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# Nanometer-sized optical waveguides fabricated by anodic oxidation using a scanning near-field optical microscope

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We have fabricated an optical waveguide with a subwavelength cross section that propagates light. A metal–oxide core is partially embedded into a metal clad by anodic oxidation using the probe tip of a scanning near-field optical microscope (SNOM). Then, using the SNOM in transmission mode we have evidence of light propagating more than 5 $\mu$m in the waveguide whose core width and thickness are 300 and 70 nm, respectively. © *2002 American Institute of Physics.*
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Currently, in the field of optical communications, research is underway to develop optical switches that are comparable in size and efficiency to electronic circuits. One problem in realizing this goal is that diffraction limits the size of optical devices including waveguides. An area of research showing potential in constructing smaller optical circuits is photonic crystals, because of their ability to manipulate light, such as dispersion control[1] and the sharp bending of light.[2] For photonic crystals, light is fundamentally confined by the difference between the refractive index of the semiconductor and the air. Thus, photonic crystals are currently larger than electric-integrated circuits.

In order to increase the difference in refractive index, materials with a negative index such as metals are employed. The metallic surface has the ability to let light pass through due to the action of surface plasmons. When surface plasmons interact with an electromagnetic field, an excitation occurs at the boundary of the metal and dielectric material to form a surface plasmon polariton (SPP).[3] While metal-clad waveguides have been studied for more than 20 years, those have mostly been applied to macrosized polarizers.[4] Recently, Takahara *et al.* have investigated waveguides with nanometer-sized metal structures. They have proved theoretically that light can be propagated in waveguides with a metal coaxial structure, even when the core size is much smaller than the wavelength.[5]

In this letter, we present a metal-clad waveguide with nanometer-order cross-section size that propagates light. By anodic oxidation using the probe tip of the scanning near-field optical microscope (SNOM), a waveguide, where the metal–oxide core is partially embedded in a clad, is created. The propagation of light in the waveguide has been determined using near-field optical techniques.

The waveguide is fabricated on a multilayer metal film consisting of copper, silver, and titanium, which are deposited on cover glass plates with thicknesses of 10, 30, and 30 nm, respectively. Using the thin copper film as the bottom layer, the roughness of the metal films is suppressed below 5 nm. The small roughness is necessary for the fabrication and for the longer propagation of the SPP, because scattering on rough surfaces is the main cause of propagation loss.[3] The titanium film is oxidized electrochemically and the resulting titanium–oxide structure is used as the dielectric core of the waveguide. The silver film is in contact with the oxide core and plays a role in the clad instead of the titanium. With a silver clad we expect the propagation length of the SPP to be 5000 times longer than that for the titanium clad.[3]

The schematic setup for the fabrication and evaluation of the waveguide is shown in Fig. 1. The waveguide is constructed using a SNOM probe tip that is made by the conventional heat and pull method and is coated by aluminum and gold for the confinement of light and for electric conductivity. The distance between the probe tip and the sample is controlled using the shear-force feedback system.[6] The film under the probe tip is oxidized electrochemically by applying a positive bias voltage.[7] By altering the bias volt-

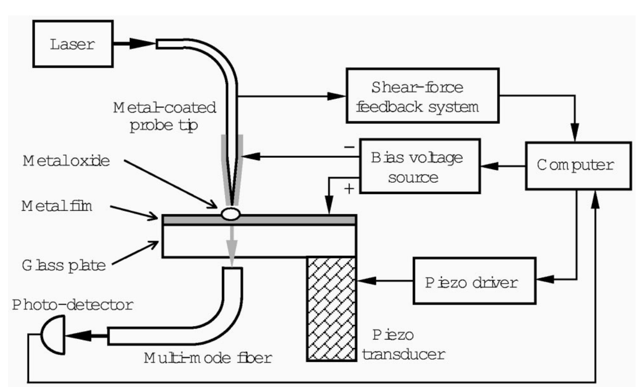


FIG. 1. Schematic setup of fabrication by anodic oxidation and observation of light propagation using a scanning near-field optical microscope.

