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Single-mode subwavelength waveguide with channel plasmon-polaritons in triangular grooves on a metal surface

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We demonstrate that single-mode operation of a subwavelength plasmonic waveguide in the form of a V-groove on a metal surface can be achieved by adjusting the depth of the groove. Strongly localized channel plasmon-polaritons (CPPs) are shown to propagate in such waveguides. If the groove depth is close to the penetration depth of the fundamental CPP mode, then all higher modes are not supported by the structure, leaving only the fundamental mode propagating in the groove. In this case, propagation distances of fundamental mode ~10 μm can easily be achieved together with strong subwavelength localization. © *2004 American Institute of Physics.*
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One of the main ideas for the design of effective subwavelength waveguides and interconnectors for integrated nano-optics is based on the use of evanescent fields in media with negative real part of the dielectric permittivity, e.g., metals.[1–12] In particular, it has been shown that highly localized plasmons can exist in chains of metallic nano-spheres,[1,2] strip-like metal films,[6–9] metal nano-rods,[4,5] on top of a trapezium metal wedge,[10,11] and in narrow gaps between two metal interfaces.[12] All of these structures can thus be used as subwavelength waveguides with typical localization that may be far beyond what is allowed by the diffraction limit.[1,4]

Recently, a type of highly localized plasmon [channel plasmon-polariton (CPP)] has been analyzed in metallic grooves.[13,14] CPPs in V-grooves have demonstrated superior features for subwavelength guiding, including a unique combination of strong localization and relatively low dissipation,[14] a possibility of nearly zero energy losses at sharp bends[15] (achieved also in photonic crystals[16] that do not allow subwavelength localization), low sensitivity to structural imperfections, broad-band transmission (not achievable in nano-chains and photonic crystals), and compatibility with the planar technology.

Previous analysis of CPPs has demonstrated the existence of several different modes, the number of which increases with increasing localization of the wave.[13,14] For example, two modes have been predicted in a 30° vacuum V-groove in silver at the wavelength 0.6328 μm.[14] Such multimode operation may be inconvenient for interconnectors in integrated nano-optics.

This letter demonstrates that all higher CPP modes can be effectively removed from the groove simply by adjusting its depth. Thus a single-mode waveguide with strong subwavelength localization of the wave, and significant propagation distance can be obtained.

The analyzed structure is presented in Fig. 1(a); ε_m and ε are permittivities of the metal and the dielectric in the groove, respectively, θ and h are the angle and the depth of the groove. The regions $x<0$ and $y>h$ have the same permittivity ε as in the groove.

The analysis has been done by means of the finite-difference time-domain algorithm.[14,17,18] CPPs are generated in the groove by means of end-fire excitation, i.e., by a bulk wave with the wavelength λ in vacuum, incident onto the end of the groove at $x=0$ [Fig. 1(a)]. The specific structural parameters used are listed in the caption of Fig. 1. If the depth of the groove is of the order of or less than λ, then an opaque metal screen of 200 nm thickness is used at $x=0$

