Experimental Demonstration of Plasmon Propagation, Coupling, and Splitting in Silver Nanowire at 1550-nm Wavelength

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***Abstract*—We experimentally demonstrate silver-nanowire-based plasmonic devices including the nanowaveguide, the nanocoupler, and the nanosplitter at optical communication wavelength of 1550 nm. The plasmon propagation loss in a 300-nm diameter silver nanowire is measured to be 0.3 dB/μm and the effective propagation length is 14.5 μm. This loss is comparatively lower than that at 980 nm. Two types of plasmonic functional devices based on the coupling between two silver nanowires, nanocouplers, and nanosplitters, are realized. For the nanocoupler, the experimental results show that the plasmonic modes can be efficiently coupled between two closely positioned nanowires. While for the nanosplitter, the plasmonic mode is split with a power ratio of 2.6:1. These demonstrations experimentally prove the feasibility of extending the operating wavelength of silver-nanowire-based plasmonic devices to current optical communication wavelength with a lower loss, which are thus important steps for potentially utilizing low-loss nanowire-based plasmonic components for photonic integrated circuits.**

***Index Terms*—Coupling, plasmonic devices, silver nanowire, surface plasmons polaritons (SPPs).**

I. Introduction

SINCE the invention of integrated circuits in 1959, the number of transistors on a single monolithic chip has continuously scaled at a pace described by Moore's law. However, the integration of modern electronic devices for information processing is rapidly approaching an interconnect bottleneck due to the increased signal delay and the high electronic power dissipation, which is thus a substantial hurdle to further advances in the electronic industry [1]–[3]. Photonic devices, on the other hand, possessing a significantly high bandwidth and reduced power dissipation, may offer new solutions for circumventing these problems [1]–[3]. However, a major problem with photonic devices is the far lower levels of integration and miniaturization available compared with their electronic counterparts. When the sizes of photonic devices shrink to the wavelength of light, the light propagation is obstructed by diffraction limit, thereby limiting the minimum size of optical structures in photonic integrated circuits (PICs). Surface plasmons polaritons (SPPs), which are optically induced oscillations of free electrons at the surface of a metal, allow the concentration of light in a nanoscale volume and thus mediate strong optical interactions within this volume. Therefore, the SPPs combine the compactness of an electronic circuit with the bandwidth of a photonic network and are thus promising for bridging the gap between the world of nanoscale electronics and microscale photonics. Thus far, the waveguiding of SPPs has been demonstrated in a number of strategies, such as metallic nanohole arrays, metal–insulator–metal structures, channel plasmon polaritons, long-range SPP waveguides, dielectric-loaded SPP waveguides, hybrid plasmonic waveguides, and metallic nanowires [3]. Among these structures, silver nanowires, which can be routinely chemically fabricated with atomically smooth surfaces, are particularly attractive for nanoscale confinement and guiding [4]–[16]. So far, the research into the SPPs in the silver nanowire has mainly focused on the excitation, the propagation, and the radiation of SPPs. Several methods for the plasmon excitation in silver nanowires have been demonstrated, including prism coupling [4], [5], focusing of light onto one end of the nanowire with a microscope objective [6]–[9], nanoparticle-mediated coupling [10], dielectric waveguide coupling [11]–[13], nanotaped fiber coupling [14], [15], and direct excitation on an laser diode chip [16]. All the aforementioned research has been conducted at wavelengths between 450 to 1000 nm. To fully take advantage of the current mature optical communication technology, the most economic operating wavelength for the potential application of SPPs in the PICs is thus around 1550 nm. Therefore, it is of vital importance to explore the feasibility of SPPs operating around this particular wavelength. In this paper, the excitation, the propagation, the coupling, and the splitting of SPP modes in the silver nanowire at the 1550-nm optical communication wavelength are demonstrated. This research is useful for the exploration of potential applications of nanowire-based plasmonic components in PICs.

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II. Silver Nanowire Synthesization and Coupling Method

A. Silver Nanowire Synthesization

The crystalline silver nanowires used in this study are synthesized using a soft, self-seeding, polyol process, as reported

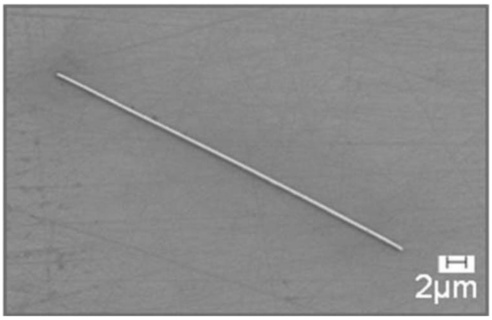

Fig. 1. (a) SEM image of a silver nanowire synthesized by a soft solution method. The nanowire has a diameter of 300 nm and a length of 45 μm.

