Low-loss nanowire and nanotube plasmonic waveguide with deep subwavelength light confinement and enhanced optical trapping forces

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Abstract With the rapid development of the micro/nano fabrication technology, the semiconductor nanowires and nanotubes with size and dimensions controllable realize wide applications in nanophotonics. In this talk, we propose two kinds of hybrid plasmonics waveguides, one is consisting of nanowires, another is consisting of nanotubes. By employing the simulating with different geometric parameters, the basic waveguarding properties, including the effective mode area, the propagation length, the mode character and the optical trapping forces can be achieved. Compared with previous plasmonic waveguide with plane metal substrate, current plasmonics waveguides with ease of fabrication have the advantage of long propagation length and effectively optical trapping of nanoparticles with deep subwavelength light confinement, which may be very useful for nanophotonic integrated circuits, nanolasers and biosensing.

1. Introduction

With the nanometer fabrication technology rising, the semiconductor nanowires/nanotube with size and dimensions controllable realize wide applications in nanophotonics, such as waveguides, sensors, photodetectors, and lasers [1-2]. However, confined to the diffraction limited, the nanowire/nanotube waveguide is difficult to achieve deep subwavelength optical scale. Breaking the shackles of the diffraction limited and manipulating photons under deep subwavelength are very important for the next-generation integrated photonic devices. On one hand, the subwavelength optical confinement can enhance the interaction between light and matter. On the other hand, the strong optical confinement can enhance optical field strength and gradient of light field, which will highly enhance the optical force in the nanoscale region [3-5].

Surface plasmon polaritons (SPPs) are a coherent oscillation of free charges in the surface of metals in resonance with the incident light wave, which have the distinguishing capabilities of enhancing the local electric field intensity as well as of confining the optical energy within the nanoscale domain [6-11]. As one of the most promising candidates for nanophotonic circuits, SPP-based nanoscale optical devices have attracted enormous interest in recent years. However, SPP based waveguides suffer huge propagation loss because of the intrinsic ohmic loss. It is difficult to balance between these two opposites to strong optical confinement and propagation loss. In recent report, a novel hybrid plasmonic waveguide consisting of a dielectric waveguide on one side of a metal surface has been proposed by R.F.Oulton et al [12]. It is able to support long range propagation length, while maintaining an ultra-small mode size due to the coupling between the dielectric cylindrical waveguide mode and the SPP mode at the metal-dielectric interface [13-19].

In this article, we propose the nanowire/nanotube hybrid waveguide by replacing the metal film with a metal nanowire. Through theory simulation and analysis, we can draw a conclusion that the hybrid mode in this structure can achieve deep-subwavelength mode, while maintaining propagation distance as well as that in the SPP. Moreover, the combination of ultra-low loss and strong coupling strength between the dielectric waveguide mode and SPP mode would lead to a much larger optical force [5]. On the whole, the proposed structure provides an excellent platform for nanoscale optical devices, such as nanolasers and nanotweezers.
2. Modal properties of the nanowire plasmonic waveguide

The nanowires hybrid waveguide geometry shown in Fig. 1, which consists of two cylindrical nanowires with a small gap distance $h$. A high-permittivity semiconductor nanowire is Si with the relative permittivity $\varepsilon_r = 12.25$. Another one is silver with diameter of $D = 200$ nm and permittivity of $\varepsilon_m = -129 + 3.3i$ at $\lambda = 1550$ nm. The surrounding dielectric layer is a low-permittivity dielectric of SiO$_2$ ($\varepsilon_d = 2.25$). In the follow study of nanowires hybrid waveguide, we vary the semiconductor nanowire diameter, $d$, and the gap distance, $h$, to adjust the mode field distribution, the propagation distance, $L_m$, and the mode area, $A_m/A_0$. The modal properties are investigated by the finite-element method using COMSOL 4.2.

![Figure 1. The geometry of the nanowire hybrid surface plasmonic waveguide. Two cylindrical nanowires with a small gap distance $h$.](image)

Figure 2 shows the dependence of the normalized modal area, $A_m/A_0$, the propagation length, $L_m$, and the distributions of electromagnetic energy density on different dielectric diameter, $d$, and gap distance, $h$. In this paper, we defined the propagation length and modal area as same as that in [20]. The propagation length is given by

$$L_m = \lambda / \{4\pi \text{Im}(n_{\text{eff}})\},$$

where $n_{\text{eff}}$ is the effective index of the hybrid mode, $\lambda$ is the wavelength of light transmission.

