Metal nanowires - a new class of plasmonic waveguides

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Abstract: *We present results of transmission measurements and mode analysis for metal nanowire waveguides with close-to-symmetric cross-sections, supporting propagation of long-range surface plasmon polariton waves. In contrast to conventional plasmonic waveguides, the waveguide structures presented here are polarization-insensitive due to the cross-sectional symmetry. At a free-space wavelength of 1064 nm, we measure a propagation loss of 0.43 dB/mm for two orthogonal polarization states. Transmission measurements at high input powers suggest that only a small part of this propagation loss can be attributed to ohmic loss in the metal.*

Introduction

The practical use of surface plasmon polariton (SPP) waveguides in integrated optical devices is hampered mainly by two factors, large propagation loss and strong polarization dependence. Two approaches have been followed in order to address the former issue; first, reducing the size of functional components to minimize propagation lengths and, consequently, the total insertion loss [1] and, second, a lowering of the propagation loss by reduction of the field-metal overlap, e.g. through the use of long-range surface plasmon polariton (LRSPP) thin-stripe waveguides as initially suggested by Berini [2]. Single-mode LRSPP waveguides with mode sizes close to that of a standard telecom fiber (e.g. SMF28) have been reported in the literature and novel integrated optical devices have been demonstrated [3-7].

The issue of polarization dependence, however, has remained largely unaddressed. A planar metal-dielectric interface only supports a TM-polarized wave having the main electric field component perpendicular to the interface, which seriously limits the applicability of devices based on conventional plasmonic waveguides, e.g. in optical networks. To circumvent this problem, a waveguide structure with a square cross-section consisting of a metallic nanowire embedded in a dielectric was proposed by Berini [8]. Transmission through such waveguides was recently demonstrated at 1550 nm wavelength in Ref. [9], where it was also shown that the effective index of the waveguide mode could be decreased by resistive heating of the waveguide core due to the negative *dn/dT* of the cladding polymer, enabling the design of a simple LRSPP-based variable optical attenuator. In the present paper, we report transmission measurements on nanowires designed to work at shorter wavelengths. We test also the nonlinear transmission of the metallic waveguides, related to heating caused by absorption of light in the core.

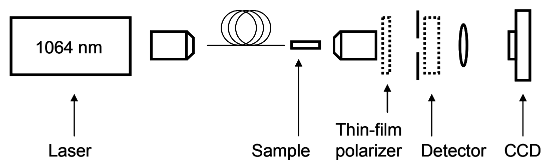

Fig. 1: Experimental set-up for waveguide transmission measurements and mode analysis.

Sample preparation and experimental set-up

Nanowire waveguides were fabricated in the following fashion: A 4” silicon wafer was coated with a 10-μm layer of a transparent polymer material (benzocyclobutane/BCB). The BCB was spin-coated with a 120-nm layer of electron-beam resist (PMMA). A series of 70-mm long stripes with nominal widths ranging from 92 nm to 108 nm was exposed in the resist using an electron beam writer (JEOL JBX 9300FS). 100-nm thick gold nanowires were fabricated by electron-beam deposition and lift-off and subsequently covered with a second layer of BCB. The wafer was diced into individual samples with waveguide lengths ranging from 2 mm to 20 mm.

The experimental set-up is illustrated in Fig. 1. Insertion loss measurements were made using 1064 nm light from a diode-pumped Nd:YAG laser (Coherent Inc.). The polarized laser light was coupled into an HB1000 polarization-maintaining optical fiber (Fibercore Ltd.). The light was transmitted to the waveguide by end-fire coupling. Fiber rotation or a waveplate in the beam path were used to generate different polarization states for the input light. The light at the output facet was picked up by a microscope objective, spatially filtered through a pinhole placed in the intermediate image plane and measured using calibrated Ge and Si photodetectors. For mode analysis, the output facet was imaged onto a CCD camera (Thorlabs Inc.) using a 10× microscope objective. A thin-film polarizer was used to distinguish between different polarizations at the output facet. High-resolution mode images were obtained by using a 100× infra-red microscope objective (Olympus MPlan IR) for imaging directly onto the CCD camera, omitting the intermediate lens and pinhole. The spatial resolution of the imaging system in this case is given by 0.6 λ / N.A. ~ 0.7 μm. For high-power transmission measurements, we used the intensity of scattered light from the input facet as a measure of the input power, in order to avoid errors due to variations in laser-to-fiber coupling efficiency.

