Micromachines **2012**, *3*, 55-61; doi:10.3390/mi3010055

OPEN ACCESS

micromachines

ISSN 2072-666X

www.mdpi.com/journal/micromachines

Article

Surface Plasmon Excitation and Localization by Metal-Coated Axicon Prism

Atsushi Ono [1,2,]*, Hiroki Sano [3], Wataru Inami [1,2] and Yoshimasa Kawata [2,3,]*

[1] Division of Global Research Leaders, Shizuoka University, 3-5-1 Johoku, Naka, Hamamatsu 432-8561, Japan; E-Mail: dwinami@ipc.shizuoka.ac.jp

[2] CREST, Japan Science and Technology Agency, 4-1-8 Honcho, Kawaguchi, Saitama 332-0012, Japan

[3] Faculty of Mechanical Engineering, Shizuoka University, 3-5-1 Johoku, Naka, Hamamatsu 432-8561, Japan; E-Mail: sano@optsci.eng.shizuoka.ac.jp

* Authors to whom correspondence should be addressed; E-Mails: daono@ipc.shizuoka.ac.jp (A.O.); kawata@eng.shizuoka.ac.jp (Y.K.); Tel.: +81-53-478-1069; Fax: +81-53-478-1128.

Received: 29 November 2011; in revised form: 1 February 2012 / Accepted: 1 February 2012 / Published: 8 February 2012

Abstract: Collimated Gaussian beams are efficiently localized at the apex of a metal-coated axicon prism by surface plasmon excitations. We observed the light scattered at the apex and the light reflected by the prism. Intense scattered light was observed with the radial polarization incidence. Further, each incidence of the radial, azimuthal, and linear polarizations provided field distributions of bright and dark intensities in the reflected images according to the surface plasmon excitation. We have demonstrated that surface plasmon waves are excited at the sides of the prism in the Kretschmann configuration and that they converge to its apex.

Keywords: surface plasmon polaritons; Kretschmann configuration; radial polarization; near-field optics; metallic thin film

---

1. Introduction

A near-field probe, whose apex is as small as several tens of nanometers, scatters evanescent fields and generates super-resolution images beyond the diffraction limit of light [1]. However, using a dielectric probe it is difficult to reconstruct an image with the resulting evanescent field components because the scattered near-field signal is relatively low due to the small area of the scattering cross-section. Hence, to increase the scattering of the evanescent field of the sample, a metallic probe utilizing surface plasmon polaritons has been proposed [2]. A silver probe, for example, with an apex radius of 20 nm enhances the electric field intensity by a factor of 80 and localizes the field within an apex area of 30 nm [3].

In recent times, photon energy has been effectively focused and concentrated on the apex of a tapered metallic probe by exciting the waveguide of the surface plasmon polaritons [4–6]. Moreover, the coupling of the waveguide mode of a fiber tip and surface plasmons propagating on the external surface of the metal coating on the fiber, leads to strong field enhancements at the tip end [7,8]. In 1997, Koglin *et al*. proposed a tetrahedral tip for the surface plasmon excitation and confinement to the nanometric dimensions in scanning near-field optical microscopy and they demonstrated 1 nm spatial resolution [9]. Further, actively developed plasmonic nanofocusing techniques significantly localize the enhanced field into a nanoscale light source.

In a previous paper, we have proposed plasmonic nanofocusing with a metal-coated axicon prism that is constructed by using the well-known method, the Kretschmann configuration [10,11]. In the Kretschmann configuration, efficient excitations of surface plasmon polaritons are achieved by matching the wave vector of the incident light in a prism with the wave vector of the surface plasmon in a metal surface [12]. Most of the photon energy of the p-polarized incident light is used for exciting the surface plasmon polariton. The excited surface plasmons on a metal-coated axicon prism propagate on the side and converge at the apex. We were able to attain electric field enhancements by a factor of 1.2×10^2 and localization within a 35-nm spot for radially polarized light having an incident wavelength of 632.8 nm.

In this article, we report experimental demonstrations and verifications of the excitation and converging of surface plasmon polaritons, *i.e.*, plasmonic nanofocusing, by observing the scattered and reflected light from an axicon prism.

2. Experimental Setup

Figure 1(a) shows a fabricated metal-coated axicon prism device for plasmonic nanofocusing. A gold thin film with a thickness of 38 nm was evaporated on the axicon prism; this is the optimal thickness for achieving excitation efficiency of surface plasmons at a wavelength of 800 nm. It is expected that the near infrared light source generate higher intensified hot spot at the apex due to the long propagation length compared with visible. Chromium (thickness: 2.5 nm) was used as the adhesion layer for the gold thin film. Chromium adhesion layer attenuates the incident power but the excitation condition of the surface plasmon does not change. Scanning electron microscopy (SEM) was used to confirm that the fabricated device including the apex is completely covered with a gold thin film. The incident angle θ_{sp} for the surface plasmon excitation on the side was fixed at 44.8 degrees, and hence, the half-cone angle was 45.2 degrees; these parameters were determined by calculating Fresnel's equations.

