# Propagation of light in serially coupled plasmonic nanowire dimer: Geometry dependence and polarization control

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# Propagation of light in serially coupled plasmonic nanowire dimer: Geometry dependence and polarization control

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We experimentally studied plasmon-polariton-assisted light propagation in serially coupled silver nanowire (Ag-NW) dimers and probed their dependence on bending-angle between the nanowires and polarization of incident light. From the angle-dependence study, we observed that obtuse angles between the nanowires resulted in better transmission than acute angles. From the polarization studies, we inferred that light emission from junction and distal ends of Ag-NW dimers can be systematically controlled. Further, we applied this property to show light routing and polarization beam splitting in obtuse-angled Ag-NW dimer. The studied geometry can be an excellent test-bed for plasmonic circuitry. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4752718]

How to propagate and localize light at subwavelength scale? This is an important question in nanophotonics[1–3] and a reliable solution has great relevance in realizing nano-circuits of light. In dielectric optics, diffraction of light has been a major hindrance to control light at nanoscale, but in recent years metallic nanostructures that support surface plasmons[4,5] have opened up new avenues to propagate and localize light at subwavelength regime.[6] This has led to tremendous interest in interaction of light with nanoscale plasmonic geometries,[4,7] such as silver nanowires (Ag-NW),[8] that can be harnessed as circuit-element in a nanophotonic circuit. For such circuits to emerge, it is necessary to further develop and understand capability of plasmonic nanowires to perform various logical functions similar to circuit elements in electronics. In the context of plasmonic nanowire circuits, there are certain issues that need to be probed and understood, such as: the capability of plasmonic nanowires to transmit light from one nanowire to another; the effect of nanowire coupling on propagation of light; the ability to control the fan-out in coupled nanowire systems. Motivated by this requirement, herein we study light transmission and emission in a specific plasmonic nanowire system: self-assembled, end-to-end coupled Ag NW dimers with a certain bending angle between them. The objective of this study was two-fold: (1) to find the effect of bending angle between the silver nanowires on surface plasmon polariton (SPP)-assisted light propagation; (2) to control the intensity of light emission at the junction and distal ends of the Ag NW dimer via polarization of incident light. As a consequence of polarization control, we also showed capability of Ag NW dimer to route light and act as polarization beam splitter.

Ag NWs have been previously studied in the context of nano-waveguides,[8–16] optical logical gates,[17] quantum optics,[10] surface enhanced Raman scattering (SERS),[15,18–20] fluorescence,[21] chiral plasmons[22] etc., indicating their versatility as nanophotonic element. In this study, we employ an end-to-end coupled Ag NW dimer and investigate their plasmon-mediated light propagation and emission properties. The advantage of this serial coupling configuration is that minimal area of the nanowire is utilized for connection, thereby leaving the lengths of the nanowire for further utility and coupling. This unique geometry can facilitate light propagation along the nanowires and localization at the nanowire junctions on a single nanophotonic platform,[15] and hence very useful in building nano-plasmonic circuits.

Self assembled Ag NW dimers were prepared as per the protocol discussed before.[15] The details of fabrication procedure and optical measurement can be found in Secs. S1 and S2 of the supplementary information (SI).[23]

In order to test the plasmon-assisted light propagation, we utilized one of the isolated Ag NW dimer that was connected in end-to-end configuration. Figure 1(a) shows a representative optical image of an end-to-end connected Ag NW dimer. To confirm that the two ends of the Ag NW are connected to each other, we recorded transmission electron microscopy image at two different resolutions as shown in Figs. 1(b) and 1(c). We clearly observed the fused ends of the Ag nanowires. This physical connection is critical for plasmons to tunnel from one nanowire to another. Also, the junction between the nanowires, which can be essentially considered as a defect in the geometry (see Fig. 1(c)), is a plasmonic hot-junction for surface enhanced optical spectroscopy.[15] The schematic in Fig. 1(d) shows the experimental configuration. A laser beam (632.81 nm) was linearly polarized using a $\lambda/2$ plate and focused through a high numerical aperture objective lens at one end of the Ag NW dimer and emitted light intensity at junction and distal ends of the NW dimers were studied. There are two important parameters in our experiment: the bending angle ($\alpha$) between the Ag NW dimer and the polarization of incident light ($\theta$). We probed the angle dependence followed by polarization dependence.

