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Interference of the surface plasmon polaritons with an Ag waveguide probed by dual-probe scanning near-field optical microscopy

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ABSTRACT

The propagation of surface plasmon polaritons (SPPs) on Ag waveguides with two different widths is directly observed using dual-probe scanning near-field optical microscopy (DSNOM). We find that the waveguide structure strongly affects the propagation of locally excited SPPs. SPPs in a flat plane structure spread radially, whereas SPPs in a 3.4-μm wide waveguide structure form two-dimensional interference fringes due to the multiple reflections at the side edges. The experimental results agree well with finite-difference time-domain calculations. The results suggest that the DSNOM technique can visualize the nanoscale characteristics of the SPP waves in various plasmonic waveguides.

1. Introduction

Surface plasmons (SPs) are plasma oscillations of free electrons bound to the interface between a dielectric material and a metal. The SPs include the electromagnetic mode called SP polaritons (SPPs) and can interact directly with photons. The most attractive characteristic of the SPPs is their larger wave vector than that of light in free space. It enables us to miniaturize waveguide structures beyond the conventional diffraction limit. Concurrently, this feature of the SPPs requires special experimental arrangements for coupling photons with SPPs, such as an attenuated total reflection [1,2] and a scanning near-field optical microscope (SNOM) [3,4]. In recent studies, two configurations have been widely used to assess SPP propagations: one is a far-field excitation and a near-field detection [5,6], and the other is a near-field excitation and a far-field detection [3,4]. However, far-field excitation hinders local access to nanoscale structures, and far-field detection suffers from a low spatial resolution. Therefore, both near-field excitation and near-field detection of SPPs are needed for the in-depth assessment of SPP propagation. Recently, SPPs guided on an Au metal waveguide have been observed by using a dual-probe SNOM (DSNOM) technique [7,8], where two probes are used for the near-field excitation and detection, respectively. However, in this technique, in order to avoid a mechanical contact between the two probes, the detection probe monitors the topography and stops its scan when the illumination probe is imaged. Therefore, it is difficult to precisely estimate the distance between the two probes, particularly when the surface is rough.

Quite recently we developed a new DSNOM system [9] with a novel distance control technique, which can independently control the sample–probe distance and the probe–probe distance, combined with a dual-band modulation (DBM) technique. The distance control between the sample and the probe was achieved by adjusting the position of the sample stage to keep the oscillation voltage of the tuning fork (resonant frequency: 32 kHz) attached to the probe constant. At the same time, the distance control between the two probes was achieved by detecting the modulation signal of the detection probe, which was mechanically oscillating at a frequency of 100 Hz. The DBM technique enables the two distances to be controlled independently and enables the two probes to approach each other to within a few tens of nanometers. We have already visualized the anisotropic in-plane diffusion of carriers in an InGaN/GaN single quantum well [9]. Our version of DSNOM is a very powerful tool to investigate the detailed SPP propagation. For instance, it is applicable for the direct identification of the edge effects occurring at the waveguide edges, which were well discussed in Ref. [10]. Furthermore, the propagation properties at a high frequency close to the SPP resonance can be measured. The reason of this is that such frequency cannot be reached by conventional techniques, because the wave vector around the resonance is large, and in turn, closer approach to the excitation position is required.

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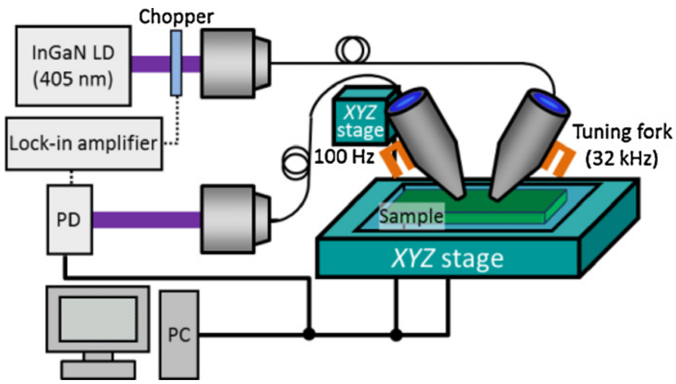

Fig. 1. Schematic image of the DSNOM system. Two *XYZ*-axis piezoelectric actuators are attached to the sample and the detection probe for scanning.

In this paper, we assess the SPP propagation properties on two Ag structures, namely an Ag plane and an Ag waveguide, using our DSNOM system. Ag is more appropriate than Au as a waveguide material for SPPs because of its longer propagation length, as quantitatively estimated in Section 3 below. The longer propagation for an Ag structure may cause SPP propagation different from that on an Au waveguide [7]. Based on finite-difference time-domain (FDTD) simulations, we estimated SPP propagation lengths and propagation properties as a function of distance from an excitation position. Comparing calculated results with experimental results, we found an interference effect in SPP propagations for a waveguide structure.