Figure 1. (**a**) Photograph of a gold-coated axicon prism. The gold thickness and the half-cone angle of the prism are optimized for the Kretschmann configuration (excitation wavelength = 800 nm); (**b**) Optical setup for the demonstration of plasmonic nanofocusing. Incident light of collimated Gaussian beam of pulsed laser excites the surface plasmons at the side of the prism. Scattered and reflected images can be observed.

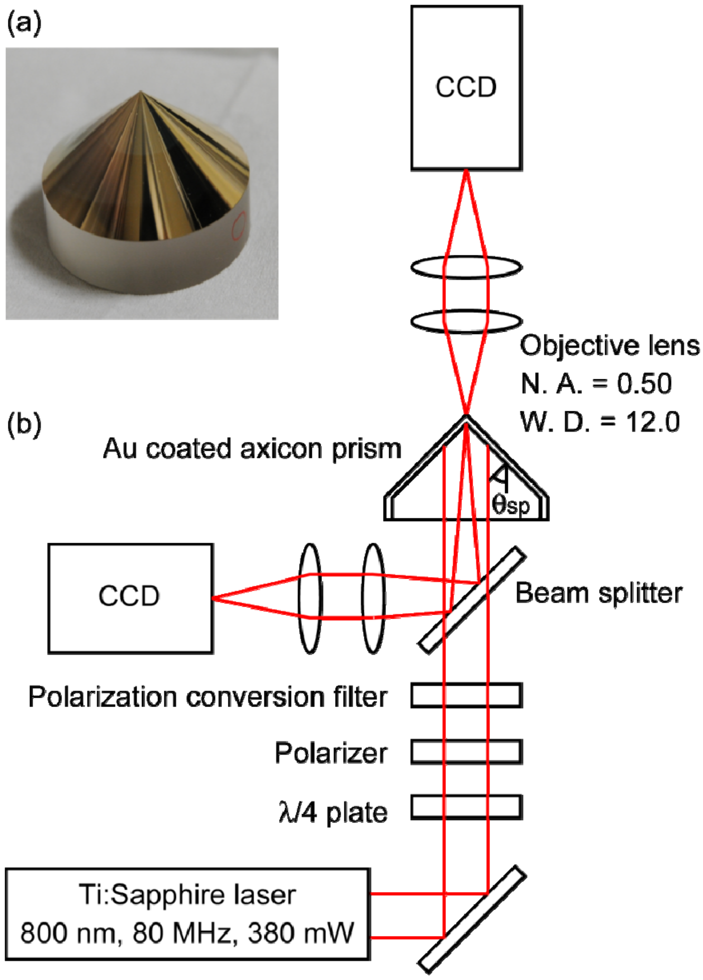


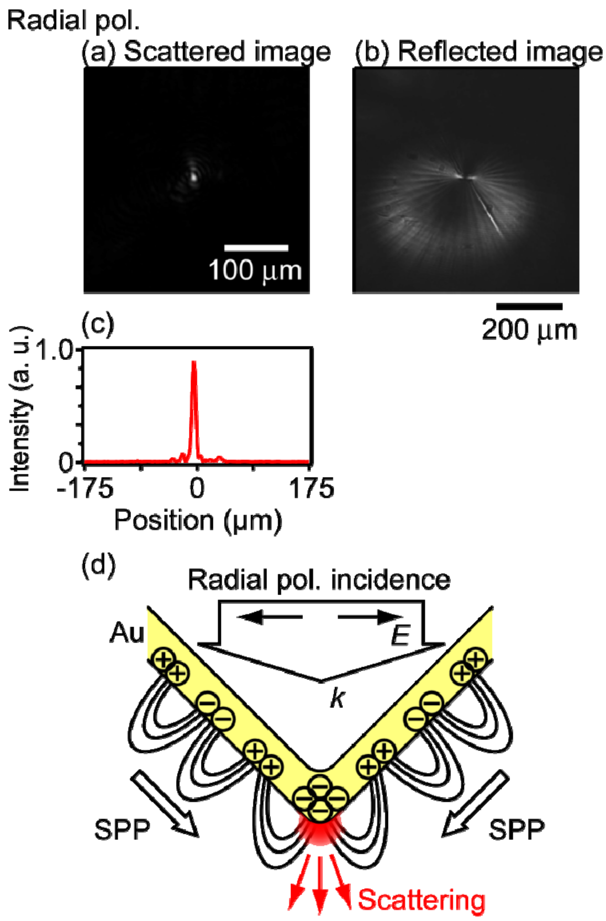
Figure 1(b) shows the optical setup for demonstrating plasmonic nanofocusing with a metal (gold)-coated axicon prism. Laser excitation was provided by a mode-locked Ti:Sapphire pulsed laser (Spectra-Physics, Tsunami 3960; wavelength = 800 nm; pulse width = 80 fs; repetition rate = 80 MHz). The Gaussian collimated beam was focused on the gold-coated axicon prism for the excitation of surface plasmons at the side surface of the prism with the Kretschmann configuration. Radial polarization, azimuthal polarization, and linear polarization were obtained by employing a quarter-wave plate, linear polarizer, and polarization conversion filter (Photonic Lattice, Inc., SWP-800), respectively. The reflection and scattering images in each polarization incidence were captured by a charge-coupled device (CCD) camera. An objective lens (Mitutoyo, M Plan Apo NIR 100×, N.A. = 0.50) with a long working distance of 12.0 mm was employed to observe the scattering light from the prism apex.