The effective mode area, $A_m$, is given as follows

$$A_m = \iint W(r)\,dA / \{\max(W(r))\}.$$  

Here, the $W(r)$ is the energy density for the hybrid plasmonic waveguide (per unit length along the direction of propagation). Due to the dispersion and material loss, the $W(r)$ can be calculated by

$$W(r) = \frac{1}{2} \left( \frac{d(\varepsilon(r)\omega)}{d\omega} \right)^2 \left| E(r) \right|^2 + \mu_0 \left| H(r) \right|^2. \tag{3}$$

$|E(r)|$ and $|H(r)|$ are the electric and magnetic fields, respectively. $8(\omega)$ is the permittivity, and $\mu_0$ is the vacuum magnetic permeability.

The normalized effective mode area is defined as the ratio of the effective mode area and the diffraction-limited area of vacuum,

$$A = \frac{A_m}{A_0} = \frac{A_m}{\lambda^2/4}. \tag{4}$$

The normalized effective mode area was used for consistently quantifying the mode confinement, and $A < 1$, indicates the confinement of the hybrid plasmonic mode is subwavelength.

As shown in Fig. 2(a), with a certain value of diameter of dielectric nanowire, the strong confinement in hybrid plasmonic waveguide results in an ultra-small mode area down to 0.0019($\lambda/2$)$^2$. As shown in Fig. 2(b), the hybrid plasmonic mode can travel through a long distance, which is more than 24 μm. Figs. 2(c-f) show the electromagnetic field distributions of energy density $W(r)$. For a small gap distance, the hybrid mode confine light energy in the gap and the hybrid mode displays both the characteristics of the dielectric mode and the SPP mode [Figs. 2(c, d)]. For a large diameter of dielectric nanowire and gap distance, the hybrid waveguide supports a dielectric-like mode that the electromagnetic energy is confined in the dielectric nanowire [Fig. 2(f)]. In this case the propagation loss of the electromagnetic wave in the waveguide is low, but the localization of the dielectric-like mode is weak. What is interesting is that, for the hybrid mode, the normalized modal area and the propagation length are improved remarkably.

![Figure 2. Propagation distance, mode area and field distributions of the hybrid mode. (a) Mode area, $A_m/A_0$ versus diameter of dielectric nanowire, $d$, for different gap width, $h$. (b)](image)
The hybrid mode’s propagation distance, (c–f) electromagnetic energy density distribution of the hybrid mode at 1550 nm. (c) \([d, h] = [400, 100]\), (d) \([d, h] = [200, 100]\), (e) \([d, h] = [200, 2]\), (f) \([d, h] = [400, 2]\).

In order to gain a deeper understanding, the dependence of the effective index of the hybrid mode \(n_{\text{hyb}}\) on the diameter of dielectric nanowire, \(d\), and gap distance, \(h\), is shown in Fig. 3(a). The hybrid mode (coloured lines) is beyond that of the pure dielectric mode (black solid line). When the diameter of dielectric nanowire, \(d\), is fixed, the effective index will increase with reducing the gap distance, \(h\). For a fixed gap distance, \(h\), the mode’s effective index increases as the diameter of dielectric nanowire, \(d\), increases. This is because that the waveguide mode has a relationship between the diameter of dielectric nanowire and gap distance.

