Plasmonic Nano-imaging with Metallic Nanolens

Atsushi Ono, Prabhat Verma, Satoshi Kawata

Abstract:

We proposed a nano-imaging system at optical frequency region with the array of metallic nanorods. We simulated the field distribution of imaging process using the finite-difference time-domain algorithm. It is found that the spatial resolution is 40 nm, which is much beyond the diffraction-limit and is limited by the array pitch. The typical configuration is a hexagonal arrangement with 40 nm periodicity of silver rods of 50 nm height and 20 nm diameter. The image formation highly depends on the coherence and the polarization of the dipole sources, the array pitch, and the source-array distance. The principle of our near-field imaging is based on the longitudinal resonance of the localized surface plasmon along a metallic nanorod. The spectral responses of the device are also investigated.

Keywords: *plasmonics, near-field optics.*

1. Introduction

It is common sense that transparent, high refractive, and curved surface materials, like an optical glass, are used as the lens and opaque; high reflective, and flat surface materials like a metal are used as the mirror. Beyond common sense, we proposed metallic nanolens which is constructed by the array of silver nanorods provides an image with subwavelength spatial resolution [1]. Local surface plasmon (LSP) resonance excited on each silver nanorods is utilized for imaging beyond the diffraction limit of light.

Electric field enhancement is observed on the metal surface, when light is irradiated to metallic nanostructure [2], [3]. This enhancement is caused by the resonant couplings between electron oscillation and the electric field oscillation of light, is so-called by the surface plasmon. Nanoplasmonics, plasmonic phenomena induced on metallic nanostructure, is very attractive research field. Metallic nanoprobe, metallic nanoshell, and metallic nanospheres have been developed for the local field enhancement, and the optical properties are utilized for plasmonic nanoimaging, plasmonic nanospectroscopy, plasmonic laser, and so on [4].

In this article, we show the imaging mechanism and the imaging characteristics of proposed metallic nanolens. We demonstrated that near-field sources in nanometer scale were plasmonically imaged through the array of silver nanorods by three-dimensional finite-difference time-domain (FDTD) algorithm. Local surface plasmon polaritons of nanorods contribute to the nano-imaging. Furthermore, our simulations show that well-designed metallic nanolens gives color imaging with subwavelength resolution [5]. The spatial resolution was 40 nm that was determined by the array pitch. It is expected that plasmonic nanorod array would be applied to optical nanoimaging, nanobiosensor, nanolithography, and nanocommunication.

2. Simulation model

The typical configuration of metallic nanolens is the hexagonal arrangement of silver rods of 50 nm height and 20 nm diameter with 40 nm array pitch. The rod diameter and the pitch should be much shorter than the wavelength, while the height can be longer than the wavelength. Drude dispersion formula was applied to FDTD simulation in the reference from experimental value [6] for the consideration of frequency dispersion of silver complex permittivity. The near-field sources in nanometer scale were plasmonically imaged through the metallic nanolens (Fig. 1). Figure 1(a) shows the bird view and the x-z cross sectional view of silver nanorod array. The rod axis is parallel to z axis. Point sources were shaped as letter λ as an object (Fig. 1(b)). The point sources were all z-polarized and incoherently oscillating like fluorescent molecules. The oscillation wavelength was 482 nm. Each source is located at the center of a rod. The silver nanorod array is located 10 nm away from the point sources. Figure 1(c) is the intensity distribution at the plane 10 nm away from the top of the rod array. The FWHM of each spot was 30 nm, and letter λ is well resolved.

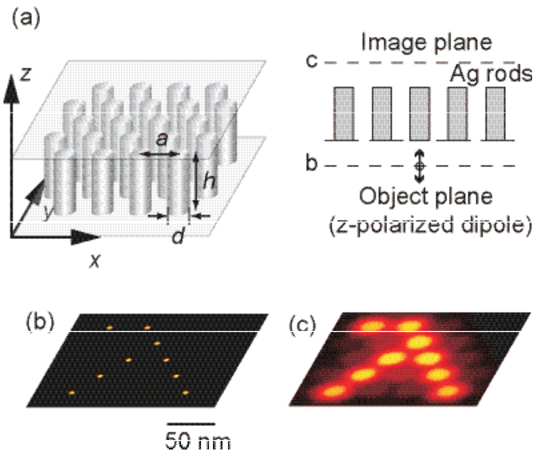

Fig. 1. Subwavelength optical imaging through the metallic nanolens, which is constructed by the array of silver nanorods. (a) model (b) object (c) image.

