Movable Fiber-Integrated Hybrid Plasmonic Waveguide on Metal Film

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***Abstract*— A waveguide structure consisting of a tapered nanofiber on a metal film is proposed and analyzed to support highly localized hybrid plasmonic modes. The hybrid plasmonic mode can be efficiently excited through the in-line tapered fiber based on adiabatic conversion and collected by the same fiber, which is very convenient in experimentation. Due to the ultra-small mode area of plasmonic mode, the local electromagnetic field is greatly enhanced in this movable waveguide, which has the potential for enhanced coherence light emitter interactions, such as waveguide quantum electrodynamics, single emitter spectrum, and nonlinear optics.**

***Index Terms*— Adiabatic conversion, nanofiber, single emitter spectroscopy, surface plasmons.**

I. Introduction

PLASMONICS in metal nanostructure are being extensively studied for its excellent capability of confining light in subwavelength scale [1]. Since the local electric field of the plasmonic mode is dramatically increased at the dielectric-metal interface, the light-matter interaction can be greatly enhanced. Thus, over the past few years, metal nanostructures including nanoparticles, nanowires and nanorings, have been studied for highly sensitive sensing, surface enhanced Raman scattering, and surface plasmonic amplification by stimulated emission of radiation (SPASER) [2]–[7]. Recently, it has also been found that when an optical emitter (e.g., a quantum dot (QD)) is placed around the silver nanowire, its spontaneous emission can be significantly modified [6], known as the Purcell effect. As a result, the plasmonic mode of nanowire provides an alternative approach to study the broadband waveguide quantum electrodynamics (QED) [6], [7], and hold great potential for the single photon source and sub-wavelength single photon transistor [8].

Manuscript received July 8, 2011; revised November 3, 2011; accepted December 12, 2011. Date of publication January 9, 2012; date of current version February 23, 2012. This work was supported in part by the 973 Program under Grant 2011CB921200 and Grant 2011CBA00200, in part by the Natural Science Foundation of China under Grant 11004184, and in part by the Knowledge Innovation Project of the Chinese Academy of Science.

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Digital Object Identifier 10.1109/LPT.2011.2180520

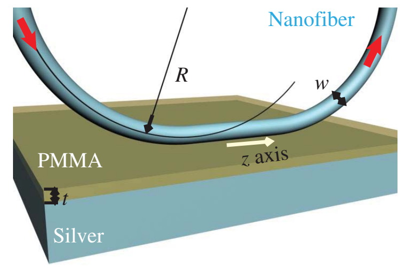

Fig. 1. Schematic diagram of the hybrid plasmonic waveguide, consisting of a bending nanofiber on a metal substrate, which is covered by a thin PMMA film (thickness t).

One of the limitation of these metal nanostructures is the high absorption loss in metal. Very recently, the hybrid dielectric-metal structures have been proposed, which are consisted of a dielectric waveguide or resonator near a metal substrate. These hybrid plasmonic modes can be low loss while remain high electromagnetic field localization [9]. In experiments, the hybrid plasmonic modes are excited and collected through free space. Unfortunately, this process suffers from low efficiency due to the mismatching of momenta of light. In this letter, we propose and numerically investigate a fiber-integrated hybrid plasmonic waveguide. Based on the adiabatic conversion, the local plasmonic mode can be excited and collected by fiber with very high efficiencies. More importantly, the movable structure can be easily fabricated and controlled, thus offering a great feasibility in future experiment.

II. Result and Discussion

Fig. 1 shows the geometry of the proposed hybrid system. A curved silica nanofiber is put on a silver substrate surrounded by air, with a nano-scale thickness (t) Poly(methyl methacrylate) (PMMA) film between them. The curved nanofiber with a sub-micrometer diameter has two symmetrical bending parts (radius R), which are connected by a straight part. In the following study, we fix the working wavelength at 633 nm. The refractive indices of silica and PMMA are $n_{silica} = 1.45$ and $n_{PMMA} = 1.49$, respectively. In experiment, the nanofiber can be pulled from a standard fiber, which has a uniform diameter (w) as small as 120 nm [10]. The interaction area of the nanofiber and substrate can be selected freely by mounting the nanofiber on a holder system with a high resolution three-axis translation stage. It is worth noting that similar structures based on nanofiber and a high refractive index dielectric membrane have been studied by Davanço et al. [11], [12] recently, where gap modes are studied for single emitter spectroscopy, which is essentially different from hybrid plasmonic mode studied here.

At the region where the nanofiber contacts with the substrate, the hybrid plasmonic modes will appear [9]. The heart of our proposal is the adiabatic conversion between the fiber guiding mode and the plasmonic mode. As the guiding mode propagates in the bending nanofiber which slowly approaches the metal substrate, the confined field in dielectric will evolute to the plasmonic mode at metal-dielectric interface. Inversely, when the nanofiber slowly deviates from the substrate, the plasmonic mode will convert back to the guiding mode. The similar adiabatic conversion of the optical mode from one mode profile to the other has also been extensively studied in fiber and waveguide optics [13], [14]. For example, in the slowly varying fiber taper in our structure, the fundamental single-mode fiber mode can be adiabatically converted to the fundamental nanofiber mode with a large evanescent tails extended to the air, with the loss less than 0.01. Therefore, the plasmonic mode can be excited and collected efficiently through a standard single-mode fiber.

