Direct measurement of propagation losses in silver nanowires

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We demonstrate a simple, direct measurement of propagation losses in single silver nanowires. Using a waveguiding nanoscale fiber taper for highly efficient launching, propagation surface plasmon polaritons are excited in the silver nanowire with high efficiency. The output intensity as light radiation at the end of the nanowire is quantified with high accuracy and repeatability. A typical propagation loss of 0.41 dB/μm (for 633 nm light) in a 260 nm diameter silver nanowire is obtained, which suggests that the propagation loss of a single silver nanowire could be lower than previously reported experimental results and should be much lower than those obtained by theoretical calculations. © 2010 Optical Society of America

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Surface plasmons polaritons (SPPs) are electromagnetic waves coupled to collective oscillations on the surface of a metal [1]. They are bound to, and propagate along, the metal–dielectric interface. In the past years, SPP in metallic nanostructures has been widely investigated, because it offers the possibility of breaking the optical diffraction limit and confining light to the deep subwavelength scale, as well as carrying optical and electrical signals in the same optoelectronic circuitry [2]. Recently, the waveguiding of SPPs along one-dimensional structures [3] has been attracting intensive attention. A number of strategies, such as metallic nanohole arrays [4,5], planar metal waveguides [6], metal nanowires [7,8], channel plasmon polaritons [9], long-range SPP waveguides [10,11], and dielectric-loaded SPP waveguides [12] have been suggested for this purpose. Among these structures, silver nanowires that can be routinely fabricated with smooth surfaces and uniform diameters are one of the most considered structures [3,8,13]. When confined to subwavelength scale, plasmonic nanostructures usually suffer from high Ohmic losses, and the loss characterization is critical to their uses as subwavelength-scale waveguides. There are several reports on the propagation loss in plasmonic waveguiding structures [14–19], but estimating the propagation loss in silver nanowires remains a challenge because of their high loss, low dimension, and inefficient SPP excitation by outside probing light. Ditlbacher *et al.* reported propagation loss of about 0.43 dB/μm for silver nanowires using a Fabry–Perot resonance method [8], in which the propagation loss was estimated from relative modulation depth of the spectra data of several nanowires. While the accuracy of this method is highly dependent on the endface reflections of silver nanowires, the endface shape of these as-synthesized silver nanowires may differ from one another. Furthermore, owing to the high losses of the silver nanowires, this method is not applicable to long silver nanowires, as there will be no observable resonance. Theoretical simulations may offer helpful loss information of silver nanowires; however, based on dielectric constants of bulk materials, theoretically calculated losses are usually much higher than the experimental values. For example, recently Chen *et al.* reported a calculated propagation loss of 0.72 dB/μm in a 328 nm diameter silver nanowire at 633 nm wavelength and 3.62 dB/μm in a 136 nm diameter silver nanowire [18]. The large divergence may arise from the fact that the permittivity of bulk silver used in the simulation is not applicable to nanoscale one-dimensional wires, whereas the values of material of such a low dimension are not well known in literature [20].

Very recently, relying on near-field interaction for SPP excitation, highly efficient coupling between plasmonic and photonic nanowires was reported by simply making the two nanowires in contact [21], which offers a convenient approach for SPP excitation in silver nanowires with good repeatability. Here, by means of near-field excitation, we demonstrate a simple and direct method to characterize the propagation loss in silver nanowires. A waveguiding nanoscale fiber taper (nanotaper) is used to excite propagation SPP from one side of a silver nanowire, and the loss information is retrieved from propagation-length-dependent output from the other side of the nanowire with good repeatability.

The silver nanowires used in this work were synthesized by a soft (with temperatures less than 200°C), solution phase approach [13]. The basic idea is reducing silver nitrate ($AgNO_3$) with ethylene glycol (EG) in the presence of poly(vinyl pyrrolidone, PVP). In a typical synthesis, 6 mL of $AgNO_3$ (0.1666 g) and PVP (0.6742 g) solution (in EG) were added dropwise to 5 ml of EG heated at 160°C in a round-bottom flask over a period of 8 min. The reaction mixture was continued with heating at 160°C for 40 min until all $AgNO_3$ had been completely reduced. As-synthesized nanowires were purified by centrifugation, once diluted in acetone (5× by volume) to remove EG and four times in ethanol (10× by volume) to remove PVP. The final product consists of silver nanowires (bicrystalline), a small fraction of silver nanoparticles, and trace amounts of PVP. Figure 1 shows typical scanning electron microscope (SEM) images of an as-synthesized silver nanowire with diameter of 260 nm. The excellent uniformity and smooth surface are clearly seen.

