Coupling of higher-mode-light into a single silver nanowire

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Coupling of higher-mode-light into a single sliver nanowire and the degree of the coupling can be controlled by adjusting the light polarization, showing that a nanowire waveguide has no request on the spatial mode of the input light. Photons with different orbital angular momentums (OAM) are used to excite surface plasmons of silver nanowires. The experiment indicates the propagating modes of surface plasmons in nanowires were not the OAM eigenstates.

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Today, the major problem to increase the speed of microprocessors is how to carry digital information from one end to the other. Optical interconnectors can carry digital data much more than that of electronic interconnectors, while fiber optical cables can not be minimized to nanoscale due to the optical diffraction limit. To solve this size-incompatibility problem, we may need to integrate the optical elements on chip and fabricate them at the nanoscale. One such proposal is surface plasmons, which are electromagnetic waves that propagate along the surface of a conductor[1]. Plasmonics, surface plasmon-based optics, has been demonstrated and investigated intensively in nanoscale metallic hole arrays[2, 3, 4], metallic waveguides[5, 6, 7], and metallic nanowires[8, 9, 10, 11, 12, 13] in recent years.

Among the various kinds of plasmonics waveguides, silver nanowires have some unique properties that make them particularly attractive, such as low propagation loss due to their smooth surface and scattering of plasmons to photons only at their sharp ends. Since the momentums of the photons and plasmons are different, it is a challenge to couple free-space light into plasmon waveguides efficiently. The typical methods for plasmon excitation include grating coupling, prism coupling and focusing of light onto one end of the nanowire with a microscope objective. Nanoparticle antenna-based approach is also proved as an effective way for optimizing plasmon coupling into nanowires[12], which realizes direct coupling into straight, continuous nanowires by using a nanoparticle as an antenna. Recently, polymer waveguides are used to couple light into several nanowires simultaneously[13] as well, aiming at providing light to a number of nanoscale devices in the future integrated photonic circuits.

Because the former researches about the nanowires always concentrate on using Gaussian mode light to excite surface plasmons, here we discuss whether surface plasmons can be launched by other higher-order-mode light. We focus laser beam with different orbital angular momentums (OAM) on one end of a nanowire and observe scattering light from the other end. Surface plasmons are launched not only by Gaussian mode light but also by higher-order-mode light. The coupling strength over light polarization is also studied for higher-order-mode light and gives the similar results with the case of Gaussian mode. The output intensity increases linearly with the input intensity rising, and is independent of the spatial mode of the input light.

Ag nanowires were synthesized through a polyol process in a mixture of ethylene glycol (EG) and poly (vinyl pyrrolidone) (PVP) at a certain temperature, which was very similar as the previous report[14, 15, 16]. Scanning electron microscope (SEM) image in Fig.1a shows that all the nanowires are straight and have uniform diameters that vary from 60 to 100nm and lengths from 10 to 40µm. A typical nanowire with diameter of 60 nm is shown in Fig. 1b. High resolution TEM image in Fig. 1c shows a lattice spacing of 0.23 nm, corresponding to those of (111) and (111) respectively. Electron diffraction pattern taken the individual nanowire can be indexed as two parallel zone axes, i.e. [011] and [111](Fig. 1d). Based on the analysis, the nanowire axis is along [100].

FIG. 1: (color online)(a) SEM image of silver nanowires. (b) TEM image taken on the end of an individual silver nanowire. (c) HRTEM image of the singe nanowire shown in (b). (d) SAED pattern taken from an individual nanowire.
The OAM of the laser (wavelength 632.8 nm) was controlled by a CGH, while the polarization was controlled by a PBS followed by a HWP. The polarized laser beam was focused on one end of a nanowire using a 100X objective lens (Zeiss, NA=0.75). The sample was moved by a three dimensional piezo-electric stage. Scattering light was recorded by a CCD camera after a microscope objective. Inset are pictures of a typical CGH ($n=1$) and the energy distribution of the produced light.