The excited surface plasmon polaritons on the side surface propagate and converge on the apex. In this manner, strong electric field enhancements and localizations could be achieved at the apex by the superposition of the surface plasmon excited on the side surface. Note that the intensity of the scattering light from the apex indirectly indicates the efficiency of the plasmonic nanofocusing.

3. Surface Plasmon Excitation and Localization

Figure 2 shows the experimental intensity distributions of scattered (Figure 2(a)) and reflected images (Figure 2(b)) from the apex of the gold-coated axicon prism with incident radial polarization. The line profile in Figure 2(c) shows the intensity plot of the center of the scattered image. The full width half maximum of the hot spot from the apex in the scattered image is approximately 3.5 µm. This spot size is based on the spatial resolution in a far-field image for our optical setup. The theoretical resolution is 0.98 µm with our objective lens of N.A. = 0.5, and in consideration of the imaging system one pixel corresponds to 1 µm. In our imaging system, the scattered light and side-lobes in the region of depth of focus is imaged on the CCD camera as well as the hot spot at the apex, so we considered that we observed the larger spot than the diffraction limit.

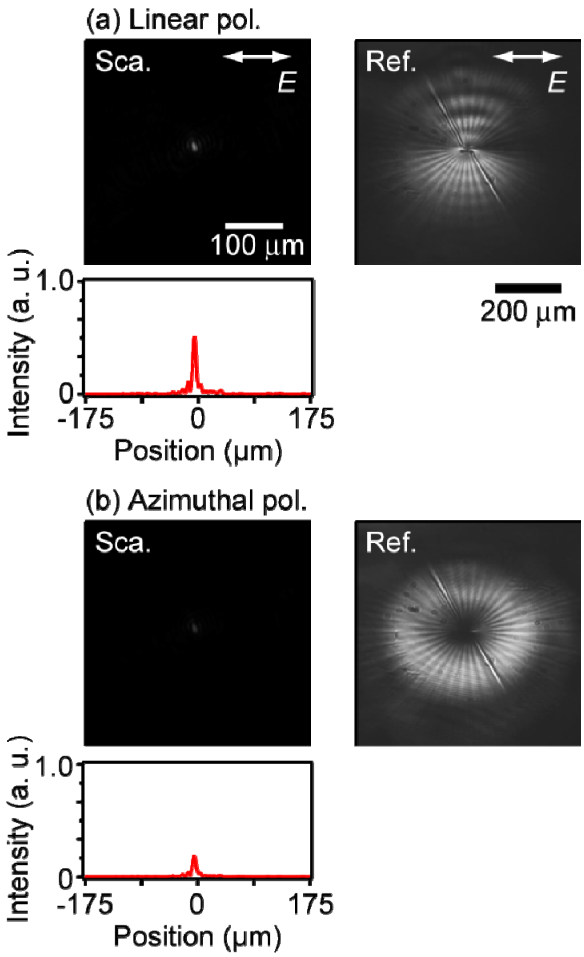
Figure 2. Observed (**a**) scattering and (**b**) reflection images for radial polarization incidence. Scattering is observed only from the apex. The reflection intensity is fairly dark due to the surface plasmon excitation; (**c**) Line profile of the intensity at the center of the scattering image; (**d**) The mechanism of the scattering from the apex is schematically explained. Constructive interference of surface plasmons occurs at the apex.



In our previously reported Finite-difference time-domain (FDTD) simulation, the diameter of the hot spot was approximately 35 nm in the near-field image [11]. Although we are unable to directly demonstrate that the hot spot is localized on the subwavelength region of 35 nm, we have been able to demonstrate that the surface plasmon was excited and converged to the apex by the radial polarization incidence and that the light was subsequently scattered from the apex (Figure 2(d)). In Figure 2(b), the surface plasmon is excited in the dark region of the reflected image. In the case of ideal radial polarization incidences, bright regions do not appear in the reflected images. However, we observed a bright area due to the optical axis alignment for the polarization converter, the incident angle for the axicon prism, and the processing accuracy for the side surface of the prism.