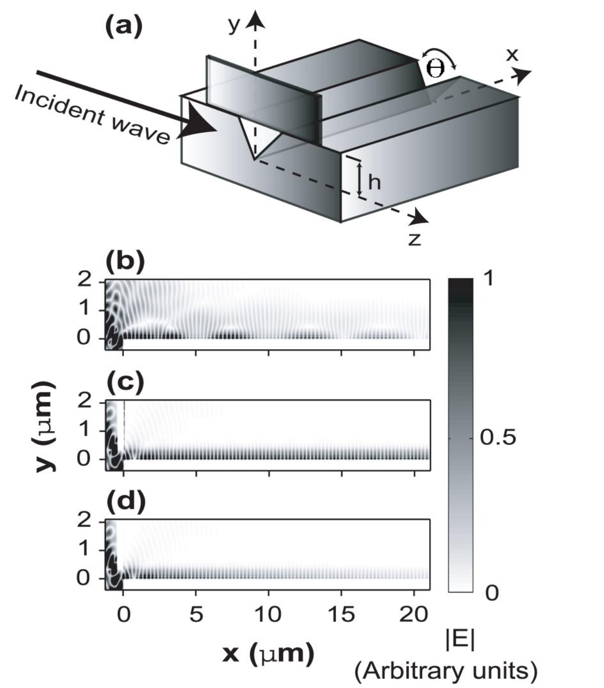

FIG. 1. (a) The structure with a triangular groove of finite depth h in a metal with an additional screen at $x=0$. (b) The distribution of the magnitude of the instantaneous electric field in an infinitely deep ($h=+\infty$) vacuum groove ($\varepsilon=1$) in silver with the free charge density $\rho \approx -7.684\times10^9$ C/m^{-3} and damping frequency $f_d=1.4332\times10^{13}$ Hz—Ref. 17 (i.e., $\varepsilon_m=-16.22+0.52i$), resulting from the end-fire excitation of CCP modes by a bulk wave incident onto the groove (at $x=0$) at the angle of 45° with respect to the x axis (a). The magnetic field in the incident wave is in the (x,y) plane, the groove angle $\theta=30°$, and λ(vacuum)=0.6328 μm. (c) Same as in (b), but with $h=316.4$ nm and $f_d=0$ ($\varepsilon_m=-16.22$, i.e., no dissipation in the metal). (d) Same as in (b) and (c), but with $h=316.4$ nm and $f_d=1.4332\times10^{13}$ Hz—Ref. 17 ($\varepsilon_m=-16.22+0.52i$).

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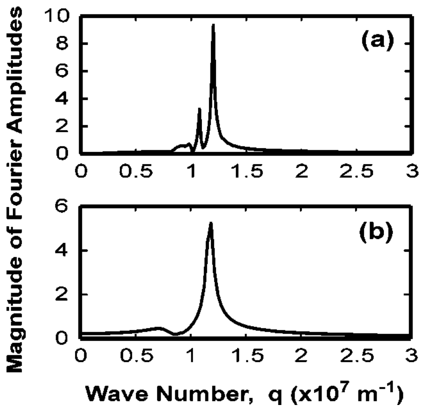

FIG. 2. The dependencies of the Fourier amplitude for the field distribution at the tip of the groove in the interval 2 μm $< x <$ 40 μm on wave number. (a) Infinite groove [Fig. 1(b)]. Two strong maxima at $q_1 \approx 1.20 \times 10^7$ m^{-1} and $q_2 \approx 1.08 \times 10^7$ m^{-1} correspond to the fundamental and second CPP modes, respectively. (b) Groove of finite depth $h = 316.4$ nm [Fig. 1(d)]. The only maximum at $q_1 \approx 1.20 \times 10^7$ m^{-1} corresponds to the fundamental CPP mode – single-mode guiding.

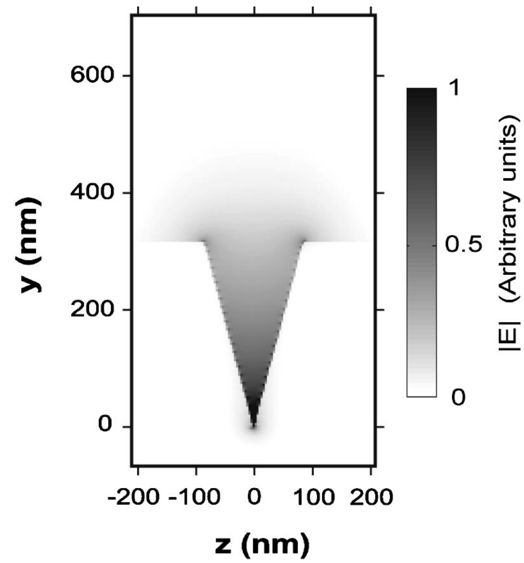

FIG. 3. The typical field distribution in a cross section of a groove with h that is close to the penetration depth of the fundamental mode into the groove ($h \sim h_{p1}$).

[Fig. 1(a)]. This is to suppress scattered bulk waves in and above the groove, which interfere with CPPs and impede the analysis.

