter and the pitch are much shorter than the wavelength, while the height can be longer than the wavelength. We numerically investigated the mechanism of plasmonic image transfer with FDTD calculation in three dimensions. In this calculation, structural values \(h\), \(d\), and \(a\) were set to 50, 20, and 40 nm respectively, and the rod axis was parallel to \(z\) axis. The calculation volume was \(200 \times 200 \times 130 \, \text{nm}^3\) for \(x\), \(y\), and \(z\) directions, and the unit cell size is \(1 \times 1 \times 1 \, \text{nm}^3\). We iterated 5400 steps of the field calculations to achieve convergence. The permittivity of silver was set as \(\varepsilon = -9.121 + i 0.304\) at 488 nm. We used point sources shaped as letter “M” as an object shown in figure 2(b). The point sources were all \(z\)-polarized and incoherently oscillating like fluorescent molecules. The oscillation wavelength was 488 nm. Each source was located at the center of a rod. The nanorod array is located 10 nm away from the point sources.

Figure 2. Subwavelength plasmonic imaging of a character pattern λ with a silver nanorod array device. (a) The structural model of the device, which is constructed by hexagonally arranged silver nanorods of 20 nm diameter, 50 nm height, and with 40 nm pitch. (b)-(f) Field propagation process in the image transfer obtained at each longitudinal position by the FDTD simulation.
Figure 2(c) shows the intensity distribution in the plane at the bottom of the rods, where we see a circular spot and a ring for each point source. Figure 2(d) shows the intensity distribution at \( z = 35 \) nm, the middle point of the rod. The intensity was attenuated in this plane. In figure 2(e), the rings without inner spots appeared again at the top of the rod array. Figure 2(f) is the intensity distribution at the plane 10 nm away from the rod array. The full-width of half-maximum (FWHM) of each spot was 30 nm, and letter “\( \lambda \)” was well resolved. This result shows that the nanopattern was image-transferred through a metallic nanorod array, containing the subwavelength resolution. The spatial resolution was 40 nm (~\( \lambda/12 \)) which was much beyond the diffraction limit, but is limited by the pitch \( a \) of rod array.

**Mechanism of image transfer through a silver nanorod array**

To find out the contribution of surface plasmons, we plotted polarization components of the field. Figures 3(a) and 3(b) show the distributions of z- and x-polarization components, \( E_z \) and \( E_x \), in the vertical cut including a rod center. In figure 3(a), it is seen that the \( E_z \) component was enhanced at the circumference of the top end of the rod. In figure 3(b), the \( E_x \) field was enhanced at the side of the rod. The results in figure 3 give us the mechanism of the image transfer shown in figure 2. A z-polarized dipole source near the entrance surface of a nanorod excites a longitudinal electron oscillation along the rod. This oscillation corresponds to the fundamental mode of the surface plasmon resonance. The oscillating \( |E_z|^2 \) field is enhanced at the rod end to provide the intensity of subwavelength image. The spot diameter is as small as that of the rod. It is well known that this resonant frequency depends on the aspect ratio of the rod height \( h \) and diameter \( d \) [5]. To obtain Figure 2, we purposely chose the structural values, rod height \( h \), and diameter \( d \), to have a resonance of plasmon oscillation for Ar⁺ laser excitation at the wavelength 488 nm.

Figure 4 shows the total intensity distribution. The right-hand side of the figure shows the intensity profile along rod axis \( a-a' \), and the graph at the bottom shows the intensity profile along the line \( b-b' \) at \( z = 70 \) nm, which is corresponding to 10 nm away from the rod exit. In each graph, a dashed line shows the intensity profile when a rod is absent, and a solid line shows the case when the rod exists. When a rod was absent, the intensity decayed in propagation, whereas when the metallic nanorod was present, intensity was preserved due to the plasmon resonance or it even increased at the exit of the rod. In the lateral line profile, the peak intensity with the metallic rod was \( 10^3 \)-\( 10^4 \) times higher than that without the rod. The intensity exponentially decreased due to the absorption loss in metal if the length was infinite, while it might increase by plasmon resonance when the length was finite. In the case of our simulation, the fundamental mode of plasmon resonance was excited at the given frequency. The higher order modes for longer rods can also be excited at the same frequency. The propagation length of surface plasmon along a nanorod has been theoretically investigated[6] and an experimental result of surface plasmon propagation along a nanowire was also reported[7, 8].

**Conclusions**

The metallic nanorod array was numerically confirmed to be a useful device for super-resolution near-field imaging. The mechanism of the super-resolutive optical imaging through the device was clarified by three-dimensional FDTD algorithm. Thanks to surface plasmon resonance generated on the metal nanorod, our device enables a deep transfer of image without loss and has the ability to parallel image transfer. The resolution in the case of our used parameters was 6 times higher than that of conventional diffraction-limited optics.

**References**