A mode character, \(|\alpha(d, h)|^2\), is employed to describe the superposition of the dielectric waveguide mode and the SPP mode \(^{(12)}\). Then it can be used to evaluate the degree to which the guided mode is dielectric-like or SPP-like.

\[
|\alpha(d, h)|^2 = \left(\frac{n_{\text{hyb}}(d, h) - n_{\text{pp}}}{n_{\text{hyb}}(d, h) - n_{\text{pp}}}\right)^2 + \frac{(n_{\text{hyb}}(d, h) - n_{\text{pp}})^2}{(n_{\text{hyb}}(d, h) - n_{\text{pp}})}.
\]  
(5)

Where \(n_{\text{hyb}}\) and \(n_{\text{pp}}\) are the pure dielectric-mode and SPP-mode, respectively. \(n_{\text{pp}}\) can be calculated by the following formula

\[
n_{\text{pp}} = \sqrt{\frac{\varepsilon_s \varepsilon_d}{\varepsilon_s + \varepsilon_d}}.
\]  
(6)

Figure 3(b) shows the dependence of the mode character derived from Eq. (5) on the diameter of dielectric nanowire, \(d\), for different gap distance, \(h\). Here, we define the mode is dielectric-like for \(|\alpha(d, h)|^2 > 0.5\) and SPP-like otherwise. If \(n_{\text{hyb}}\) is larger than \(n_{\text{pp}}\), \(|\alpha(d, h)|^2 > 0.5\) that the hybrid mode more bias the dielectric waveguide modes. In this case, the light energy is confined in the dielectric nanowires. On the contrary, when \(|\alpha(d, h)|^2 < 0.5\), the hybrid mode is more like a SPP mode. When \(h\) is fixed, the mode character increases with the increase of the diameter of dielectric nanowire (Fig. 3(b)). A larger \(d\) and \(h\) lead to a larger mode character. The hybrid mode is a dielectric-like waveguide mode. On the other hand, with the decrease of the diameter of dielectric nanowire, a smaller mode character can be achieved, then the hybrid mode is a more SPP-like mode. For a moderate side length, \(d_{\text{nm}}\), the hybrid mode displays both the characteristics of the dielectric and the SPP mode \(|\alpha(d, h)|^2 = 0.5\). This case is corresponded to the condition \(n_{\text{hyb}}(d) = n_{\text{pp}}\), indicating that polarization charge and plasma oscillations move in phase and maximize the effective optical capacitance of the waveguide \(^{(12)}\).

3. The influences of structure dimension on the performance parameters of nanotube hybrid plasmonic waveguide

Figure 4 schematically shows the geometry of the nanotube hybrid surface plasmonic waveguide, where a high index semiconductor nanotube was embedded in a low index dielectric and placed on a metal nanowire with a small gap distance, \(h\). In this section, the relative permittivity of material and mode character are defined as the same as that in nanowire hybrid surface plasmonic waveguide.

![Figure 4. The geometry of the nanotube hybrid surface plasmonic waveguide](image)

In the following, we defined the diameter of the nanotube outer surface and inner surface as \(d\) and \(d_i\), respectively. Figs. 5(a, b) show the propagation length and modal area of the nanotube hybrid mode on the diameter of the Si nanotube outer surface, \(d\), for the different gap distance \(h\). For a fixed diameter of the nanotube inner surface, \(d_i = 50\) nm, the modal area and the propagation length are decline at first and then gradually increased. We can see that there exists a point with \(d = 150\) nm, that both of the modal area and propagation length is minimum.
According to the coupled mode theory, in this point, the coupling strength gets its maximum value and the dielectric nanotube mode and SPP mode satisfy the phase-matched condition \( n_{nm} = n_{qpp} \). Then, we will further explore the changed the inner surface diameter of nanotube to confirm the influence of the air hole on field enhancement. As shown in the Figs. 5(c, d), the outer surface diameter of nanotube is fixed of 200 nm, and the diameter of air hole is from 0 nm to 180 nm. Certain monotonous variation of the modal area and the propagation length curve appear with the different size of air hole, \( d_i \). The modal area and propagation length can be increase by enhancing the diameter of air hole, \( d_i \), for a fixed gap distance, \( h \). This can be explained that the optical confinement in hybrid mode couples is weaken gradually as \( d_i \) increase.

\[
\alpha = 4\pi r^2 \varepsilon_s \frac{\varepsilon_s - \varepsilon_i}{\varepsilon_s + 2\varepsilon_i}.
\]

The strong optical confinement of the hybrid mode in the gap region, will enhance the optical trapping forces and enable to trap single nanoparticle. Figure 6 shows the system of the optical trapping with a dielectric nanoparticle. In this paper, we used a polystyrene nanoparticle with diameter of 5 nm and refractive index \( n_p = 1.59 \) for studying the optical trapping forces. The environmental medium surrounding the waveguide is water with refractive index of \( n_s = 1.33 \). [22]