In order to optimize the design parameters of nano-optical waveguides, it is important to characterize the bending and coupling losses.[14] In plasmonic nanowire waveguides and networks,[13] there is an intricate relationship between the geometrical coupling between nanowires and propagation characteristics of SPPs. In the context of light propagation, we found an interesting trend in our Ag NW dimer system. The Ag NW dimers that we studied were prepared by bottom-up approach, and the formation of the dimer

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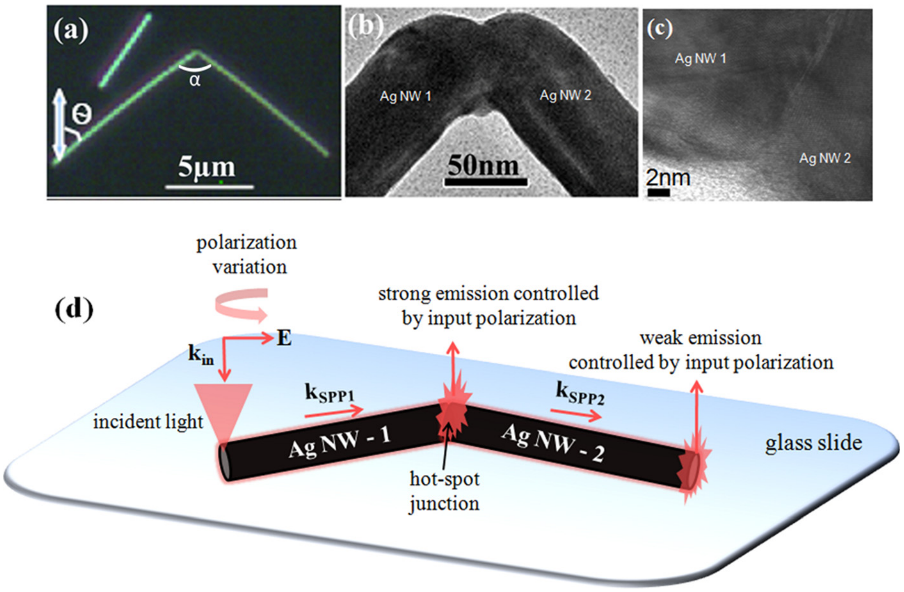

FIG. 1. (a) Optical image of a silver nanowire dimer, and $\alpha$ and $\theta$ are bending angle between the wires and angle of input polarization, respectively; (b) transmission electron microscopy image of the silver junction; (c) high-resolution transmission electron microscopy image of the silver nanowire junction; and (d) schematic of the experiment to show polarization controlled emission at junction and distal ends of Ag NW dimer.