Figure 3 shows the intensity distributions of the scattering and reflection images for the linear and azimuthal incident polarizations. A comparison of the line profiles shown in Figure 2(c) and in Figure 3(a,b) reveals that the scattering light intensities for the incident linear and azimuthal polarizations exhibit lower intensities, about 57% and 20%, than that for the radial polarization incidence.

Figure 3. Scattered and reflected images for (**a**) linear and (**b**) azimuthal polarization incidences. The experimental conditions identical to those for the radial polarization incidence. The scattered intensities are relatively low due to the excitation efficiency of the surface plasmon excitation. The dark area in the reflected images indicates the area of excited surface plasmons.



Moreover, the difference in the intensities depends on the efficiencies of the surface plasmon excitation, and it is appropriate for referring to FDTD simulation results [11]. A fan-shaped intensity distribution can be observed in the reflected image for the linear polarization incidence. The incident light is linearly polarized to a lateral direction relative to the image. Therefore, the electric field component of the p-polarized light excites the surface plasmon resulting in the appearance of dark regions. On the other hand, the electric field component of s-polarization does not excite the surface plasmon and is reflected. The reflected light for the linear polarization led to the appearance of sectorial bright patterns. For azimuthal polarization incidence, the incident polarization is regarded as s-polarization at all the side surfaces of the axicon prism. Since surface plasmons are unexcited by the s-polarized incident light, annular intensity field distributions are observed in the reflected image for the azimuthal polarization incidence.

4. Conclusions

In conclusion, we have demonstrated that a collimated Gaussian beam having radial polarization excites surface plasmons and is plasmonically localized on the apex of a gold-coated axicon prism. The scattering field from the apex was clearly observed. The scattering intensity changed in the case of the incident polarization due to the differences in the excitation efficiency of surface plasmons at the side surface of the axicon prism. Further, the reflection image represents the excitation area of the surface plasmon on the side surface of the prism. Metal-coated axicon prisms having the Kretschmann configuration promote high-efficiency plasmonic nanofocusing. Further, it is useful as a near-field light source for optical microscopy beyond the diffraction limit. Moreover, nonlinear effects and responses confined to nanoscale regions can be expected due to the high photon density at the apex due to the plasmonic enhancement.

References

1. Kawata, S. *Near-Field Optics and Surface Plasmon Polaritons*; Springer: Berlin, Germany, 2001.
2. Inouye, Y.; Kawata, S. Near-field scanning optical microscope with a metallic probe tip. *Opt. Lett.* **1994**, *19*, 159–161.
3. Hayazawa, N.; Inouye, Y.; Sekkat, Z.; Kawata, S. Metallized tip amplification of near-field Raman scattering. *Opt. Commun.* **2000**, *183*, 333–336.
4. Stockman, M.I. Nanofocusing of optical energy in tapered plasmonic waveguides. *Phys. Rev. Lett.* **2004**, *93*, 137404.
5. Issa, N.A.; Guckenberger, R. Optical nanofocusing on tapered metallic waveguides. *Plasmonics* **2007**, *1*, 31–37.
6. Gramotnev, D.K.; Vogel, M.W.; Stockman, M.I. Optimized nonadiabatic nanofocusing of plasmons by tapered metal rods. *J. Appl. Phys.* **2008**, *104*, 034311.
7. Bouhelier, A.; Renger, J.; Beversluis, M.R.; Novotny, L. Plasmon-coupled tip-enhanced near-field optical microscopy. *J. Microsc.* **2003**, *210*, 220–224.
8. Babayan, A.E.; Nerkararyan, Kh.V. The strong localization of surface plasmon polariton on a metal-coated tip of optical fiber. *Ultramicroscopy* **2007**, *107*, 1136–1140.
9. Koglin, J.; Fischer, U.C.; Fuchs, H. Material contrast in scanning near-field optical microscopy at 1–10 nm resolution. *Phys. Rev. B* **1997**, *55*, 7977–7984.
10. Kawata, Y.; Suzuki, T. Localization of surface plasmon by using a metal coated axicon prism. *Scanning* **2004**, *25*, l16–l20.
11. Kato, K.; Ono, A.; Inami, W.; Kawata, Y. Plasmonic nanofocusing using a metal-coated axicon prism. *Opt. Exp.* **2010**, *18*, l3580–13585.

12. Kretschmann, E.; Raether, H. Radiative decay of nonradiative surface plasmons excited by light. *Z. Naturforsch.* **1968**, *A23*, 2135–2136.