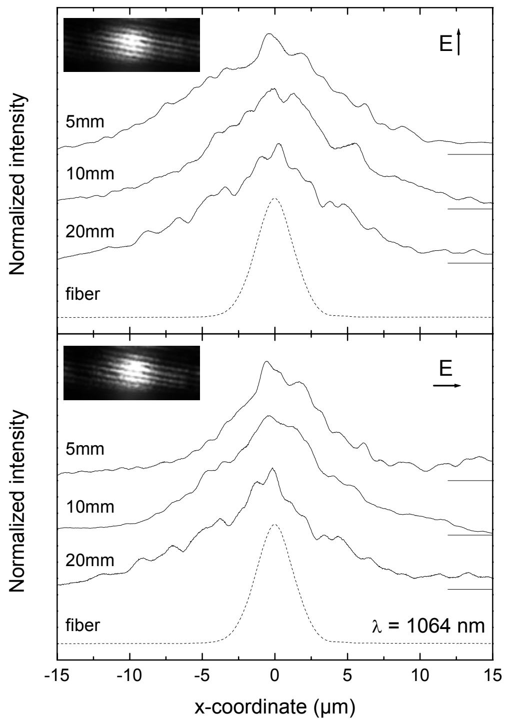

Fig. 2: Mode profiles recorded of at the output facets of nanowire waveguides samples of different lengths for orthogonal input polarizations. Irregularities in the intensity plots are due to dicing marks on the facet, as seen in the inset figures. The fiber mode is shown for reference.

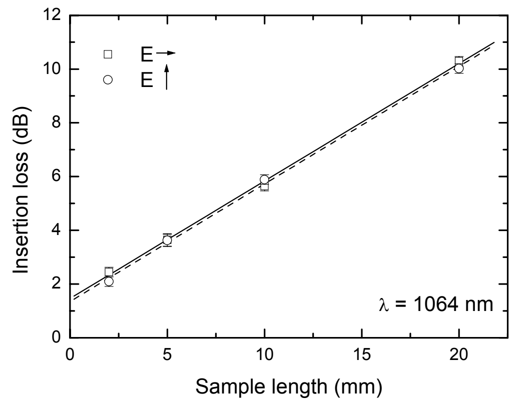

Fig. 3: Cutback measurements on nanowire waveguides for different input polarizations. The solid and dashed lines show the least-squares fit to the data points for horizontally and vertically polarized input fields, respectively, giving a propagation loss of 0.43 dB/mm for both polarizations.

Results

Images of waveguide modes at the output facet obtained using a 100× objective for horizontal and vertical input polarization are shown in Fig. 2 and the corresponding mode profiles along the x-direction (parallel to the cladding layers) are plotted for different sample lengths. The mode field diameter is approximately 20 μm for both polarizations and we do not observe significant changes in the mode shape with increasing sample length. Similar mode profiles were observed for 150 × 150 nm wires excited at 1550 nm wavelength [9].

Cutback measurements were performed using 4 sample lengths as shown in Fig. 3. A set of 15 waveguides was measured on each sample, consisting of 5 groups of 3 nominally identical nanowires. The width of the wires in the exposure file varied from 92 nm to 108 nm in steps of 4 nm. All waveguides transmitted both polarizations and no systematic difference in insertion loss for different waveguide widths was observed. Each data point in Fig. 3 therefore represents an average over several waveguide widths. A propagation loss of 0.43 dB/mm is observed for both polarizations. A 1.5-dB coupling loss from fiber to waveguide is measured. It should be emphasized, however, that this value is obtained by collecting light from the whole output facet and fiber-to-fiber loss measurements have yet to be conducted.