Figure 1(b) presents the typical distribution of the electric field in the (x, y) plane for an infinitely deep (h is much larger than the penetration depth of CPP up the groove) silver-vacuum V-groove for $\lambda = 0.6328$ μm and $\theta = 30°$.[14] No metal screen has been used in this case, and noticeable bulk scattered waves can be seen in Fig. 1(b). It can be seen that clear periodic modulation of the field distribution occurs in the groove [Fig. 1(b)]. This is actually due to beats between two different CPP modes.[14] Indeed, the dependence of the Fourier amplitude of the field on wave number [Fig. 2(a)] displays two distinct maxima at $q_1 \approx 1.20 \times 10^7$ m^{-1} and $q_2 \approx 1.08 \times 10^7$ m^{-1}, corresponding to the fundamental and second CPP modes. Their interference results in the observed beats [Fig. 1(b)].[14]

However, the second CPP mode in this multimode plasmonic waveguide can easily be eliminated by reducing depth of the groove. It can be estimated that the penetration depth of the second CPP mode along the y axis (up the groove) is $h_{p2} \sim 800$ nm [Fig. 1(b)], while the penetration depth for the fundamental CPP mode in the same direction is $h_{p1} \sim 300$ nm [Fig. 1(b)]. If we reduce the depth of the groove to $h \approx h_{p1}$, then the second mode is not supported by the structure (since h is significantly less than h_{p2}), while the fundamental mode will still be effectively guided by the groove. Indeed, Fig. 1(c) presents the field distribution in the same groove as for Fig. 1(b), but with the additional 200 nm screen, $h = 316.4$ nm (15 grid cells from the tip) and no dissipation in metal, i.e., $\mathrm{Im}\{\varepsilon_m\} = 0$. It can be seen that the screen affectively suppresses bulk scattered waves in the structure. In addition no second CPP mode is observed in the groove and only the fundamental mode propagates along the groove, with no visible beat pattern—Fig. 1(c) (this is still the case even without the metal screen).

Introducing dissipation in silver ($\varepsilon_m \approx -16.22 + 0.52i$ for $\lambda = 0.6328$ μm[17]) results in decay of the amplitude of CPP along the groove [Fig. 1(d)]. The typical propagation distance (≈ 10 μm) of the fundamental CPP mode in the considered single-mode plasmonic waveguide is thus determined by dissipation in the metal.

The conclusion that only one mode exists in the considered groove with $h = 316.4$ nm is clearly confirmed by the Fourier analysis of the field at the tip of the groove in the presence of dissipation (and with 30 grid cells over the depth of the groove)—Fig. 2(b)). Only one maximum is displayed by this figure, demonstrating that only the fundamental mode exists in the groove. Dispersion of this mode is hardly different from its dispersion in an infinitely deep groove, determined in Ref. 14.

The typical field distribution across the groove in the fundamental CPP mode is presented in Fig. 3. Expectedly, the field is maximal near the tip, and decays up the groove. However, an interesting aspect is the slight local increase of the field near the edges of the groove. In addition, the field of the fundamental CPP mode also extends outside the groove, producing a weak dome-like feature (Fig. 3). However, this field is nonperiodic, which indicates that there is no leakage of the fundamental mode (periodicity would have corresponded to a bulk wave propagating away from the groove). The dome structure in Fig. 3 is thus due to the evanescent field of the fundamental CPP mode decaying outside the groove. This dome field rapidly decreases in intensity with increasing depth of the groove.

Increasing groove angle, results in decreasing number of different CPP modes supported by the groove. If the angle is sufficiently large, only one (fundamental) CPP mode can exist even in an infinitely deep groove. In the silver-vacuum structure at $\lambda = 0.6328$ μm, this occurs within the angular range $\sim 50° < \theta < \theta_c \approx 75°$ (if $\theta > \theta_c$, no CPP can exist in the groove[14]). However, it is important that strong localization of CPP (i.e., subwavelength guiding) can be achieved only in grooves with sufficiently small angle (in the considered structure must be $\theta \leqslant 30°$). In this case, an infinitely deep V-groove supports several different modes (two in the considered structure). As demonstrated earlier, making groove depth comparable to the penetration depth of the fundamental mode, results in a single-mode subwavelength plasmonic waveguide with strong localization of the field. If the groove angle is decreased, the penetration depth of the fundamental mode along the y axis also decreases (localization increases).

Therefore, the groove depth of the corresponding single-mode groove waveguide should decrease with decreasing θ. For example, decreasing groove angle in the silver-vacuum structure to 20° and 15° results in decreasing groove depth (required for single-mode guiding) to ~200 and ~100 nm, respectively. This can be seen as an advantage in terms of fabrication of these waveguides for integrated nano-optics (fabrication of deep grooves might have been more difficult).

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