Excitation of surface plasmons in a single silver nanowire using higher-order-mode light

Guo-Ping Guo, Rui Yang, Xi-Feng Ren, Lu-Lu Wang, Hong-Yan Shi, Bo Hu, Shu-Hong Yu, Guang-Can Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei 230026, People’s Republic of China
Division of Nanomaterials and Chemistry, Hefei National Laboratory for Physical Sciences at Microscale, Department of Chemistry, University of Science and Technology of China, Hefei, Anhui 230026, People’s Republic of China

Article info
Article history:
Received 29 October 2009
Received in revised form 25 December 2009
Accepted 18 January 2010
Available online 25 January 2010

Keywords:
Surface plasmon
Nanowire
Orbital angular momentum

Abstract
Excitation of surface plasmons in a single silver nanowire using higher-order-mode light shows that nanowire waveguide has no request on the spatial mode of the input light, which is determined by its orbital angular momentums (OAM) in the experiment. The excitation efficiency can be controlled by adjusting the light polarization. Experimental result also indicates that the propagating modes of surface plasmons in nanowire are not the OAM eignenstates.

© 2010 Elsevier B.V. All rights reserved.

Today, the major problem to increase the speed of microprocessors is how to carry digital information from one end to the other faster. Optical interconnectors can carry much more digital data than that of electronic interconnectors, while fiber optical cables cannot 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 [2–4], metallic waveguides [5–7], and metallic nanowires [8–16] 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 direct coupling into straight, continuous nanowires [13]. Recently, polymer waveguides are used to couple light into several nanowires simultaneously [15] as well.

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. The higher-order-mode light is produced by changing the orbital angular momentum (OAM) of photons, since photons have different orbital angular momentum corresponding to light with different spatial energy distribution. We focus higher-order-mode laser beam 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 even for higher-order-mode 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 [17–19]. They have well-defined crystal structure [20–22] and their smooth surface help to minimize surface plasmons damping due to scattering at roughness, domain boundaries or defects. Scanning electron micrograph (SEM) image in Fig. 1(a) shows that all the nanowires are straight and have uniform diameters that vary from 60 to 100 nm and lengths from 10 to 40 μm. A typical nanowire with diameter of 60 nm and a tapered end is shown in Fig. 1(b). High resolution TEM image in Fig. 1(c)
shows a lattice spacing of 0.23 nm, corresponding to those of \(\{1\ 1\ 1\}\) and \(\{1\ 1\ 1\}\), respectively. Electron diffraction pattern taken the individual nanowire can be indexed as two parallel zone axes, i.e. \{0\ 1\ 1\} and \{1\ 1\ 1\} (Fig. 1(d)). Based on the analysis, the nanowire axis is along \{1\ 0\ 0\} and this single crystalline structure ensures that the propagation length could reach several micrometers or above [11].

The spatial mode of the input light is determined by its OAM. If the photons have the OAM of \(l\), the electromagnetic field amplitude of light can be described by means of pure Laguerre–Gaussian (LG\(_p^l\)) mode with winding number \(l\) [23]. 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. 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 \(l\neq0\), the energy distribution of light likes a doughnut due to their helical wavefronts (see inset of Fig. 2) and this kind of light was defined as \(l\)th-order-mode light. We usually use computer generated holograms (CGHs) [24,25] (a kind of transmission holograms) to change the winding number of LG mode light. Inset of Fig. 2 shows part of a typical CGH \((n=1)\) with a fork in the center. Corresponding to the diffraction order \(m\), the \(n\) fork hologram can change the winding number of the input beam by \(\Delta m = m - n\). In our experiment, we use the first order diffraction light \((m=+1)\) and the efficiencies of our CGHs are all about 40%.

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 (we used a CGH with \(n=2\) in the experiment), 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 surface plasmons excitation 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 μm using a 100 × 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.

It has been proven that surface plasmons can propagated along the length of nanowires when they are excited by Gaussian mode light ($l=0$), even the diameters of nanowires are much smaller than the wavelength of light. In our experiment, higher-order-mode lights ($l=2$) were focused on one end of a nanowire (length 9.3 μm) and the emission was observed from the other end clearly, which verified that the higher-order-mode light can also be used to excite surface plasmons in silver nanowires (Fig. 3(a)). Since every photon of the input light carries a well-defined OAM, the light coupling to the nanowire must have the OAM property, even only part of the light incidents on the nanowire end. The far field energy distribution of the emission light was analyzed (Fig. 3(b)) and it was not the same as the input light which had a null hole in center but similar with the Gaussian mode. This phenomenon is different from the cases of extraordinary optical transmission through nanohole structures, where the OAM eigenstates can be preserved [26–29]. If the propagating modes of surface plasmons in nanowires are the OAM eigenstates, the spatial distribution of output light should be as the same as the input light. A potential explanation is that the two kinds of modes are different and the OAM of photons is changed in the surface plasmons excitation and propagating process. This may be useful for the investigation of plasmonics (surface plasmon based optics).

The excitation efficiency was measured by changing the polarization of the input light. For each polarization, the emission intensity was determined by averaging the four brightest pixels at the other end of the nanowire in the CCD images. The emission changed with the polarization of input light due to the different excitation efficiencies. Fig. 4 showed the relations between the excitation efficiency and the polarization of the input light. The far-field emission curves as a function of polarization angle were approximately in accord with the theoretical prediction (cosine or sine function) [13]. As a comparison, the case of Gaussian mode light was investigated and gave the similar curve.

---

**Fig. 3.** (Color online) (a) Dark image of the laser spot and the nanowire. The 2nd-order-mode light was focused on one end of a nanowire (length 9.3 μm) and the emission was observed from the other end clearly, which verified that the higher-order-mode light can also be used to excite surface plasmons in silver nanowire. (b) The far field energy distribution of the emission light. The experimental data fits well with a Gaussian function, which indicated that the spatial mode of the emission light had been changed after propagating along the nanowire.

**Fig. 4.** (Color online) Polarization dependence of surface plasmons excitation efficiency at nanowire end. The Gaussian mode light (a) and the higher-order-mode light ($l=2$) (b) were focused on the end of nanowire. The far-field emission curves as a function of polarization angle were approximately in accord with the theoretical prediction (cosine or sine function).
Since the laser spot (which has a diameter of 5.5 μm) is much bigger than the diameter of the nanowire, we moved the end of the nanowire through the laser spot and emission intensity from the other end was recorded. Energy illuminated on the end was changed in the different section of laser spot, so the emission intensity was changed accordingly in this process. This gave the relation 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 2nd-order-mode light, as shown in Fig. 5, which showed that emission intensity changed proportionally to the input intensity, even for the higher-order-mode light.

In conclusion, we experimentally demonstrate that higher-order-mode light can also excite surface plasmons in silver nanowires. The surface plasmons could propagate along the nanowire and scatter back to photons at the other end. The excitation efficiency 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, thus the OAM of photons are changed in the whole process. These results may give us more hints to the understanding of the waveguide properties of silver nanowires.

This work was supported by National Fundamental Research Program (nos. 2006CB921900 and 2005CB623601), National Natural Science Foundation of China (nos. 10604052, 10904137, 50732006, 20621061 and 20671085), Chinese Academy of Sciences International Partnership Project, the Partner Group of the CAS-MPG, Anhui Provincial Natural Science Foundation (Grant no. 090412053) and Science and Technological Fund of Anhui Province for Outstanding Youth (Grant no. 2009SQRZ001ZD).

References