It has previously been established that absorption in LRSPP waveguides can lead to a measurable heating of the waveguide core [5]. Furthermore, a lowering of the effective index of LRSPP waveguides induced by a temperature increase in the polymer cladding obtained by driving electrical current through the waveguide core has been used to efficiently reduce waveguide transmission [4,9]. It is clear, therefore, that sufficiently high input power will result in reduced waveguide transmission due to absorptive heating of the waveguide core. In order to investigate this effect we measured transmission through a 5-mm long waveguide for input powers up to 325 mW, as shown in Fig. 4. At input powers above 200 mW, the transmission starts to deviate significantly from linear behavior, reaching a 0.5 dB (10%) extinction at 350 mW input power. We did not observe a significant change in the mode profile at the output of the waveguide when the input power was increased, consistent with the fact that the absorbed power decreases along the length of the waveguide and the weakening of the confinement should therefore be most pronounced close to the input end of the waveguide.

Discussion

Although the propagation loss in LRSPP waveguides is low compared to other SPP configurations, it is still much higher than in typical dielectric waveguides with the same degree of field confinement. The propagation loss can be partly accounted for by absorption in the metal film and in comparatively thick (>15 nm) stripe waveguides transmitting light at 1550 nm, this contribution has been shown to be dominating [7]. For thinner (<15 nm) stripe waveguides [7] and, in particular, for nanowire waveguides [9], the loss measured at 1550 nm is larger than expected. It is plausible to assume that the propagation loss in this case is limited by scattering

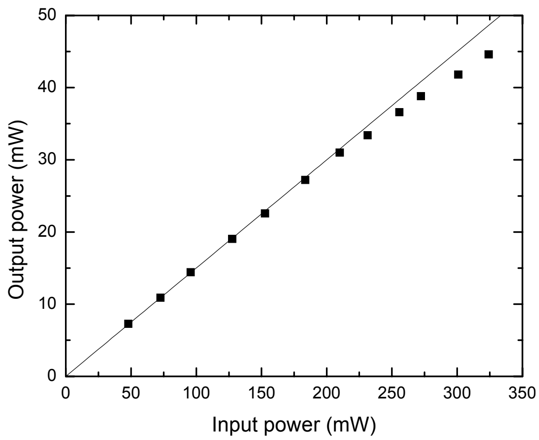

Fig. 4: Non-linear transmission through a 5-mm long nanowire waveguide. At high input powers, absorption in the waveguide core results in a heating of the waveguide which lowers its effective index and reduces the transmitted power.

due to structural imperfections in the waveguide core, absorption and scattering in the cladding layers, and coupling to the substrate and the top surface due to the finite thickness of the cladding layers. For shorter wavelengths, contributions from scattering as well as metal absorption should be more pronounced. Conversely, propagation loss in BCB is lower at 1064 nm wavelength (0.05 dB/mm) than at 1550 nm (0.2 dB/mm) [11].

We can make a rough comparison between the results plotted in Fig. 4 and data for extinction modulators based on nanowire waveguides operating at 1550 nm wavelength, reported in Ref. [9]. The confinement of the LRSPP mode is similar in the two cases due to the different wire geometries. In the case of the extinction modulator, 1.2 mW of electrical power passed through 1 mm of the waveguide is sufficient to reduce transmitted power by 10%. Taking into account 1.5 dB of coupling loss, we need only 0.02 dB/mm of propagation loss due to metal absorption to account for the observed decrease in transmission in Fig. 4. This value is similar to the theoretically predicted propagation loss for 150 × 150 nm gold nanowires embedded in SiO_2 [8].

In spite of the differences in geometry and wavelength between the two cases, the above comparison strongly suggests that significantly lower propagation losses can be obtained by improving the structural quality of the metallic waveguides. Recent measurements on short (10's of µm) silver nanowires showed a dramatic difference in the optical quality of single-crystalline and polycrystalline wires in the wavelength range 600–800 nm [12]. Fabricating centimeter-long single-crystal metallic nanowires with a symmetric cross section remains a technical challenge but advances in this field will certainly have a strong impact on applied plasmonics.

Conclusions

We have reported measurements on a new class of plasmonic waveguides based on metal nanowires embedded in a transparent polymer. We have demonstrated that waveguides with symmetric cross-sections are polarization insensitive which makes them particularly interesting for practical applications. The observed propagation loss is among the lowest reported for any SPP-based waveguide and high-power transmission measurements indicate that this can be further reduced if the structural quality of the waveguides can be improved.

Acknowledgments

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