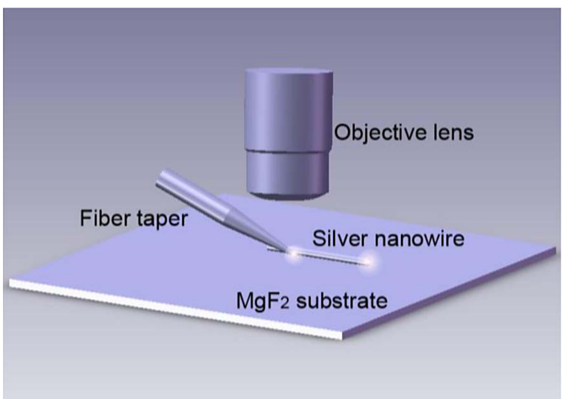

Fig. 2. Sketch of the optical excitation of SPP at 1550 nm in the silver nanowire.

previously [17], [18]. The basic idea is reducing the 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) are 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 is continued with heating at 160 °C for 40 min until all $AgNO_3$ is totally reduced. The synthesized nanowires are washed via centrifugation once in acetone to remove EG, and then twice in ethanol to remove PVP. The final product consists of silver nanowires (bicrystalline), a small fraction of silver nanoparticles, and trace amounts of PVP and ethanol. Fig. 1 shows typical scanning electron microscope (SEM) image of a silver nanowire with a diameter of approximately 300 nm and a length of 45 μm.

B. Nanotaper Coupling

To efficiently launch light into a single silver nanowire, a nanoscale fiber taper is exploited for the excitation of SPPs in the silver nanowire, as is shown in Fig. 2. The nanotaper, which has a tip diameter of around 200 nm, is fabricated from standard glass fibers (Corning SMF-28) using a flame-heated drawing technique [19]. The nanotaper is then mounted on a stage and the tip is moved in close contact with a silver nanowire on top of the MgF_2 substrate. Due to the inclusion of substrate, the SPPs in silver nanowires are leaky modes with part of the energies

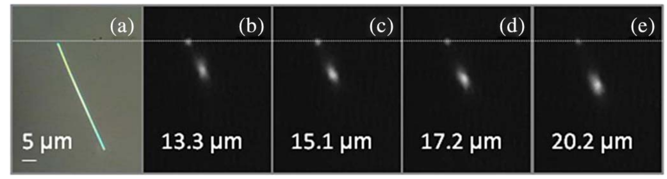

Fig. 3. (a) Optical microscope image of nnaowaveguide. The SEM image is shown in Fig 1. (b)–(e) Dark-field optical microscope images of light coupled into the nanowire at different exciting spots, showing the SPP propagation in silver naowires. The lower bright spots are the SPPs excitation at different locations. The upper bright spots correspond to nanowire ends where the SPPs couple to free-space photons. The distances between the excitation spots and the wire ends in four measurements are also indicated.

leak to the substrate. The choice of the substrate is based on two considerations: 1) to reduce the portion of energy leaking to the substrate, the substrate with a refractive index close to 1 is preferable; and 2) to facilitate the efficient coupling from the nanoscale silica fiber taper, the refractive index of the substrate should be lower than 1.45. In our experiment, the MgF_2 with a refractive index of 1.38 is chose as the substrate material. When the 1550-nm probe light is launched from the nanotaper into the nanowire, it excites SPPs, which propagate along the length of the silver nanowire and couple to free-space photons at the end. An objective lens is used to collect the scattered light and a near infrared camera (MicronViewer 7290 A) is employed to observe the scattered intensity along the silver nanowire.

III. Silver-Nanowire-Based Plasmonic Devices

A. Nanowaveguide

By using the nanotaper, the 1550-nm probe light is coupled to excite the SPPs in the nanowire shown in Fig. 3(a). Fig. 3(b)–(e) shows the dark-field optical microscope images of the SPP propagation when the light is coupled into the silver nanowire from different points along the length of the nanowire. Bright spots from the other end can be clearly seen, demonstrating the effective excitation of SPPs in the silver nanowire. The output intensity from the end of the nanowire decreases exponentially with the SPP propagation length. Therefore, the SPP propagation loss in the silver nanowire can be retrieved from the propagation-length-dependent output intensity from the end of the nanowire [14].

