Improving field enhancement of 2D hollow tapered waveguides via dielectric microcylinder coupling

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Abstract

We numerically study a novel scheme to improve the field enhancement of 2D hollow tapered waveguides (HTWs). A dielectric microcylinder is embedded into a metal–insulator–metal (MIM) HTW for resonant exciting gap surface plasmons (GSPs), which is different from the lowest propagating mode (TM₀) excitation via the conventional fire-end coupling method. The physical mechanism of the field enhancement and the influence of critical parameters such as numerical aperture (NA) of the lens, permittivity of the microcylinder and the incident wavelength are discussed. The substantial improvement of the GSP excitation efficiency via dielectric microcylinder coupling shows potential in designing tapered MIM waveguides for nanofocusing and field enhancement.

Keywords: plasmons, metal–insulator–metal structures, optical waveguides and couplers

(Some figures may appear in colour only in the online journal)
become an important issue in modern nanophotonics and nano-optics. Converting light into surface plasmons polaritons (SPPs) is deemed as one of the most promising approaches toward fulfilling this goal. Plasmonic nanofocusing is typically achieved using tapered metallic waveguides which can be divided into two categories: insulator–metal–insulator (IMI) structures such as tapered metal rods [14], nanopramids [15], metal film tapers [16] and nanowedges [17] for slow surface plasmon (SSP) nanofocusing, and MIM structures such as tapered field lines [18], tapered gaps [19], tapered V-grooves [20] and nanocampanile (or 3D linear taper) [21,22] for gap surface plasmon (GSP) nanofocusing. Comparing to tapered IMI structures, tapered MIM structures can generate nanoscale confined light spots immune to the external background with higher field enhancement (FE) [23], which are qualified as aperture near-field scanning optical microscopy (NSOM) probes.

Efficient coupling of the electromagnetic radiation into tapered plasmonic waveguides is critical for realizing plasmonic nanofocusing. SPP excitation in an input entrance of larger scale and concentrating into a nanoscale region results in an extremely high FE in theory. However, for the tapered MIM structures, GSPs are generally excited by the $TM_0$ mode using the fire-end coupling method through bulk light or guided modes coupling. To reduce the reflection and scattering losses, the taper angles and the sizes of the input entrance of tapered MIM structures are generally smaller than the critical taper angle (usually less than 10 degrees to meet the adiabatic conditions) and the wavelength of the input beam, respectively [24, 25], which is an obstacle for the design and application of tapered plasmonic waveguides.

In this paper, to the best of our knowledge, we report for the first time that FE in a 2D HTW of large taper angle and input entrance size can be remarkably improved via microcylinder coupling. A standard tapered MIM structure is chosen to study the physical phenomenon and the excitation mechanism of the GSPs. The influences of critical parameters such as the NA of the focusing lens (FL), the permittivity of the microcylinder and the incident wavelength are discussed.

The schematic diagram of a 2D HTW is illustrated in figure 1. The structure of the 2D HTW is assumed to be uniform and infinite in the y direction. Aluminum, which has smaller skin depth than noble metal and is commonly used in NSOM, is chosen as the metallic material for preventing optical leakage. Based on the 3D near-field probe used in our previous experiment [26], the metal thickness, entrance width $D_i$, aperture width $D_o$ and taper angle of the HTW are 100 nm, 3 µm, 5 nm and 60°, respectively. The incident light is a linearly TM polarized Gaussian beam at $λ = 500$ nm with a 9 nm full width at half maximum (FWHM), which is further restricted by an aperture diaphragm (AD) of 9 mm diameter. The NA of the FL is 0.55 and the focal spot is assumed to be exactly located at the entrance of the 2D HTW. The dielectric microcylinder is tangent with the inner walls and its radius is chosen as $530$ nm after optimization calculation.

The optical evolutions in the 2D HTWs are simulated by our self-developed finite difference time domain (FDTD) numerical model as in our previous work [27]. The grid cell is set as $Δx = Δz = λ/500 = 1$ nm for accurately describing the nanoscale waveguide structures. An anisotropically perfectly matched layer absorbing boundary condition is adopted for the truncation of FDTD lattices. The Lorentz–Drude model presented by Racic et al [28] is adopted to describe the permittivity of aluminum related to incident wavelength. The permittivities of the microcylinder, air and aluminum walls are taken as $ε_1 = 2.2$ (commonly used glass regardless of the dispersion), $ε_2 = 1$ and $ε_Al = -34.2 + 9.0i$, respectively. Unless otherwise specified, the following calculations are based on the above parameter values.