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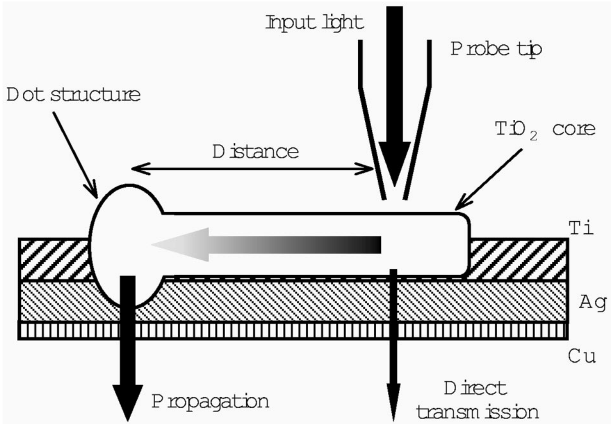


FIG. 2. Schematic structure of waveguide A with a dot structure for confirmation of the light propagation. Light injected from the probe tip is propagated in the waveguide, and is scattered to free space at the dot structure.

age, the thickness of the oxide layer can be controlled.[8–10] But, the width of the oxide appears to be determined by the curvature of the probe tip. Using the same SNOM in transmission mode, the optical properties of the waveguide are measured. A laser light with the wavelength of 830 nm and the polarization parallel to the waveguides is injected into the probe and illuminates the sample from a small aperture with a diameter of about 200 nm. The light transmitted through the sample is collected by a multimode fiber that corresponds to an objective lens with the numerical aperture of 0.2.

In order to confirm the light propagation, we have created a waveguide that has a dot structure at the end of it, as illustrated in Fig. 2. Light is injected from the probe tip at various positions on the waveguide. The background SNOM signal is measured by transmitting light directly through the metal clad. Since the near-field light has widely distributed wave numbers, parts of the injected light can couple with the surface plasmon and propagate as the SPP in the waveguide. When the SPP reaches the dot structure, a portion of the SPP is scattered into the free space as light. Light transmission is easier through the silver clad at the dot, because the clad is thinner there. Therefore, if the SPP reaches the dot structure, we expect the SNOM signal for the waveguide with the dot to be stronger than the waveguide without a dot.

Figure 3 shows topographic images of the waveguides measured using the SNOM probe tip. Waveguide A is

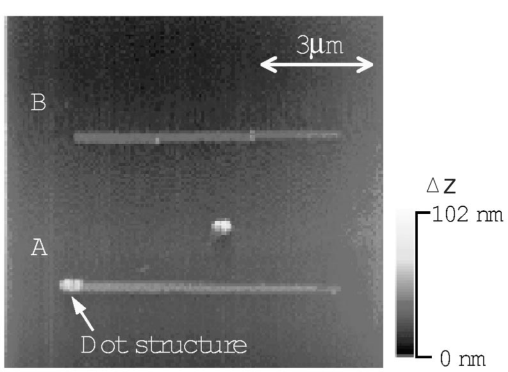


FIG. 3. Topographic images of the fabricated waveguides with the same width, thickness, and length of 300 nm, 70 nm, and 7 $\mu$m. Waveguide A has a dot structure with a radius of 400 nm and a height of 70 nm at the left end, and waveguide B has no dot structure.

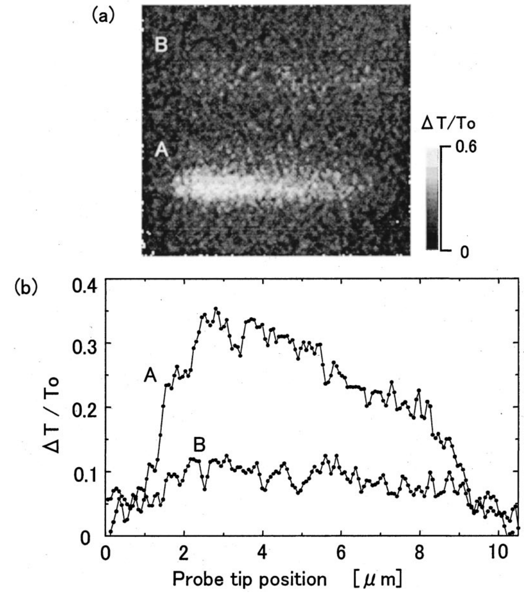


FIG. 4. (a) Transmission SNOM images of the waveguides corresponding to Fig. 3. (b) Cross-section profiles along waveguides A and B.

