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Adiabatic nanofocusing of the fundamental modes in plasmonic parabolic potentials

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ABSTRACT

We investigate the adiabatic nanofocusing of the fundamental modes in plasmonic parabolic potentials. The potentials are obtained in the metal–dielectric–metal structure, of which the dielectric layer width is modulated quadratically in the horizontal direction and linearly in the longitudinal direction. In such a structure, light is compressed in both transverse directions due to increasingly stronger parabolic potentials and decreasing dielectric layer width. We show by both closed form analytical descriptions and numerical simulations that there is a critical tapering angle, above which the field could be enhanced. In contrast to previously reported tapered structures in the adiabatic regime without transverse potentials, the structure proposed in this paper shows stronger focusing capability and allows monotonic increasing field enhancement over longer propagation distances.

1. Introduction

The flourishing field of plasmonics deals mainly with surface plasmon polaritons (SPPs), which exist as the coupled excitations of photons and electrons on the surface of metallic nanostructures [1]. As SPPs can be confined down to the nanoscale that is beyond the diffraction limit [1–3], they stand out as one of the most promising candidates for applications in highly integrated optical devices and all-optical circuits, which are vital in next generation high-speed communications and calculations. Moreover, SPPs can be employed for various other applications, including single molecule sensing [4], super imagining [5], nonlinear effects enhancement [6], explosive detection [7] and even cancer treatment [8], to name but a few.

However, SPPs are highly lossy due to the intrinsic Ohmic loss of metal and this poses a great challenge for its further applications. To address this challenge, various structures are proposed and experimentally verified for the nanofocusing of SPPs (see Refs. [9–12] and references therein). Among all the structures proposed, tapered metal–dielectric–metal (MDM) slot waveguides have attracted enormous attention due to the fabrication simplicity, high coupling efficiency and strong focusing effects [11–19]. In two-dimensional MDM structures shown in Refs. [14–16], although significant field enhancement can be achieved, for realistic beams carrying finite energy, light is confined in only one transverse direction within the dielectric layer but would diffract in the other one, thus rendering the nanofocusing incomplete.

Different approaches have been employed to compress light in the other transverse direction, including decreasing the transverse dimensions [17,20], introducing an extra potential by transverse modulation [18] or through incorporating materials with nonlinearities [19]. However, all those approaches have specific problems. For structures truncated finite in the transverse direction as shown in Refs. [17,20], the edge effects would be strong and SPPs confined would be too sensitive to the edge roughness and other surrounding perturbations. For the structure shown in Ref. [19] where a Coulomb potential is introduced, light is fully localized within the edge when the opening angle is smaller than the critical angle and thus this structure is hard to be applied for applications in visible light regime (the critical angle of visible light is large and this will set a limit for the opening angle and hence significantly suppress the nanofocusing effects). Moreover, the Coulomb potential is asymmetric and the coupling efficiency would be low if the incident beam is symmetric. Although introducing nonlinearities [18] would avoid problems mentioned above, the nanofocusing would be undermined by the nonlinear saturation [21] and also nonlinearity based devises would be highly intensity sensitive, which is not desirable for on-chip signal processing.

In this paper, we introduce symmetric plasmonic parabolic potentials to confine light in one of the transverse directions. In

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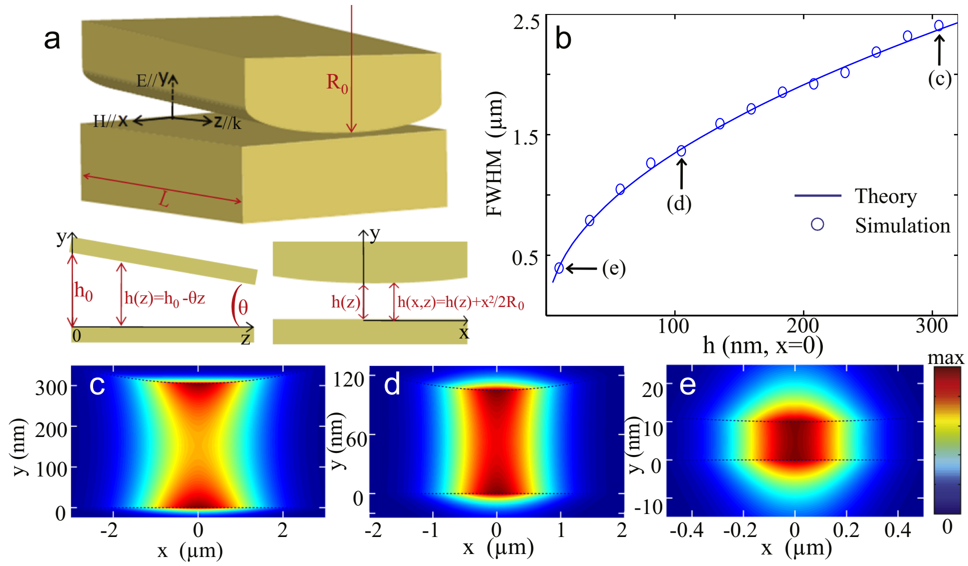