Figure 2 shows the time-averaged electric field intensity distributions in the 2D HTW. In absence of a microcylinder, most optical energy is reflected and absorbed by the metal wall due to the nonadiabatic conditions before evolving from $TM_1$ mode into $TM_0$ mode at the tip region, as shown in figure 2(a). The stimulated $TM_0$ mode is then reflected back along the internal walls or scattered back into the optical field. As a result, GSP excitation approaching the apex is not obvious and a FE of about 346 is obtained (the FE is defined as the ratio of the peak field intensity at the aperture to the average field intensity at the entrance). This GSP excitation, as a matter of fact, belongs to the usual fire-end coupling method.

With the microcylinder, the situation is quite different. Pure SPPs are primatively excited by the evanescent fields existing in the microcylinder-wall gaps close to the microcylinder-wall contact points (gap width between the two walls is too large to support the GSP modes). The excited SPPs propagate forward along the walls and are coupled into GSPs gradually in the tip region when the gap width of the two walls is small enough to support the GSP modes. Most of the GSPs are reflected back by the aperture edge and convert back into SPPs along the metal walls. The superposition of the forward and backward SPP (GSP) waves constructs strong standing waves, which results in a FE of about 1384 at the 5 nm aperture (compared with the situation without microcylinder, the light field coupling efficiency is improved by 5.3 times). In this case, the GSP excitation mainly comes from the near-field coupling of the microcylinder-wall gaps, which is completely different from the fire-end coupling method without microcylinder. The reflection coefficients for
the two cases without and with microcylinder are 41.71\% and 25.28\%, respectively.

To view insight into the physical phenomenon of the GSP resonant excitation, the relationship between the FE and the microcylinder radius is investigated for various NAs of the FL, permittivities of the microcylinder and incident wavelengths, respectively.

Firstly, in order to excite a pure SPP on an inner metal wall, the component of the wave vector of the incident light parallel to the metal surface must equal the wavenumber of the pure SPP

$$k_{sp} = \frac{\omega}{c} \sqrt{\frac{\varepsilon_2 \varepsilon_{AI}(\omega)}{\varepsilon_2 + \varepsilon_{AI}(\omega)}}$$

(1)

The evanescent fields existing in the microcylinder-wall gaps close to the contact points present abundant wave vectors larger than the wave vector of the incident wave, so the wave vector of the SPPs readily matches with the wave vector of the evanescent fields by itself and pure SPPs are primitively excited on the inner metal walls close to the contact points. The contact points and the corners of the aperture edges compose a Fabry–Perot kind of resonator, so the SPPs (GSPs) are resonantly excited and magnified by the multiple reflections of the counter-propagating SPPs (GSPs). For resonant excitation of the SPPs (GSPs), the distance \(L\) between the contact points and the corners along the walls must comply with the standing wave condition

$$2 \int_0^L \beta_{SPP,GSP}(l) dl + \varphi_R = 2m\pi, \quad m = 1, 2, 3, ...$$

(2)

where \(\beta_{SPP,GSP}\) is the propagation constant of the SPPs (GSPs). It is a constant when the gap width is large enough (SPPs) and increases with the decrease of the gap width in the tip region (GSPs), \(l\) is the spacing between the contact points and the corners along the wall and \(\varphi_R\) is the total reflection phase.

Figure 3 shows the FE at the 5 nm aperture as a function of the microcylinder radius for various NAs.

Figure 4 shows the FE at the 5 nm aperture as a function of the microcylinder radius for various permittivities of the microcylinder.
stated in figure 1). By increasing permittivity from $e_1 = 2.0$ to $e_1 = 2.6$, the whole FE curve moves up and the microcylinder radii corresponding to the resonant peaks decrease slightly. This illustrates that a microcylinder with larger permittivity can transfer more optical energy into the near field in the microcylinder-wall gaps and results in a slightly larger GSP propagation constant in the microcylinder-wall gaps. Figure 4 also shows that when $e_1$ further increases from 2.6 to 2.8, the maximum resonant peak of the FE curve decreases abnormally. It indicates that the permittivity cannot be too large; otherwise, the optical reflection on the incident cylindrical surface is large enough to decrease the GSP excitation efficiency in return.

Figure 5 shows the FE at the 5 nm aperture as a function of the microcylinder radius for various incident wavelengths (the other parameters are the same as those stated in figure 1). It indicates that the shorter the incident wavelength is, the larger the FE will be. With the decrease of the incident wavelength, the resonant peaks become clearer and more highlighted and move toward the left entirety. On the one side, a shorter-wavelength light field is more conducive for focusing via coupling lens. On the other side, a shorter-wavelength light field excitation results in a relatively larger GSP propagation constant which is advantageous to the stronger field localization of the GSPs and the locations of the nodes and antinodes move left accordingly.

In summary, we find that the field intensity of a 2D HTW in nonadiabatic conditions can be greatly enhanced via embedding a dielectric microcylinder. The efficient excitation and compression of GSPs in the 2D HTW result in the high FE, which is advantageous to the stronger field localization of the GSPs and the locations of the nodes and antinodes move left accordingly.

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