geometry is essentially a thermodynamically driven self-assembled process. It was interesting to note that for almost all the Ag NW dimers that we observed during the course of experiments exhibited a sharp bending angle between the Ag NW which was either acute or obtuse (see sample dark-field optical images in S3 of SI). We were interested in probing the dependence of this bending angle ($\alpha$) on the SPP-assisted light propagation in our Ag NW dimers. We observed that whenever the bending angle between the Ag NW dimer was acute ($\alpha < 90$), as shown in Fig. 2(a), we evidenced intense light emission at the junction, and very negligible emission intensity at the distal ends of the Ag NW dimer. In contrast, when the bending angle between NWs was obtuse ($\alpha > 90$), as shown in Fig. 2(b), we observed greater emission intensity at the distal end of the Ag NW dimer, with scattering losses at the NW junction. Similar observations were made on a variety of acute- and obtuse-angled Ag NW dimer (S4 in SI). These angle-dependent light emissions can be understood by simple geometrical arguments as follows: Consider the k vector of plasmon propagation in Ag NW dimer as shown in Fig. 2(c). The excitation of plasmon polariton at one end of Ag NW dimer (red dot in Fig. 2(c)) leads to SPP propagation as shown by the $\mathbf{k_1}$ vector (red arrow). Now there are two scenarios for the $\mathbf{k_1}$ vector to propagate depending upon the bending angle between the Ag NWs: one is that if the angle between the Ag NWs in acute ($\alpha < 90$), the $\mathbf{k_1}$ vector scatters at the nanowire junction leading to light emission, and further propagates as vector $\mathbf{k_{2\text{-}acute}}$ along the second nanowire (green dashed line). As one may observe, there is a large curvature in the acute angle scenario, leading to a greater bending loss and hence very weak emission at the distal end of the Ag NW dimer (see Fig. 2(a)). On the other hand, when the bending angle between the Ag NWs is obtuse ($\alpha > 90$), the $\mathbf{k_1}$ vector scatters off the junction and further propagates as vector $\mathbf{k_{2\text{-}obtuse}}$ as shown in Fig. 2(c) (blue dashed arrow). Note that the curvature for the obtuse angle scenario is less leading to lesser bending loss and hence greater intensity of light is observed at the distal end of the Ag NW dimer (see Fig. 2(b)). We emphasise that such subtle difference in the angle between the Ag NWs plays a critical role in SPP-mediated transmission characteristics, and hence should be taken into consideration during the design of SPP based circuits.

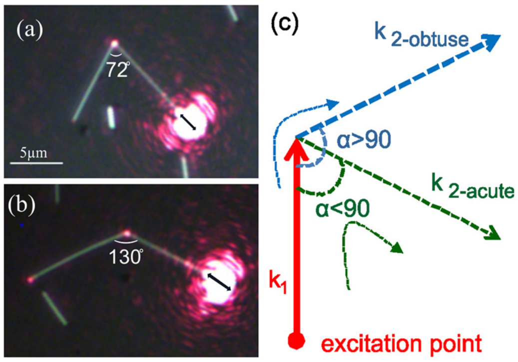

FIG. 2. Optical image of plasmon-assisted light propagation in Ag NW dimer with a bending angle of (a) 72° and (b) 130°. Black arrows indicate polarization of incident light at 632.81 nm wavelength. (c) Vector representation of plasmon propagation in acute and obtuse angled wire.

Other parameters relevant in the context of nano-waveguides are the in-coupling and propagation losses. We estimated that for a 633 nm laser spot of 2 $\mu$m diameter with 10 mW power at the sample, the coupling efficiency was between 1% and 2%. To further improve the in-coupling efficiency, one could use tapered nano-fibers instead of a high numerical aperture objective lens. The transmission losses in the nano-waveguide were calculated according to Ref. 15, and the estimated losses for obtuse (130°) and acute (72°) angled Ag NW dimer were found to be 0.29 dB/$\mu$m and 0.86 dB/$\mu$m, respectively.

With the hindsight that obtuse-angled nanowires exhibit better propagation of light, we probed the light emission characteristics in obtuse-angled Ag NW dimers as a function of polarization of incident light. In Figs. 3(a) and 3(b), we have shown polarization-controlled light emission at the junction and distal end of Ag NW pair. When the polarization of incident beam was along the direction of the input Ag NW, we observed light emission at the junction and distal ends of the Ag NW dimers, which represents ON state. When the polarization was oriented