To efficiently launch light into a single silver nanowire, we use a nanotaper for SPP excitation [21], as shown in Fig. 2(a). We first fabricate a nanotaper with tip diameter down to 200 nm from standard glass fibers (Corning SMF-28) using a flame-heated drawing technique and mount it on a precise three-dimensional moving stage [22]. Second, the as-fabricated silver nanowires are dispersed onto a microscope glass slide. Then, we move the nanotaper to make a close contact with a silver nanowire under an optical microscope. When the probing light is launched from the nanotaper into the nanowire, we carefully adjust the angle and position of the nanotaper until the coupling is optimized with maximum output observed from the output end of the silver nanowire.

The propagation loss α is inversely proportional to the propagation length L_0 as

$$\alpha = \frac{-10 \times \log(1/e)}{L_0} \approx \frac{4.343}{L_0}, \tag{1}$$

where L_0 is the propagation length over which the intensity of SPPs decreases to $1/e$ the initial values. The propagation length of the silver nanowire can be estimated from the light intensity output from the end of the nanowire, which exponentially decreases as

$$I(x) = I_0 \times e^{-x/L_0}, \tag{2}$$

where I_0 is the initial intensity and x is local position along the length. By measuring the output intensity of a silver nanowire with different propagating distances (x), the propagation length L_0 and subsequently the propagation loss α can be determined.

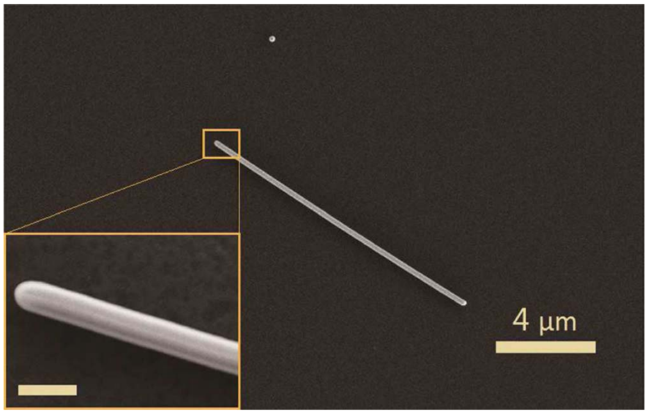

Fig. 1. (Color online) SEM image of a 260 nm diameter silver nanowire synthesized by a soft solution method. The inset shows a close-up image of one end of the silver nanowire. Scale bar, 400 nm.