In the experiment, the nanotaper is moved along the length of the nanowire while the contact angle between the nanotaper and the nanowire is kept unchanged to maintain a constant coupling efficiency. From Fig. 3 (b)–(e), it can be seen that the shape and brightness of the excitation spot are almost kept unchanged when the nanotaper is moved, demonstrating that the coupling efficiency is almost constant. The brightness in the output end increases as the nanotaper moves close to the end. Fig. 4 provides the plot of logarithm of intensity from the output end versus the distance between the excitation spot and the wire end. The solid line is a fit of the data to an exponentially decaying function. The obtained propagation loss α is 0.3 dB/μm at 1550 nm in the 300-nm diameter silver nanowire. The effective propagation length L_0, which is inversely proportional to the propagation

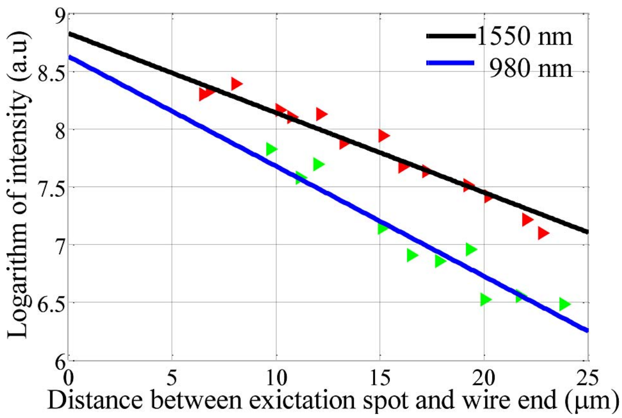

Fig. 4. Plot of the logarithm of output intensity from the end of the nanowire versus the distance the between excitation spot and the wire end. The black and blue solid lines represent fitting of the data to exponentially decaying functions at 1550 nm and 980 nm, respectively.

loss α, is 14.5 μm. Fig. 3 also provides the data when the probe light wavelength is 980 nm. The obtained propagation loss is 0.41 dB/μm and the effective propagation length L_0 is 10.5 μm at this wavelength. Therefore, the SPP has a longer propagation length at 1550 nm than at 980 nm due to comparatively low loss of silver at 1550 nm. The observed comparatively short propagation length in the nanowire probably originates from the rough surface. Although the surface of the silver nanowire seems smooth in the optical microscope image, it is still quite rough as seen from the SEM image at a high magnification.

B. Nanocoupler

We next demonstrate coupling between two silver nanowires. We form the nanocoupler by positioning two silver nanowires in close proximity to each other. In the experiment, the nanowires are positioned by micromanipulation under an optical microscope. A scanning tunneling microscope probe, synthesized by electrochemical etching method, is mounted on a precisely controlled 3-D moving stage to position the two nanowires. Fig. 5 shows the SEM image of the nanocoupler. The inset shows a close-up image of the coupling region. The lengths of the left and the right waveguides are 12.6 and 15.5 μm, respectively. The diameters for both nanowires are around 400 nm. The length of the coupling region is 6 μm and the air gap between the two nanowires varies from 0 to 180 nm.

When the 1550-nm probe light is launched from one end of the nanocoupler, it will couple to another nanowire due to the directional coupling in the contact region. Fig. 6(a) provides the dark-field optical microscope image of the light observed from the objective when the light is launched from point A. Fig. 6(b) shows the intensity profile of the output light along the cut lines AC and BD. Spots B and C correspond to the two ends of the coupling region, which are discontinuities in the SPP propagation direction. These discontinuities heavily scatter propagating SPPs into free-space photons and can thus be detected by the camera. Spot D is the bright scattering light spot at the end of the other nanowire, which is a direct demonstration

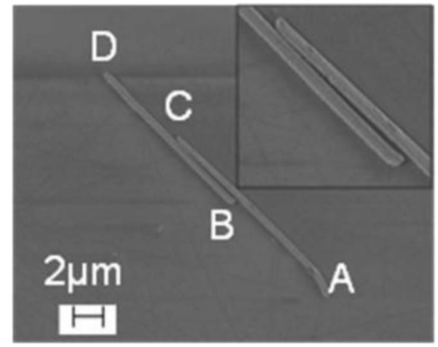

Fig. 5. SEM image of the nanocoupler. The inset shows a close-up image of the coupling region.