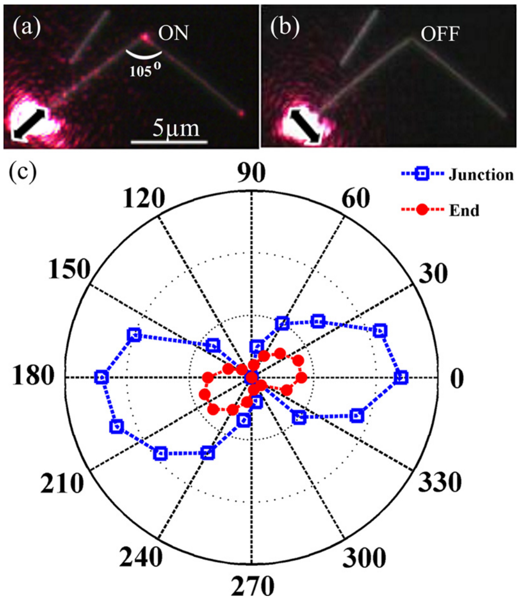

FIG. 3. Polarization controlled emission from Ag NW dimer. (a) Optical image of the ON state: light is emitted at the junction and distal end of Ag NW dimer; (b) corresponding OFF state: no light emitted at the junction and distal end of Ag NW dimer. The black arrows indicate the direction of electric field polarization, (c) polar plot indicating input polarization tuned light emission from the junction (square, blue) and distal end (round, red) of Ag NW dimer.

perpendicular to the length of the input Ag NW, no light was observed at the junction and distal ends of Ag NW dimer, representing an OFF state. Furthermore, when the input polarization direction was in between parallel and perpendicular to the Ag NW length, we observed systematic $\cos^2\theta$ dependence in the intensity of emitted light at the junction and distal ends of Ag NW dimers (see polar plot in Figure 3(c)). The physical origin of this observation is as follows: for the given cylindrical geometry of the Ag NW, there are two allowed modes:[22,24] $m = 0$ and $m = 1$. The $m = 0$ mode is represented by electric field along the length of the nanowire, and $m = 1$ mode is represented by electric field perpendicular to the length of the wire. The $m = 0$ mode, results in the light emission at the distal end, whereas $m = 1$ mode does not result in emission of light. Section S5 in SI confirms this particular concept with experiments and finite element methods simulations on single Ag NW. In the context of Ag NW dimer, this indicates that when the polarization of light is along the length of input nanowire, the $m = 0$ mode is excited, and a major part of the plasmon polaritons are converted into free photons at the junction leading to the ON state (Fig. 3(a)). Interestingly, a small fraction of the plasmon polaritons does tunnel into the second nanowire, further leading to emission of light at the distal end. In the OFF state (Figure 3(b)), the input polarization is perpendicular to the length of the nanowire ($m = 1$ mode). This configuration does not facilitate light emission either at the junction or at the distal end of the Ag NW dimer. For any other polarization angle, the excitation is a combination of $m = 0$ and $m = 1$ mode leading to systematic variation in the intensity of the emitted light at the junction and distal end of Ag NW pair. These observations clearly indicate that by varying the input polarization of light at one end of the Ag NW dimer, one can control the light emitted at the junction and distal ends. Such remote excitation and control of emission of plasmonic nano-junction can have implications in scenarios where there is a necessity to create spatial off-set between the input excitation and output emission channels in plasmonic circuitry, thus avoiding effects of interference.

Can this polarization dependence be used to route light in Ag NW dimers? To answer this question, we further tested our Ag NW dimers for light routing capability of obtuse-angled Ag NW dimer. The excitation configuration was different as compared to Fig. 1. In Fig. 4(a), we show the experimental schematic to test the light routing capability in Ag NW dimer. The location of illumination was at the Ag NW junction; and by varying the polarization of the incident light