3. Imaging mechanism

Longitudinal resonant mode of LSP excited on each silver nanorods contributes to this super-resolutive imaging. We have examined the field distribution of the electric field components, Ez and Ex, in the vertical cut including a rod center (Fig. 2). It is found that the Ez component is enhanced at the circumference of the top end of the rod and it contributes to provide the hot spot at the image plane as shown in Fig. 2(a). In Fig. 2(b), it is seen that the field of Ex component is enhanced at the side of the rod and fundamental mode of the LSP resonance is excited. The resonant frequency was analyzed by time resolved Fast Fourier Transform (FFT) of the intensity at the image plane which was 10 nm away from the top end of rods on impulse response of z-polarized dipole source (Fig. 3).

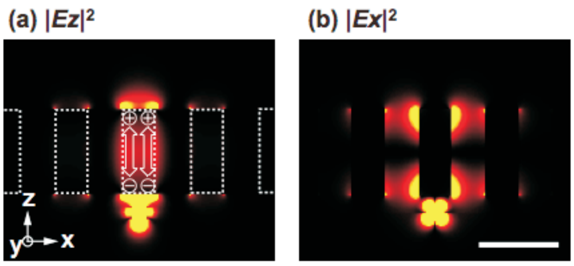

Fig. 2. Intensity field distributions for individual polarization components obtained at the vertical (x-z) cross section of the nanorod array including the centric rod-axis and a z-polarized dipole source. (a) Ez component. (b) Ex component. The size of the scale bar is 50 nm.

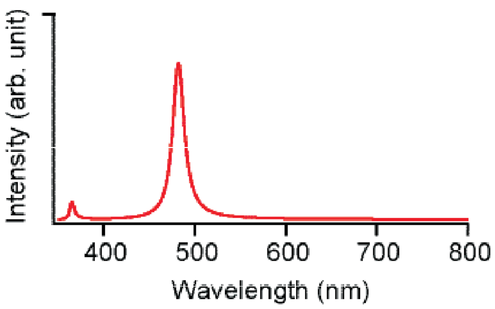

Fig. 3. FFT spectrum of near-field intensity at the image plane. Impulse signal is detected at the image plane through a silver nanorod. A peak is observed at the wavelength of 482 nm.

4. Imaging properties

It was investigated that the relationship between the peak intensity at the image plane for the source-array distance to confirm the contribution of near-field components. The peak intensity at the image plane were plotted when the z-polarized dipole source was far from the bottom of the rod array from 2 to 100 nm. Figure 4 shows peak intensity in the image plane as a function of source-array distance. The peak intensity decreased in proportional to the source-array distance and it fitted well to an exponential decay curve (dashed curve in the figure). This indicates that a major contribution to plasmon coupling with the dipole radiation is the evanescent components of near-field photons.

The array pitch of the nanorod array contributes to the spatial resolution for the optical nano-imaging. Therefore the narrow pitch is better for super-resoltive imaging. The image field distribution dependence on the array pitch was investigated when the rod diameter and height were fixed to 20 and 50 nm. Figure 5 shows the peak intensity at the image plane as a function of hexagonal array pitch a. Insets in Fig. 5 show the intensity distribution of the image obtained with the array pitch of 30 and 40 nm. The peak intensity became smaller as the array pitch decreased. When the distance between rods is less than 40 nm, there is the coupling between local surface plasmons in the neighboring rods, and then coupling out or smearing of the peak intensity occurred. Therefore the image became broadened, not forming nanospot, at a less than 40 nm array pitch. When the array pitch is larger than 40 nm, local surface plasmon coupling between rods became negligible and the peak intensity is almost constant that means the spot formed by this nanorod array is as same as the single nanorod case. In conclusion, a pitch of 40 nm is the best pitch for this model, since the image resolution depended on the pitch.