Now, we analyze the adiabatic process in the present structure. The light propagates along the waveguide, defined as z-axis. Similar to the time evolution of quantum states in Schrödinger function, the evolution of light in waveguides can be expressed as [13], [14]

$$i\frac{\partial}{\partial z}\left|\varphi\left(z\right)\right\rangle = H\left(z\right)\left|\varphi\left(z\right)\right\rangle, \qquad (1)$$

where $H(z)$ is position (z) dependent Hamiltonian due to the variation of waveguide-substrate space, and $|\varphi(z)\rangle$ is the wavefunction at the cross section. At any position of the hybrid waveguide, there exist instantaneous nondegenerate eigenstates of $H(z)$. In the basis of eigenmodes $\{\beta_m, |\varphi_m(z)\rangle\}$, the electromagnetic field can be expanded as

$$\Big|\varphi(z)\rangle = \sum a_m(z)e^{-i\int \beta_m(z)dz}\Big|\varphi_m(z)\rangle, \qquad (2)$$

where β_m is the propagation constant of mode $|\varphi_m(z)\rangle$, and $a_m(z) = \langle\varphi_m(z)|\,\varphi(z)\rangle$ is the corresponding coefficient. Substituting Eq.(1) and Eq.(2) into the expression $\langle\varphi_k(z)|\, i\frac{\partial}{\partial z}\,|\varphi(z)\rangle$, we can obtain

$$\frac{\partial}{\partial z}a_k(z) = -\sum g_{km}(z)e^{-i\int(\beta_m(z)-\beta_k(z))dz}a_m(z), \qquad (3)$$

where $g_{km}(z) = \langle\varphi_k(z)|\,\frac{\partial}{\partial z}\,|\varphi_m(z)\rangle$. By solving the equation $\langle\varphi_k(z)|\,\frac{\partial}{\partial z}(H(z)\,|\varphi_m(z)\rangle) = \langle\varphi_k(z)|\,\frac{\partial}{\partial z}(\beta_m(z)\,|\varphi_m(z)\rangle)$, we obtain

$$g_{km}(z) = \frac{\left\langle\varphi_k(z)\left|\frac{\partial H(z)}{\partial z}\right|\varphi_m(z)\right\rangle}{\beta_k(z)-\beta_m(z)}, \qquad (4)$$

when $k \neq m$. Therefore, we can finally obtain

$$\frac{\partial}{\partial z}a_k(z) = -\left\langle\varphi_k(z)\left|\frac{\partial}{\partial z}\right|\varphi_k(z)\right\rangle a_k(z) - \sum_{n\neq m} g_{km}(z)e^{i\int(\beta_m(z)-\beta_n(z))dz}a_m(z). \qquad (5)$$

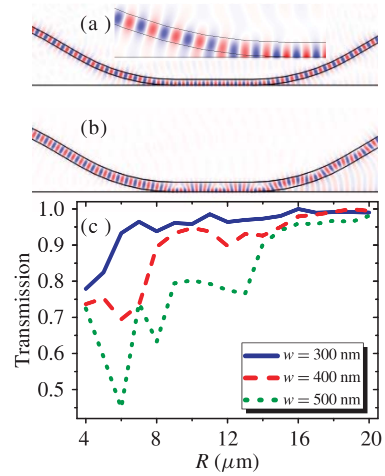

Fig. 2. (a) and (b) Filed distributions for $w = 300$-nm and $w = 500$-nm waveguide, respectively, with $R = 10\ \mu$m and $t = 0$. (c) Transmission of the hybrid waveguide for different w and R, with $t = 0$. Inset: the detail of adiabatic conversion

The evolution of states in the hybrid waveguide at the bending region can be obtained by solving the array of equations for all $a_k(z)$. The first term of Eq.(5) stands for the Berry phase, which does not play a significant role here since we just concern about the energy conversion. The second term represents the coupling between eigenmodes, which reveals the requirement for efficiently adiabatic mode conversion, i.e. $g_{km}(z) \ll 1$. Since the variance of $H(z)$ depends on the air space (s) between waveguide and substrate, we can rewrite $g_{km}(z)$ as $g_{km}(s)\frac{\partial s}{\partial z}$ where $g_{km}(s) = \langle\varphi_k(s)|\,\frac{\partial H(s)}{\partial s}\,|\varphi_m(s)\rangle/(\beta_k(s)-\beta_m(s))$. When nanofiber approaches the substrate $(s \approx \lambda)$, $\frac{\partial s}{\partial z} \approx -\sqrt{\frac{s}{2R}}$. Therefore, the adiabatic conversion requires $R \gg \lambda$. In addition, the nanofiber should work in the single mode regime to exclude high order modes, with the single mode criterion $V = (\pi w/\lambda)\sqrt{n^2-1} < 2.405$.