straight with a dot structure at the left end, and waveguide B is identical to waveguide A except for the dot structure. We can observe the oxidized area as the upheaval structure, because the molar volume of the titanium oxide is 2.5 times larger than that of the metal titanium. From this value, we estimate that 40% of the volume of the oxide is embedded in the metal, and that the thickness of the oxide is 1.7 times the observed height. Selecting a bias voltage of 35 V and scanning the probe tip with a velocity of 8 nm/s, straight waveguides 7 $\mu$m long, 300 nm wide, 70 nm thick, and a roughness of 5 nm or less are fabricated. For this bias voltage, the bottom of the oxide core is in contact with the silver clad. A dot with a diameter of 400 nm and a height of 70 nm is added to waveguide A by raising the bias voltage to 45 V. It is possible that the silver clad may be partially oxidized at the dot structure.

Figure 4(a) shows the transmission SNOM images corresponding to Fig. 3. Both waveguides show a larger transmission compared to the unoxidized metal surface, but the transmission for waveguide A is much larger than that for waveguide B. Waveguide A also shows an intensity gradient. The optical images of the wagveguides are three times wider than the topographic images. The differences may be caused by the aperture size of the probe tip and by the field size of the waveguide mode, and we guess another origin that the near field at the probe apex spreads along the gold film coating.[11] To analyze the details, the cross-section profiles of the SNOM images along each waveguide are compared using the transmission change $\Delta T/T_o=(T-T_o)/T_o$, where $T$ and $T_o$ are the transmission intensity at the probed position and that at the unoxidized surface, respectively. Since transmission increases uniformly in $\Delta T/T_o$ by $\sim 0.1$ along waveguide B with decreasing the clad thickness, we can conclude that the signal for waveguide B is originated from the background signal.[10] But, for waveguide A the value of $\Delta T/T_o$ is gradually increasing up to 0.35 from the right end to the dot structure.

Even though waveguides A and B are identical except

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for the dot structure on waveguide A, transmission signals for waveguide A are dependent upon the position of the probe, whereas waveguide B is not. Therefore, we conclude that the difference of the SNOM signals confirms light propagation in the waveguide structure. By subtracting the transmission signal for waveguide B from that for waveguide A, we can estimate the portion of the signal originating from light propagation. The signal of the propagated light is decreased by half for the distance of 5 $\mu$m. We conclude that the propagation length (assuming 1/*e* decay) is at least 5 $\mu$m. Our research suggests that SPP plays an important role in light propagation of metal-clad waveguides. As shown in Fig. 4(a), the near-field light can be coupled to the waveguide mode within 0.5 $\mu$m around the core. It suggests that light propagates confined two-dimensionally in the SPP mode. Propagation of SPP on flat metal surfaces has been investigated theoretically. Using dielectric parameters for silver and $TiO_2$, we estimate a propagation length of 11 $\mu$m. Our experimental result could be smaller than the theoretical calculation, because the SPP is confined two-dimensionally in the waveguide, because of absorption losses by the titanium metal, and because of scattering by the roughness of the core.

In conclusion, we have fabricated nanometer-sized waveguides by anodic oxidation using the SNOM probe tip and have demonstrated light propagation of several micrometers. While there is large propagation loss, our prototype waveguide is as small as wires in electronic-integrated circuits. In the future, lower-loss waveguides could be created by combining several nanofabrication techniques with higher accuracy and by selecting different materials. These waveguides could be key in constructing optical-integrated circuits.

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