is known that photons have both spin angular momentum and OAM. The light fields of photons with OAM can be described by means of Laguerre-Gaussian ($LG_l^m$) modes with two indices $p$ and $l$\cite{17}. The $p$ index identifies the number of radial nodes observed in the transversal plane and the $l$ index describes the number of the $2\pi$-phase shifts along a closed path around the beam center. If the mode function is a pure LG mode with winding number $l$, then every photon of this beam carries an OAM of $\hbar l$. This corresponds to an eigenstate of the OAM operator with eigenvalue $\hbar l$\cite{17}. For the sake of simplification, here we just consider the cases for $p = 0$. When $l = 0$, the light is in the general Gaussian mode, while when $l \neq 0$, the energy distribution of light likes a doughnut due to their helical wavefronts (see inset of Fig. 2). We usually use computer generated holograms (CGHs)\cite{18,19} to change the winding number of LG mode light. It is a kind of transmission holograms. Inset of Fig. 1. shows part of a typical CGH($n = +1$) with a fork in the center. Corresponding to the diffraction order $m$, the $l$ fork hologram can change the winding number of the input beam by $\Delta l = m \ast n$. In our experiment, we use the first order diffraction light ($m = +1$) and the efficiencies of our CGHs are all about 40%. The Gaussian mode light can be identified using mono-mode fibers in connection with avalanche detectors. All other modes light have a larger spatial extension, and therefore cannot be coupled into the single-mode fiber efficiently.

The experimental setup was shown in Fig. 2. The wavelength of the laser beam was 632.8 nm, which was much bigger than the diameter of the nanowires (about 100 nm). The OAM of the laser was controlled by a CGH, while the polarization was controlled by a polarization beam splitter (PBS, working wavelength 632.8 nm) followed by a half wave plate (HWP, working wavelength 632.8 nm). Rotating the HWP allowed us to investigate the relation between the coupling efficiency and the polarization of light. The polarized laser beam was directed into the microscope and focused on one end of a nanowire with the light diameter about 5.5 $\mu$m using a 100X objective lens (Zeiss, NA=0.75). The sample was moved by a three dimensional piezo-electric stage (Physik Instrumente Co., Ltd. NanoCube XYZ Piezo Stage). Scattering light from the nanowire was reflected by a beam splitter (BS, 50/50) and recorded by a CCD camera.

The momentum of the propagating plasmon($k_{pp}$) is larger than that of the incoming photon($k_{ph}$), there needs an additional wavevector($\Delta k$) to sustain the momentum conservation condition. Surface plasmons in nanowires can be excited when the symmetry were broken, for example, at the ends and sharp bends\cite{8,9,10,11}, because an extra wavevector ($\Delta k_{scatter}$) is provided according to the scattering mechanism at this situation. It has been proved that surface plasmons can propagated along the length of nanowires when they were excited by Gaussian mode light, even the diameter of nanowires were much smaller than the wavelength of light. In our experiment, higher mode lights ($l = 1$ and 2) were focused on one end of a nanowire (length 9.3 $\mu$m) and the emission was observed from the other end clearly, which verified that the higher-mode-light can also be transmitted by the sliver nanowire. In our experiment, higher mode lights ($l = 1$ and 2) were focused on one end of a nanowire (length 9.3 $\mu$m) and the emission was observed from the other end clearly, which verified that the higher-mode-light can also be transmitted by the sliver nanowire.
FIG. 4: (color online) Polarization dependence of coupling efficiency at nanowire end. (a) The Gaussian mode light was focused on the end of nanowire. (b) The higher-order-mode light \((l = 2)\) was focused on the end of nanowire. The two cases give the similar curve.

As a comparison, the case of Gaussian mode light was observed and gave the similar curve.

The end of the nanowire was also moved from one edge to the other of the laser spot (which has a diameter about 5.5\(\mu\)m) to give the relationship between the input intensity of laser beam and the emission intensity from the end of the nanowire. The results were measured for the cases of Gaussian mode light and higher-order-mode light \((l = 2)\), as shown in Fig. 5, which showed that the emission intensity increased linearly with the pump intensity and was almost independent of the spatial mode of the input light.

In conclusion, we experimentally demonstrate that higher-order-mode light can also excite surface plasmons in silver nanowires. The surface plasmons can propagate along the nanowire and scatter back to photons at the other end. The coupling strength is correlated with the polarization of input light, as the same as the case of Gaussian mode light. The OAM eigenstates are not the propagating modes of surface plasmons in nanowires. These results may give us more hints to the understanding of the waveguide properties of silver nanowires.

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