In order to verify the losslessly conversion between fundamental modes under reasonable parameters, we numerically solve the stationary harmonic propagation of optical field in the nanofiber contacting with silver by two-dimensional finite element method (COMSOL Multiphysics 3.5a). Figs. 2(a) and 2(b) show the field distribution as light propagating in the hybrid waveguide, which are obtained by solving the in-plane wave model, with scattering boundary condition and H-field plane wave incident at the end of the waveguide. For $w = 300$nm, the fundamental dielectric modes are almost totally converted to plasmonic mode, as shown in the inset of Fig. 2(a). However, for $w = 500$nm, we can find that the mode is not totally converted to the plasmonic mode, and the mode in the contact region and transmitted light is multimode. The metal loss is neglected here, so the transmission directly indicates the adiabatic conversion efficiency. Fig. 2(c) shows the transmission of the hybrid waveguide structure, where the waveguide mode converts to the plasmonic mode and then converts back. Clearly, when the radius R is larger, the conversion efficiency is higher. When R is small, the dynamics is complex, since the adiabatic condition is not fulfilled.

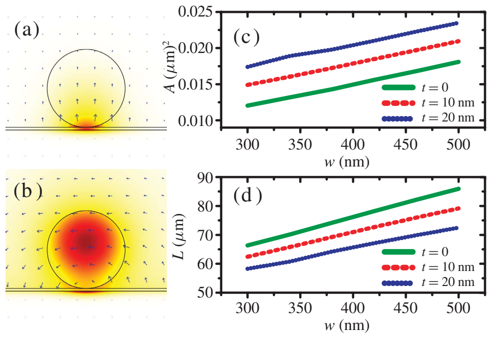

Fig. 3. (a) Energy density distribution at the cross section of the hybrid waveguide for the TE mode. (b) TM mode with $w = 300$ nm and $t = 10$ nm. The arrows indicate the directions of electric field. (c) Mode area. (d) Propagation length of the hybrid plasmonic mode (a) with $t = 0$, 10, 20 nm for various waveguide widths.

For different nanofiber diameter w (Fig. 1(c)), thin fiber shows better performance. The dependence of adiabatic conversion on w and R agree with the theoretical analysis above.

As the lossless adiabatic conversion is confirmed, we turn to analyze the properties of the hybrid plasmonic mode. In the contact region, the cross section is uniform along z-axis, and the hybrid plasmonic mode propagates harmonically along the waveguide. By employing the perpendicular waves model, we can investigate the eigenmodes travel along the z-axis at the two-dimensional cross section [15], as shown in Figs. 3(a) and 3(b). For the transverse electric (TE) polarization, the energy is localized at the nanofiber-substrate interface, while the transverse magnetic (TM) mode is well confined in the nanofiber. It is evident that the mode area of TE mode is greatly reduced, and the maximum of the electric field is located around nanofiber-substrate interface. We plot the mode area (A) and propagation length (L) against the waveguide width (w) for different t in Figs. 3(c) and 3(d).

Due to the one-dimensional waveguide confinement, the density of states changes near the nanofiber. As a result, the spontaneous emission rate is modified, which is known as Purcell effect. The maximum emission enhancement can be expressed as $F_p = \frac{3n_g}{4\pi}\frac{(\lambda/n)^2}{A}$, where n_g is the group index. For nanofiber with $w = 300nm$, and $g = 10nm$, the enhancement of spontaneous emission rate is $F_p = 9.9$ for a emitter in air and $F_p = 6.0$ for emitter embed in PMMA. The corresponding collection efficiency of the single emitter fluorescence is $F_p/(1+F_p) = 90.8\%$ in air and 85.8% in PMMA. Combining with the high efficiency adiabatic conversion, we can finally obtain a high collection efficiency of single emitter emissions directly by fiber.

By a 3D translation stage, this hybrid waveguide can be manipulated or moved easily. Benefiting from the greatly enhanced light-matter interaction, this hybrid plasmonic waveguide structure is potential for experimental realization of the single photon transistors [8], [16] or phase flip gate for quantum information science. It should be noted that the enhancement of light emitter interaction is broadband, permitting efficient interaction with quantum dots which have broad emission spectra. For single emitters disperse on the substrate, this hybrid structure can also be use for single photon source or spectrum analyze [11]. Further improvement on this structure to enhance the emitter-light interaction can be done by introducing the bragg-grating mirrors on the nanofiber [17].

III. Conclusion

In summary, we have proposed and numerically studied the adiabatic conversion of energy between a dielectric nanofiber and a nanofiber-metal film hybrid plasmonic waveguide structure. The conversion efficiency can exceed 99%, and the movable structure is convenient to be realized in experiment. The hybrid plasmonic mode has very small mode area and low optical loss, permitting strong coherence light-matter interaction, which is potential for studying broadband waveguide QED, single emitter spectrum with high collection efficiency, and nonlinear optics.

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