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Propagation losses in gold nanowires

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ABSTRACT

We report direct measurement of propagation losses in single gold nanowires around visible and near-infrared bands. By directly measuring the propagation-distance-dependent output of the nanowire via fiber-taper-assistant near-field-coupling technique, we obtain a typical loss of 0.89 dB/μm at 785-nm wavelength in a 210-nm-diameter gold nanowire. We have also investigated the dependences of propagation losses on the nanowire diameter and light wavelength, and shown that the propagation loss is averagely increased with decreasing diameter and wavelength. Our results from direct measurements offer an unambiguous loss information of gold nanowires, as well as a helpful reference for gold-nanowire-based plasmonic circuits and devices.

1. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic waves coupled to free-electron oscillations at the surface of a conductor. Owing to the possibilities of breaking optical diffraction limits [1–3], as well as carrying optical and electrical signals in the same optoelectronic circuitry [4,5], one-dimensional plasmonic waveguides have shown great promise in areas such as nanophotonic devices and circuits [6–8]. Among various types of plasmonic waveguides [2,9–17], chemically synthesized metal nanowires [13,14] have been attracting increasing attentions owing to their single crystallinity, atomic surface smoothness, uniform diameters and high yields [15–17].

When being confined to deep-subwavelength scale, plasmonic modes propagated in nanowires usually suffer from absorptive losses originated from internal damping of radiation in metals (i.e., Ohmic losses of the metal). In recent years, SPP propagation in silver nanowires, which suffers the lowest intrinsic losses in visible and near-infrared (NIR) spectral ranges, has been extensively investigated [7,8,18]. However, silver is chemically unstable under ambient conditions, readily reacting with oxygen and hydrogen sulfide, which results in a short lifetime of silver nanowires (typically several days) and prevents their uses in open air and many other atmospheres.

Gold, by contrast, provides very high chemical stability and relatively low loss for plasmonic waveguiding [19,20] as have been demonstrated for plasmonic applications in various structures including film, strips and wires [11,21–26], and have shown great potential for plasmonic waveguiding in NIR spectral ranges. Gold nanowires with diameters down to tens of nanometers and lengths up to tens of micrometers, have been synthesized with excellent structural properties similar to those of the silver nanowires, and have shown great potential in applications including optical sensors and nanophotonic interconnects [27,28]; however, compared to silver nanowires, gold nanowires suffer additional damping at optical frequencies due to interband absorption, resulting in relatively shorter propagation lengths. To determine such a tradeoff between propagation losses and chemical stabilities, it is therefore critical to quantitatively measure the propagation losses of the gold nanowires. Previously, propagation losses in gold nanowires have been investigated either theoretically or experimentally [29–32]; however, the reported propagation losses or lengths are largely divergent, mainly due to the indirect measurement technique, inefficient SPP excitation by outside probing light and the short decay length in the gold nanowire.

In 2010, we demonstrated a simple, direct measurement of propagation losses in single silver nanowires [33]. With a tapered fiber for highly efficient launching, propagation SPPs were excited in the nanowires with high efficiency. The loss information was retrieved from propagation-length-dependent output from the other side of the nanowire with good repeatability. Based on this direct measurement technique, here we investigate the propagation lengths of gold nanowires in a more systematic way, and report the loss information of gold nanowires unambiguously, as well as the self-consistent dependences of propagation losses on the nanowire diameter and light wavelength.

2. Experimental

The gold nanowires used here were synthesized by a typical ultrasonic-assisted seed-mediated growth method [34] and washed

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afterward [16]. The as-synthesized gold nanowires, suspended in an aqueous solution, were then deposited on a glass slide and dried under ambient conditions. Fig. 1 shows scanning electron microscope (SEM) images of a typical nanowire with smooth surface and excellent uniformity.

The optical excitation and loss measurement system is schematically illustrated in Fig. 2. To effectively excite SPPs in a gold nanowire, we utilize a fiber taper to evanescently coupling light into the nanowire via near-field interactions. We draw one end of a fiber into sharp taper using a flame-heated taper-drawing technique [35]. By controlling the drawing speed of about 5 m/s, relatively sharp fiber taper with distal end size of about 200 nm can be repeatedly fabricated. The as-fabricated fiber taper is mounted on a precise three-dimensional moving stage and brought into close contact with the gold nanowire under an optical microscope by micromanipulation. The precision stage with tapered fiber is mounted on the optical table and maintain a relatively constant position with the whole system. Using an ultra-long work distant objective, we can clearly see gold nanowires on a glass slide. Adjust the axes to push the fiber tip into the field of view under the microscope, and the fiber tip will be blurred because of the limit of the depth of field. Then we travel the vertical axis of the stage until the fiber tip and the gold nanowire are in the same horizontal plane, i.e., can be seen clearly through the microscope. Next we adjust the x and y axes to bring the fiber taper into close contact with the gold nanowire. When the probing light is launched from the fiber taper into the nanowire, we carefully adjust the angle and position of the fiber taper until the coupling is optimized with maximum output observed from the output end of the nanowire.

