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Numerical and experimental investigation of wedge tip radius effect on wedge plasmons

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We report numerical analysis and experimental observation of strongly localized plasmons guided by triangular metal wedges and pay special attention to the effect of smooth (nonzero radius) tips. Dispersion, dissipation, and field structure of such wedge plasmons are analyzed using the compact two-dimensional finite-difference time-domain algorithm. Experimental observation is conducted by the end-fire excitation and near-field scanning optical microscope detection of the predicted plasmons on 40° silver nanowedges with the wedge tip radii of 20, 85, and 125 nm that were fabricated by the focused-ion beam method. The effect of smoothing wedge tips is shown to be similar to that of increasing wedge angle. Increasing wedge angle or wedge tip radius results in increasing propagation distance at the same time as decreasing field localization (decreasing wave number). Quantitative differences between the theoretical and experimental propagation distances are suggested to be due to a contribution of scattered bulk and surface waves near the excitation region as well as the addition of losses due to surface roughness. The theoretical and measured propagation distances are several plasmon wavelengths and are useful for a range of nano-optical applications. © 2008 American Institute of Physics. [DOI: 10.1063/1.2960543]

I. INTRODUCTION

Modern microelectronics is rapidly approaching its limit in terms of speed and efficiency of information processing. Therefore, alternative means for sustainable advancement of computer technology, information processing, and storage are urgently required. One of such alternatives is related to using light as an information carrier in integrated circuits and devices. This means replacing conventional electronic devices and circuits by much more efficient optical counterparts.

However, conventional optical devices and interconnectors using dielectric waveguides and structures suffer from a significant drawback. This is the diffraction limit of light, which means that electromagnetic waves cannot be localized within a region with dimensions that are much smaller than the wavelength in the structure.1–3 This is a major obstacle in achieving a high degree of miniaturization and integration of optical devices and circuits. One of the main approaches to overcome this problem is the use of highly localized surface plasmons in metallic nanostructures, such as metal nanostrips,4,5 nanorods,6,7 nanochains,1,2,7,16 nanotrapeziums,8 gaps,9–12 grooves,13–19 etc., which may eventually lead to the replacement of the current electronic integrated circuits by their faster and more effective all-optical counterparts.1,19

Another interesting type of strongly localized plasmons that were recently predicted and experimentally observed are wedge plasmons (WPs).20,21 WPs are guided along the sharp tip of a metallic wedge surrounded by a dielectric and the localization near this tip can be particularly strong.21 For example, for a 40° Ag wedge in vacuum the predicted beam width was ~50 nm for the excitation wavelength in vacuum of λ = 632.8 nm.21 At the same time, the analysis of guided modes in a plasmonic waveguide in the form of a nanogap in a thin metal film/membrane has revealed that the fundamental mode guided by the gap can be represented by four coupled WPs propagating along the four corners/wedges of the formed by the gap in the film.12 However, in practice the fabricated wedges can have some nonzero radii at the tip. The detailed investigation of WPs on wedges with smoothed tips is important for practical understanding of the behavior of these strongly localized modes. Moreover, since the field is strongly localized near the wedge tip,12,21 it is reasonable to expect that even a small smoothness of the tip (~10 nm at optical wavelengths) can have a drastic effect. Therefore, the aim of this paper is in the analysis of WPs propagating on metallic wedges with smooth tips of varying tip radius. Dependence on excitation wavelength, wedge angle and tip radius, field distribution, dissipation, and existence conditions of such WPs will be determined and analyzed.
The Drude model with the free charge density smooth silver-vacuum interface. Permittivity in the silver is determined by the damping frequency $\omega$.

**II. NUMERICAL ANALYSIS OF TRIANGULAR WEDGES WITH VARYING TIP RADIUS**

The analyzed structure consists of a triangular metallic wedge surrounded by a dielectric [Fig. 1(a)]. The tip of the wedges can be either triangular [Fig. 1(a)] or rounded with some radius of curvature, $r$ [Fig. 1(b)]. We consider the situation where the curved surface of a rounded tip is connected smoothly with the flat sides of the wedge (without additional corners between the rounded tip and the flat sides of the wedge) [Fig. 1(b)]. In the present analysis the wedges are made of silver and surrounded by vacuum. The numerical analysis of the Maxwell equations in the considered structures is carried out by means of the compact two-dimensional (compact-2D) finite-difference time-domain (FDTD) algorithm.