Fig. 1. (a) A MDM structure with quadratic (effective radius R_0) and linear modulation of the dielectric layer width in the x and the z direction respectively. The tapering angle along the z direction is θ and the structure length is L. The dielectric layer width at the input end ($x = z = 0$) is h_0 and would change to $h(z)$ along z. On the $x-y$ plane the width of the quadratically modulated dielectric layer can be expressed as $h(x, z) = h(z) + x^2/2R_0$. (b) FWHM of $|H|^2$ along the x direction for the fundamental modes at different z of different dielectric layer widths [$h(x = 0)$]. The radius of the metallic wire is fixed at $R_0 = 100$ μm. Both theoretical (solid lines) and numerical (circles) results are shown. (c)–(e) Transverse field distributions (simulation, $|H|^2$) for the three cases marked in (b).

the MDM structure shown in Fig. 1(a), the dielectric layer width is modulated quadratically in the horizontal direction to produce a parabolic potential and tapered linearly in the longitudinal direction with a tapering angle θ. During propagation, light would be more and more tightly confined in both transverse directions due to the increasingly stronger potential and narrower dielectric layer width. To describe the nanofocusing process, we derive closed form analytical formulas and deploy simulations to show that there is critical tapering angle above which the field can be enhanced. More importantly, we find in our proposed structure, due to the strong field confinement in the parabolic potential, monotonic increasing field enhancement is achievable over longer propagation distances compared to other MDM structures reported for SPPs nanofocusing.

2. Expressions for field evolutions in tapered parabolic potentials

In this paper, without losing the generality, the dielectric is set to be air ($\varepsilon_d = 1$) and we use the Drude model for the metal layers, $\varepsilon_m = 1 - \omega_p^2/(\omega^2 + i\omega\omega_c)$, where $\omega_p = 1.37 \times 10^{16}$ rad/s and $\omega_c = 7.25 \times 10^{13}$ rad/s (the parameters fit silver well in the spectral regime we study in this paper). In a flat MDM structure, the effective refractive index of the symmetric mode (with respect to the magnetic field distribution) can be expressed as [22–24]: $n_{\rm eff}(h) = a/h + b = (a_1 + ia_2)/h + b_1 + ib_2$, where both a and b are complex numbers and can be extracted from data fitting.

We show the structure we study in Fig. 1(a). This is a modified MDM structure where the upper metal plate is tilted by an angle θ with respect to the z direction and is quadratically modulated with an effective radius of R_0. This corresponds to a broad metallic nanowire (with the radius R_0 and tilted by an angle of θ placed above another metal plate). The light inside is prorogating along the z direction. As a result, in the structure shown in Fig. 1(a), the width of the dielectric layer can be expressed as $h(x, z) = h(0, z) + x^2/2R_0$, when $R_0 \gg h_0 = h(0, 0)$ [here h_0 is the dielectric layer width at the input end along y with $x = z = 0$; see the lower part of Fig. 1(a)]. We define that $h(z) = h(0, z)$, and with the tapering angle θ we get $h(z) = h_0 - \theta z$. In this waveguide, we obtain a longitudinally (along the z direction) changing transverse parabolic plasmonic potential under the condition of $x^2 \ll 2h(z)R_0$

$$\varepsilon_{\rm eff}(x, z) = n_{\rm eff}^2(x, z) = n^2(z)[1 - \Omega^2(z)x^2], \tag{1}$$

where $n(z) = a/h(z) + b$, and $\Omega(z) = \sqrt{a/[n(z)R_0h^2(z)]}$, which indicates the focusing strength of the parabolic potential. In this potential, we consider only the adiabatic nanofocusing (adiabatic here means that the cross section of the waveguide changes so slowly that during propagation the backward reflection and cross-mode coupling can be effectively neglected) of the fundamental mode, as it is symmetric along horizontal direction and is mainly excited by end-fire coupling [23,24]. Throughout this paper, for simplicity we characterize the nanofocusing effect by the enhancement of the magnetic field, which is similar to what is shown in Ref. [14]. Meanwhile, it is worth mentioning that the electric field enhancement is quite different and can be deduced from the enhancement of magnetic field [16]. Based on the expressions of the fundamental mode in parabolic potentials shown in Ref. [23,24], the adiabatic approximation [9] and the TM mode approximation (neglect the components of H_y, H_z and E_x), the magnetic field can be expressed as

$$H(x, y, z) = H_x(x, y, z) = H_0(z)\exp\left[i\int_0^z \beta(z)\,dz\right]\exp\left[-\frac{x^2}{2\mu^2(z)}\right]A(x, y, z) \tag{2}$$

where $H_0(z) = H_x(0, 0, z)$, $\beta(z) = n(z)k_0 - \Omega(z)/2 = \beta_1(z) + i\beta_2(z)$ (k_0 is the angular wavenumber in vacuum), $\mu(z) = [k_0 n(z)\Omega(z)]^{-1/2}$ (effective mode width along x), and $A(x, y, z)$ is the eigenfield distribution of H_x, the expressions of which can be found in Ref. [1, Chapter 2]. In Fig. 1(b) we show FWHM (full width at half maximum) of $|H|^2$ for the fundamental mode along the x direction at different h with $R_0 = 100$ μm and λ=632.8 nm. In theory FWHM=$2\sqrt{\ln 2}\,|\mu(z)|$ for the field distribution along the x direction. Along the y direction, since most of the fields are confined within the dielectric layer, we can use directly the dielectric layer width $h(z)$ to characterize the width of the field distribution along this