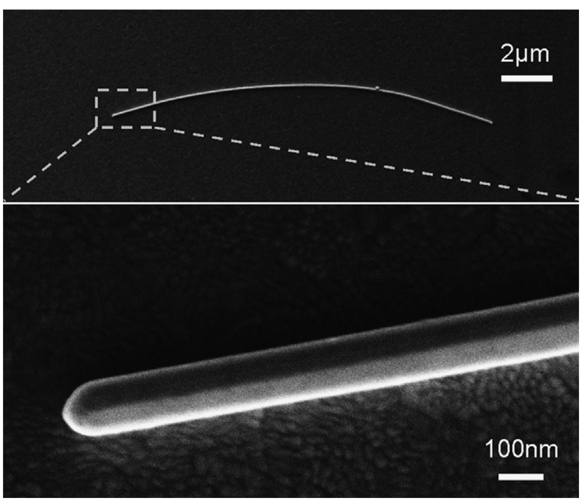

Fig. 1. SEM image of a gold nanowire synthesized by an ultrasonic-assisted seed-mediated growth method. The gold nanowire, about 130 nm in diameter and 15 μm in length, was placed on an indium tin oxide (ITO) substrate for SEM observation. Bottom, a magnified image of one end of the nanowire.

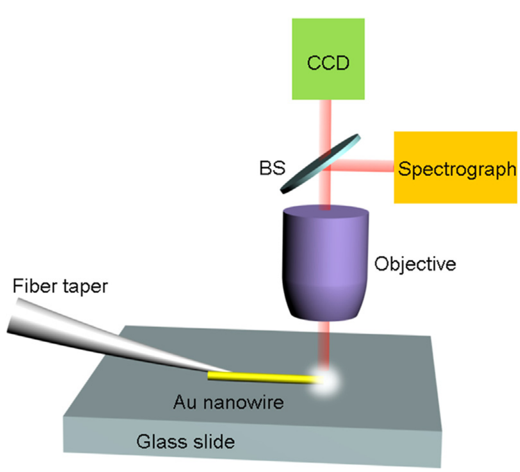

Fig. 2. Schematic illustration of the optical excitation and loss measurement system. With a beam splitter (BS) to divide the output beam into two parts, a CCD camera and a spectrograph can be used to observe and to measure the output intensities of a gold nanowire, respectively.

3. Results and discussions

Fig. 3 shows microscope images of a 200-nm-diameter gold nanowire supported on a glass slide when monochromatic lasers of wavelength 785 nm, 650 nm and white light from a halogen lamp are used as light sources to excite the SPPs in the nanowire, respectively. Evident light scattered from the end of the nanowire are observed. Due to the higher fractional output and lower propagation loss of propagation plasmons at longer wavelengths, the white-light excitation results in red light output at the output end. Polarization dependences of the nanowire outputs in Fig. 3(e–f) are investigated with a linear polaroid. When the polarization is parallel to the nanowires, the output from the gold nanowire is maximized and conversely, when the polarization is perpendicular to the nanowires, the output from the gold nanowire vanishes.

To investigate the propagation loss (α), it is more convenient to use the propagation length (L_0) for characterization. The propagation length is usually defined as the energy decay length of the SPPs propagating along the nanowire, that is,

$$I(x) = I_0 \exp\left(\frac{-x}{L_0}\right) \quad (1)$$

where I_0 is the initial intensity and x is local position along the length. By measuring the normalized output intensity of a gold nanowire with different propagating distances, the propagation length L_0 is obtained, and the propagation loss α, which is inversely proportional to L_0, can thus be determined [33].

In the measurement, to keep the coupling efficiency a constant, we horizontally move the fiber taper along the length of the nanowire without changing the contact angle between the fiber taper and the nanowire. We measure the output intensities from the other end of the nanowire while changing the coupling position along the nanowire simultaneously, and obtain the relationship between the output intensities and the propagation distances.

Fig. 4 shows the x-dependent normalized output intensities $I(x)$ of a 210-nm-diameter gold nanowire at 980-nm (black square), 785-nm (red dot) and 650-nm (blue triangle) wavelength, respectively. Using a nonlinear least-squares fitting method, the experimental results are fitted with solid curves. We obtain SPP propagation lengths L_0 of 5.6 μm (980 nm), 4.9 μm (785 nm), 3.4 μm (650 nm) and calculate the propagation losses to be 0.78 dB/μm (980 nm), 0.89 dB/μm (785 nm), 1.28 dB/μm (650 nm), respectively. Compared with the silver nanowire (propagation length typically on the 10-μm level), the gold nanowire exhibits a much smaller propagation length, or equivalently much higher propagation loss. The low deviation of the measured values with respect to the fitted curves shows that the measurement is self-consistent. Also, it is reasonable to see higher losses at shorter wavelengths.

Meanwhile, we have also investigated the propagation losses of gold nanowires with different diameters. The propagation-distance-dependent normalized output intensities of 100-nm (green triangle), 120-nm (purple triangle), 180-nm (red dot), 270-nm (black square) diameter gold nanowires at 785-nm wavelength are shown in Fig. 5.