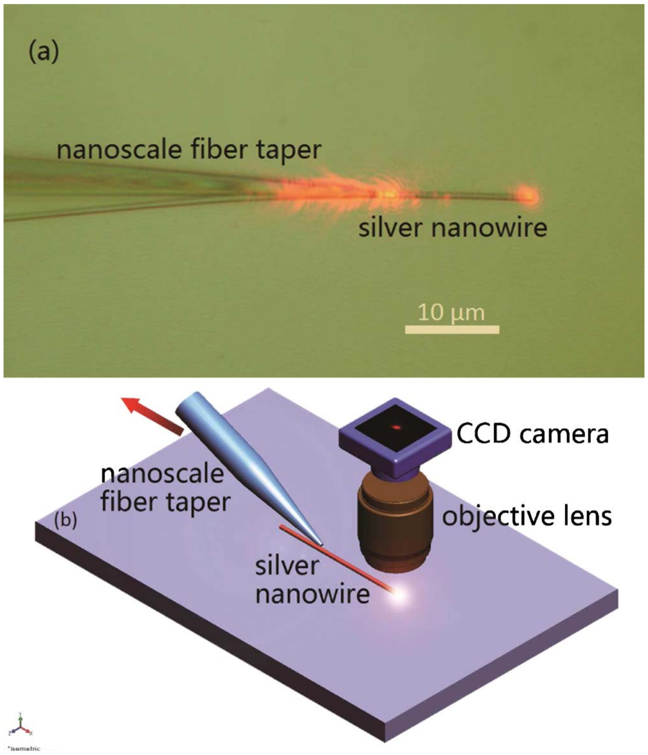

Fig. 2. (Color online) (a) Image of the excitation of SPPs in a silver nanowire under a microscope. (b) Sketch of the optical excitation and loss measurement system. The red arrow indicates the direction along which we move the nanotaper. A microscope with 100× objective lens and a CCD camera were employed to observe the output intensity of a silver nanowire excited by a nanotaper.

The loss measurement system is schematically shown in Fig. 2(b). To obtain the x-dependent output intensity $I(x)$ of the nanowire, we horizontally move the nanotaper along the length of the nanowire without changing the contact angle between the nanotaper and the nanowire (so that the coupling efficiency is kept constant). In the measurement, we first image the output intensity of the nanowire by using a calibrated CCD camera (DXM1200F, Nikon) without saturation, select an 80×80 pixel area (centered on the output spot) of the captured image, and transform the brightness into gray level information by using Adobe Photoshop (a similar approach was employed in recent work [19]), and then obtain the normalized output intensity by summing up the gray values, as shown in Fig. 3, in which a 260 nm diameter silver nanowire was investigated at 532, 633, and 980 nm wavelengths, respectively.

Using a nonlinear least-squares fitting method based on Levenberg–Marquardt algorithm on the x-dependent $I(x)$ shown in Fig. 3, we obtain SPP propagation lengths L_0 of 6.77 μm (532 nm), 10.56 μm (633 nm), and 13.27 μm (980 nm) of the silver nanowire, respectively, and calculate the propagation losses by using Eq. (1) with 0.64 dB/μm (532 nm), 0.41 dB/μm (633 nm), and 0.33 dB/μm (980 nm), respectively. Compared with previous work, propagation losses of the silver nanowire obtained here are much lower than the theoretical calculations [18] and seem to support indirect experi-

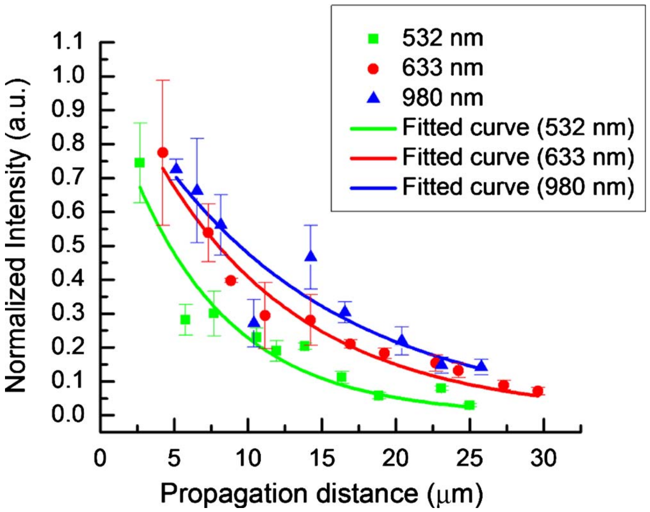

Fig. 3. (Color online) Propagation-distance-dependent normalized output intensities (dots) of a 260 nm diameter silver nanowire at 532, 633, and 980 nm wavelengths, respectively. The solid curves fit the experimental results by use of a nonlinear least-squares fitting method. The error bars show the standard deviations of output intensities from data collected within 1 μm ranges.

mental estimations [8,19] with possibly lower values. Also, it is reasonable to see relatively low loss in the IR region. In addition, in Fig. 3, the fitted curves show good agreement with the experimental data, indicating that the coupling efficiency is almost kept constant during the measuring process, verifying the validity of the direct measurement approach used in this work.

In conclusion, we introduce a simple and direct method for characterizing the propagation loss in silver nanowires. A typical loss of 0.41 dB/μm for 633 nm wavelength light in a 260 nm diameter silver nanowire is obtained, which is much lower than those obtained by theoretical calculations and tends to support previous reported experimental results with possibly lower values.

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