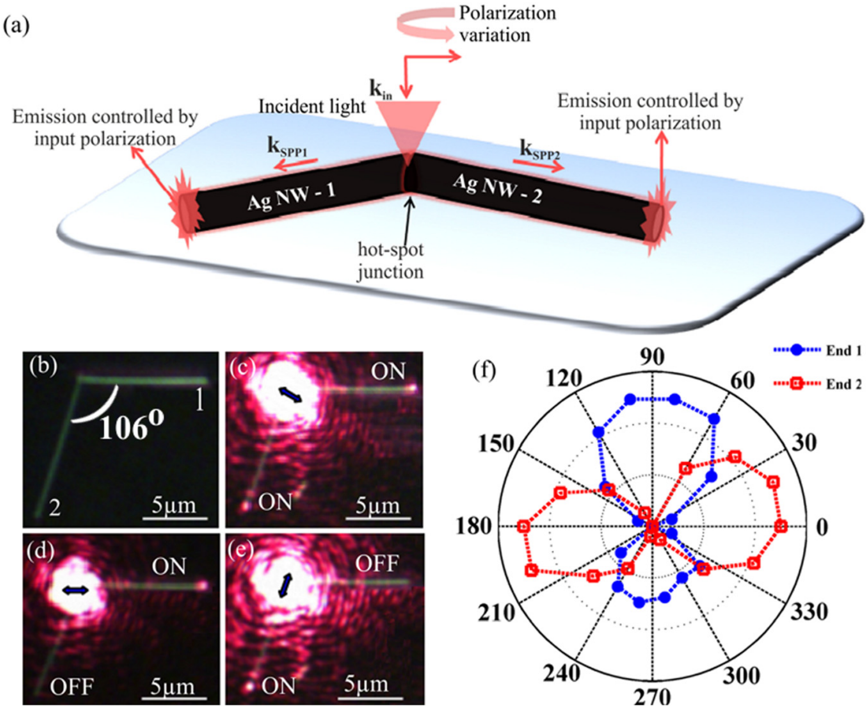

FIG. 4. (a) Schematic of the experimental configuration to show plasmon routing capability of Ag NW dimer. (b) Optical image of Ag NW dimer used for the study; (c) shows the emission of light at the both ends of Ag NW; (d) end 1 is in ON state and end 2 is in OFF state; (e) end 2 is in ON state and end 1 is in OFF state; and (f) Polar plot indicating the input polarization controlled plasmon routing at the end 1 (circle, blue) and 2 (square, red).

at the NW junction, we observed the emission of light at two ends of the Ag NW. Figure 4(b) shows the optical image of Ag NW dimer. In Fig. 4(c), we observed emission at both ends of the Ag NW when the polarization of the incident beam had projection on both of the nanowire axis. However, when the polarization was oriented such that the electric field was along one of the axis of nanowires (see Figs. 4(d) and 4(e)); we observed emission of light from only one end of the Ag NW dimer. In polar plot shown in Fig. 4(f), we show the variation of emitted light intensity at the two ends of the Ag NW dimer as a function of input polarization at the Ag NW dimer junction. Clearly, we observed that the emission patterns at two ends of Ag NW dimer are complementary to each other. The above discussed data imply that by varying the incident electric field polarization at the nano-junction of Ag NW dimer, the plasmons could be routed along the desired path. It is to be noted that the plasmon routing capability in our work has been achieved without changing the location of the illumination, and hence such optical configurations can find applications in on-chip plasmonics where it is desirable to have minimum number of illumination channel with multiple emission ports.

Another important issue in nanophotonic circuitry is the polarization beam splitting of light at subwavelength scale.[13] We performed experiments to test the output polarization of the light emitted at the nanowire junction and distal ends and possibility of polarization beam-splitting. The experiment was performed in two excitation configurations (distal and junction excitation) and three polarization collection configuration (no analyzer, vertical analyzer, and horizontal analyzer) as shown in Figure 5. Figure 5(a) shows the optical image in which incident light was polarized (indicated by black arrow) and the collected images were not filtered with any polarization analyzer. This configuration resulted in bright emission at the junction and distal ends of Ag NW dimer. In the next case (Fig. 5(b)), the excitation polarization was same as in Fig. 5(a), but we introduced a vertical polarization analyzer before the CCD camera. The white arrow in Fig. 5(b) shows the direction of polarization of the emitted light. This configuration resulted in brighter emission at junction and a very weak emission at the distal end, indicating that the majority of the photons emitted at the junction were vertically polarized. For the next case (Fig. 5(c)), we turned the polarization analyzer to horizontal direction (see white arrow in Fig. 5(c)), and observed brighter emission at the distal end and a very weak emission at the Ag NW junction, indicating that the majority of the photons emitted at the distal end were horizontally polarized. Next, we repeated these experiments by illuminating the Ag NW dimers at the junction (Figs. 5(d)–5(f)). The most interesting observation was that by illuminating Ag NW dimers at the junction, one could use this configuration as polarization beam splitter (compare Figs. 5(e) and 5(f)). We observed that each arm of the Ag NW dimer facilitated complementary paths for light emission with respect to output polarization, thus showing the capability of Ag NW dimer as a polarization beam splitter at subwavelength scale. The above experiments show the versatility of Ag NW dimer configuration with respect to input and output parameters of light and can be further harnessed as nanophotonic circuit element.