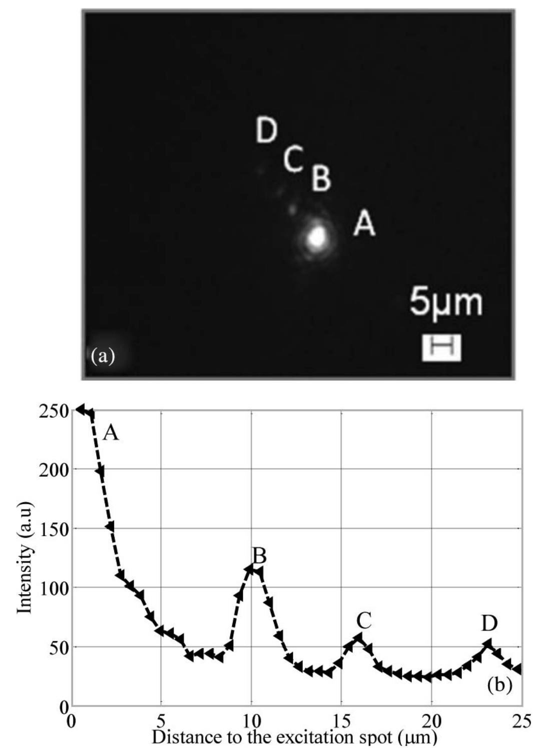

Fig. 6. (a) Optical microscope image illustrates the propagation of light along the nanowire coupler. (b) Intensity profile of the output light along the cut lines ABCD as indicated in (a).

of the efficient SPP coupling between the two silver nanowires.

C. Nanosplitter

By utilizing the directional coupling between two adjacent silver nanowires, a nanosplitter is further constructured. The SEM image of the silver nanosplitter is shown in Fig. 7. The two branches of the nanosplitter are placed with an angle of 30°. The lengths of the two branches of the nanosplitter are 7 and 9.3 μm, respectively. The diameters for both branches are around 200 nm.

The 1550-nm probe light is launched from right end (Point A) and it will then split at the cross of the two branches (Point B). The gray-scale optical microscope image of the light

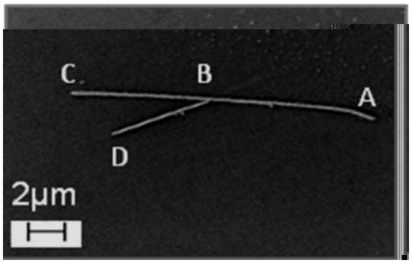

Fig. 7. SEM image of the nanosplitter.

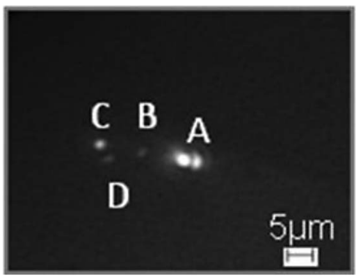

Fig. 8. Dark-field optical microscope image of the light propagation through the nanosplitter. Two bright light spots (C and D) are observed at the ends of the two branches of the nanosplitter.

propagation through the splitter is shown in Fig. 8. Two bright spots from the ends of the two branches (Spots C and D) can be observed, demonstrating effective SPP power splitting between the two silver nanowires. The output intensity ratio between the two branches is 2.6:1.

IV. Conclusion

In conclusion, we have demonstrated the excitation, the propagation, the coupling, and the splitting of SPP modes in silver nanowire at the 1550-nm optical communication wavelength. Three nanoscale plasmonic components, namely a nanowaveguide, a nanocoupler, and a nanosplitter, have been demonstrated and their optical properties have been characterized. At the communication wavelength, the propagation loss of the SPPs in the 300-nm diameter silver nanowire is measured at 0.3 dB/μm, which is comparatively lower than that at 980 nm. For the nanocoupler, an efficient light coupling from one silver nanowire to another is demonstrated. A two-port output nanosplitter consisting of two adjacent nanowires has also been realized. A power ratio of 2.6:1 between the two output branches is obtained. These demonstrations experimentally prove the feasibility of extending the operating wavelength of silver-nanowire-based plasmonic devices to the optical communication wavelength with a lower loss, which are essential steps for utilizing low-loss nanowire-based plasmonic components for PICs.

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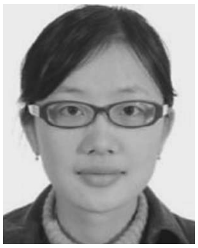

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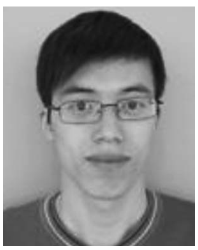

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