![Figure 6. The schematically of optical trapping. The nanoparticle in figure was a polystyrene nanoparticle with refractive index \( n_p = 1.59 \) with diameter of 5 nm. The medium around the waveguide is water with refractive index of \( n_s = 1.33 \). The illustration shows the nanotube trapping system.](image)

According to Eq. (7), the optical trapping force, at the position where the optical field gradient becomes largest, was maximized. Figure 7(a) shows the nanowire optical trapping force dependence on \( D = 200 \) nm, \( d = 200 \) nm, for \( h = 10, 20, \) and 30 nm, respectively. As the gap distance reduces, the optical trapping force increases. At \( h = 10 \) nm, the maximum of optical trapping force per unit input optical power is 1187 nW for the proposed hybrid plasmonic mode. The optical trapping potential profiles along x direction with trapping force integration (Fig. 7(a)) was shown in Fig. 7(b). We define the zero-point potential as the particle is 100 nm away from the waveguide center \( (x = -100 \) nm\). The optical trapping potential \( U_r \) is around 10.1 Ks/T/W right underneath the waveguide at \( h = 10 \) nm, which means that the kinetic energy of the optical trapping force was 10.1 times larger than the kinetic energy of Brownian motion \( (K_sT = 4.1 \times 10^{-21} \) J at room temperature, where \( K_s \) is the Boltzmann constant and \( T \) is absolute temperature [25]). In this case, when the particle moves across the \( x = 0 \) point, the particle can be trapped effectively in the gap region.

Figures 7(c, d) shows the influence of the air hole on the optical trapping force and corresponding trapping
potential along x-direction. In a simulation, we set up the 
\( D = 200 \text{ nm}, d = 200 \text{ nm} \) and \( h = 10 \text{ nm} \). As the inner 
surface diameter of nanotube increases, the optical 
trapping force decreases. The optical trapping force gets 
its maximum value at the inner surface diameter of 
nanotube \( d_i = 0 \text{ nm} \). As mentioned above, the effective 
index of the nanotube decreases monotonously along 
with the inner surface diameter increasing. As a result, 
the effective index mismatch between the dielectric 
mode and the SPP mode, the coupling strength become 
weaken gradually. What is interesting is that, for the 
nanowire/nanotube hybrid mode, the optical force can be 
significantly larger than that of previous hybrid 
plasmonic structures \(^5\). In summary, the combination of 
low loss and strong coupling strength between the 
dielectric waveguide mode and SPP mode would lead to 
a large averaged optical force per unit propagation length 
along the waveguide.

Figure 7. The optical trapping forces along x direction \( F_x \) 
applied on a single polystyrene nanoparticle of 5 nm diameter 
for the hybrid plasmonic mode. (a) The dependence of the 
optical trapping forces on the nanowire system with \( d = 200 \text{ nm}, \) 
\( D = 200 \text{ nm}, \) for \( h = 10, 20, \) and \( 30 \text{ nm} \), respectively. (c) The 
dependence of the optical trapping forces on the size of the air 
hole, \( d_i \). (b, d) The corresponding trapping potential along x 
direction \( U_x \) for (a, c).

5. Conclusion
We have proposed a hybrid plasmonic waveguide system consisting of 
nanowire/nanotube. Simulation results based on the FEM method, the basic waveguide 
properties, including the effective mode area, the 
propagation length, the mode character and the optical 
trapping forces, can be achieved. Compared with previous 
plasmonic waveguide with plane metal substrate, current plasmonics waveguides with ease of 
fabrication have the advantage of long propagation length and effectively optical trapping of nanoparticles 
with deep subwavelength light confinement. Additionally, we discussed the effect of the size of 
nanowire and nanotube air hole on the modal properties of the hybrid plasmonics waveguide. In future 
experimental, the nanowire/nanotube hybrid waveguide can be fabricated easily by current 
nanofabrication technology and be useful for nanophotonic integrated 
circuits, nanolasers and biosensing.

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