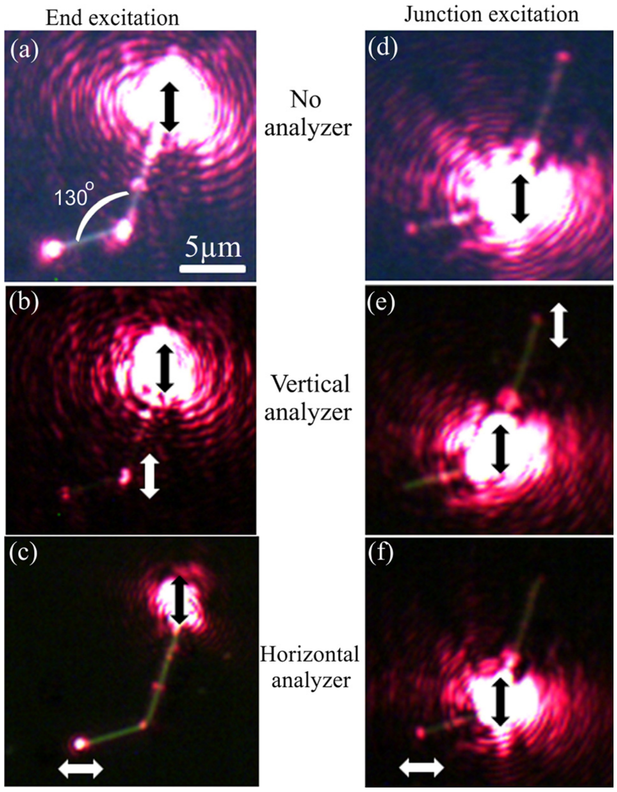

FIG. 5. Optical images of Ag NW dimer emitting polarized light. The left and the right columns indicate two different configurations of excitation. The left panel shows excitation channel at one of the Ag NW dimer and emission at the junction and distal ends; (a) without analyzer, (b) with vertical analyzer, and (c) with horizontal analyzer. The configuration of right panel is similar to the left except that the excitation is at the junction of the Ag NWs. In all the images, the black arrow indicates input polarization and the white arrow indicates output polarization. Images (e) and (f) indicate polarization beam splitting of Ag NW dimers.

To summarize, we have shown that angle between the self-assembled Ag NW dimer plays a critical role in light propagation. The polarization of incident light can be harnessed to control the emission at the junction and distal end of Ag NW dimer. Such nano-plasmonic configurations can be employed as plasmonic circuit elements for on-chip nanophotonics and plasmon resonance tunnelling.[25] In the current study, we used single excitation wavelength (632.81 nm) to create plasmons. By employing multiple excitation wavelengths, our geometry can be extrapolated to realize multicolour light routing. By further tailoring our design, one could include multiple channels for plasmonic routing, where the distal end of Ag NW can be further utilized as nanoscale light sources. Thus, we have shown that Ag NW dimer structures can indeed be an extremely versatile geometry for nanophotonics, and we envisage that many other interesting concepts can be derived from this simple, yet effect design at nanoscale.

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