2. Experimental setup

The experimental setup of the DSNOM is illustrated in Fig. 1. Pencil-shaped fiber probes with a 40° cone angle were coated with Ni, Au, and Al with 10, 25, and 50 nm, respectively. An aperture with a diameter of 200 nm was then formed by pounding. The excitation and the detection probes were tilted in opposite directions at 30°, so that the two probes come as close as possible without degrading excitation and detection efficiencies. We used an InGaN laser diode (λ = 405 nm in vacuum) as the excitation source. SPPs were locally excited by a near-field light localized at the tip of the excitation probe. The SPPs propagated along the surface and were detected by a photo diode and a lock-in amplifier through the detection probe. The excitation probe kept illuminating the same position, and the detection probe scanned around it and observed propagating SPPs.

The Ag waveguide structure on a glass substrate was fabricated by conventional photolithography and lift-off. The surface images of the plasmonic waveguide are shown in Fig. 2. Fig. 2(a) shows a scanning electron microscope (SEM) image of several waveguide structures with different lengths and widths, connected to a large $200 \times 200\,\mu\text{m}^2$ homogeneous thin film. We measured SPP propagation for the two structures surrounded by dotted circles: (A) is the plane structure with a width much longer than a SPP propagation length and (B) is the waveguide structure with a 3.4-μm width. Fig. 2(b) shows an atomic force microscope (AFM) image acquired close to the center of the Ag plate in Fig. 2(a). The measured root mean square roughness, δ, was determined to be 3.76 nm from the AFM image.

If a metal film inserted between two dielectric materials is sufficiently thin, two SPP modes arising at the top and the bottom interfaces couple and create two different modes, namely a symmetric mode (S mode) and an asymmetric one (AS mode) [11,12]. The critical thickness to form these modes depends on the penetration length of the SPPs' electromagnetic field into the metal. The penetration length of the SPPs, d, is given by

$$d = \frac{c}{\omega}\sqrt{\left(\frac{\varepsilon_{\rm m}+\varepsilon_{\rm d}}{-\varepsilon_{\rm m}^2}\right)} \tag{1}$$

where $\varepsilon_{\rm m}$ and $\varepsilon_{\rm d}$ are relative permittivities of the metal and dielectric, respectively, ω is the frequency of the SPP, and c is the speed of light. Here we ignore the imaginary part in the complex relative permittivity of a metal. The relative permittivity of Ag is $\varepsilon_1 = -4.41$ [13] at λ = 405 nm, and the relative permittivities of the top and the bottom dielectric materials are $\varepsilon_2 = 1$ (air) and $\varepsilon_3 = 2.426$ (glass), respectively. We then acquire the critical thickness for our waveguide structure from Eq. (1) to be d = 24.7 nm (Ag/glass) + 27.0 nm (Ag/air) = 51.7 nm. The wave vector of the AS mode is smaller than that of the light line in the adjacent dielectric with a larger relative permittivity. This makes the AS mode radiative, which attenuates the electric field intensity of the laterally propagating SPPs [12]. To prevent the two modes from being created, we designed a 160-nm-thick Ag film.

3. FDTD calculations

We performed three-dimensional FDTD (Poynting for Optics, FUJITSU) calculations in order to estimate SPP propagation lengths. The structure used in the simulation is shown in Fig. 3. The thickness of an Ag film was set at 100 nm, which is above the critical thickness. A 100-nm-diameter disk-shaped source with a random polarization at 405 nm is set 10 nm above the top surface (+z direction) for exciting SPPs at the interface between air and Ag. The pseudo-random polarization was made by the superposition of the linear polarizations rotated every 45° in the xy plane. SPP propagation properties were evaluated for two structures – an Ag plane with an infinite width and a 3.4-μm wide Ag waveguide. Each structure

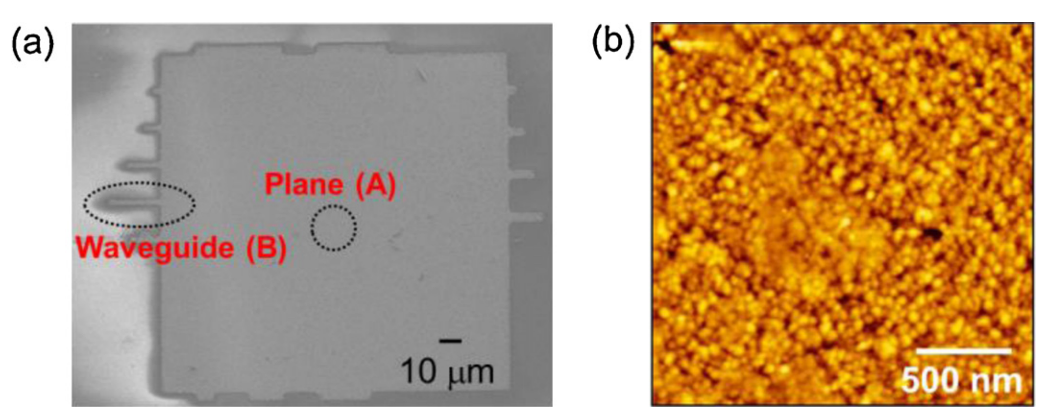

Fig. 2. Surface images of the waveguide structure. (a) SEM image with the plane (A) and the waveguide (B) structures. (b) AFM image close to the center of (a).