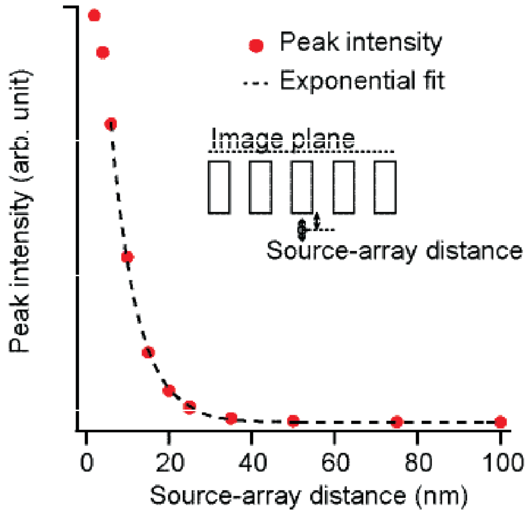

Fig. 4. Relationship between the peak intensity (dots) as a function of the source-array distance and exponential fitting for the dot marks (dashed curve).

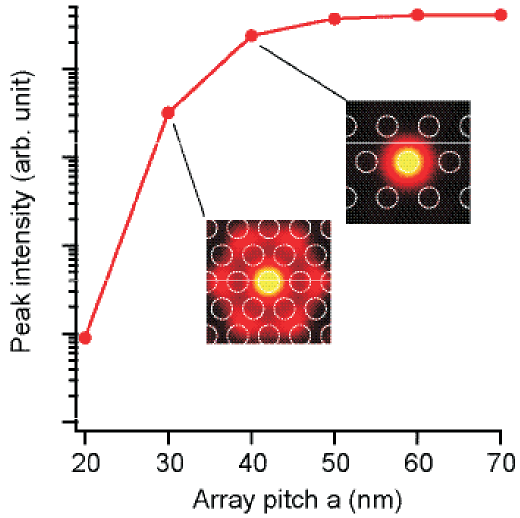

Fig. 5. Hexagonal array pitch dependence on the peak intensity at the image plane. Insets show the intensity distributions of the image obtained with the pitch of 30 and 40 nm.

5. Conclusion

In conclusion, subwavelength image transfer process by silver nanorod array was discovered and proposed. The theoretical calculation work was done and the mechanism of the super-resolutive optical imaging through plasmonic nanorod array was clarified by three-dimensional FDTD algorithm. The spatial resolution is limited by not the wavelength but the array pitch. The resolution in the case of used parameters was six times higher than that of conventional diffraction-limited optics. It was found that the image formation depends on the source-array distance and the polarization of the dipole sources, array pitch, and the coherence by the FDTD simulation.

AUTHORS
Atsushi Ono* - Division of Global Research Leaders, Shizuoka University, 3-5-1 Johoku, Naka-ku, Hamamatsu 432-8561, Japan. E-mail: daono@ipc.shizuoka.ac.jp.
Prabhat Verma - Department of Frontier Biosciences, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan. E-mail: verma@ap.eng.osaka-u.ac.jp.
Satoshi Kawata - Department of Applied Physics, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan. E-mail: kawata@ap.eng.osaka-u.ac.jp.
* Corresponding author

References

[1] Ono A., Kato J., Kawata S., "Subwavelength Optical Imaging through a Metallic Nanorod Array", *Phys. Rev. Lett.*, vol. 95, 2005, no. 267407.
[2] Shalaev V.M., editor, *Optical Properties of Nanostructured Random Media*, Springer, Berlin, 2002.
[3] Kawata S., editor, *Near-field and Surface Plasmon Polaritons*, Springer, Berlin, 2001.
[4] Ichimura T., Hayazawa N., Hashimoto M., Inouye Y., Kawata S., "Tip-enhanced coherent anti-Stokes Raman scattering for vibrational nano-imaging", *Phys. Rev. Lett.*, vol. 92, 2004, no. 220801.
[5] Kawata S., Ono A., Verma P., "Subwavelength colour imaging with a metallic nanolens", *Nature Photonics*, vol. 2, no. 7, 2008, pp. 438-442.
[6] Johnson P.B., Christy R.W., "Optical Constants of the Noble Metals", *Phys. Rev. B*, vol. 6, no. 4370, 1972.