The compact-2D FDTD analysis and three-dimensional FDTD have previously shown that there exist numerical solutions to the Maxwell equations, representing the electromagnetic fields strongly localized near the sharp tip of a metallic wedge and propagating along this tip in the $x$ direction [Fig. 1(a)].\(^{21}\) The typical dispersion curves for the fundamental WP mode in sharp triangular wedges [Fig. 1(a)] are presented in Fig. 1(c) for three different wedge angles. It can be seen that for all wedge angles, increasing $\lambda$ (decreasing $\omega$) results in decreasing relative difference between the WP wave number and the number of the surface plasmons on the sides of the wedge [Fig. 1(c)]. This means that localization of WPs decreases with increasing wavelength, and vice versa. This effect is especially significant at smaller wedge angles $\theta$ [Fig. 1(c)].

Taking into account these results for the sharp metal wedge and the previous analysis of plasmons on a parabolic wedge,\(^{20}\) it is also possible to expect that localized plasmons should exist if the tip of the triangular wedge is not sharp but has a radius $r$ [Fig. 1(b)]. Indeed, Fig. 2(a) shows the typical distribution of the magnitude of the total electric field in the $(y,z)$ plane on the rounded tip of a triangular metal wedge. In particular, it can be seen that the field is strongly localized near the tip, similar to how it was for the sharp tip.\(^{23}\) This is a clear indication that, as expected, the strongly localized
WP modes can exist in the presence of the rounded tip of a triangular metal wedge. These modes are localized near the rounded tip and propagate along it [i.e., along the x axis, Fig. 1(b)] an infinitely large distance, if the dissipation in the metal is neglected. The field in these modes rapidly decay in the (y, z) plane with increasing distance from the tip [Fig. 2(a)].

As shown in Ref. 25 WP modes are formed by the symmetric coupled film plasmons. By symmetric film plasmon we refer to those with the symmetric distribution of the electric charges across the film (antisymmetric distribution of the tangential component of the magnetic field) in a uniform dielectric. If the thickness of the metal film (membrane) is reduced to zero, the wave number of the symmetric plasmon increases to infinity,23,24 which means that the effective refractive index for this plasmon increases to infinity. The other type of coupled film plasmon (antisymmetric film plasmon) in a metal membrane with the antisymmetric distribution of the charges (and symmetric distribution of the tangential component of the magnetic field) does not possess such a property, and its wave number decreases to the wave number in the surrounding dielectric, if the thickness of the film tends to zero.

Therefore, a metal wedge can be thought of as a metallic membrane of thickness that decreases to zero as we approach the tip. Therefore, the symmetric film plasmon in a metal wedge propagates in the effective medium with the refractive index that increases (to infinity) when the plasmon approaches the wedge tip. As a result, we have a type of a waveguide with gradually changing dielectric permittivity (increasing toward the tip), and the guided symmetric film plasmons in such a waveguide, successively reflecting from the tip and a turning point (simple caustic), form the WP modes.25 The same physical interpretation of WP modes is applicable for a wedge with a rounded tip [Fig. 1(b)].

The antisymmetric film plasmon cannot be guided by this structure as the corresponding effective permittivity decreases with decreasing thickness of the metal wedge (membrane). Therefore, WP modes with antisymmetric charge distribution across the wedge do not exist.

Similar to sharp metal wedges,21 wedges with rounded tips can support different WP modes. In general, the smaller the wedge angle and/or the radius of the tip, the larger the number of different WP modes supported by the structure. The field distribution in Fig. 2(a) corresponds to the fundamental mode (only such mode can exist in the considered wedge).

Since the guided WP mode is highly localized near the tip of the groove [Fig. 2(a)], it is reasonable to expect that even small variations in the tip radius can significantly affect the WP wave numbers, etc. For example, typical dependencies of the wave number $k_{WP}$ of the fundamental WP mode on wedge angle $\theta$ for various tip radii are presented in Fig. 2(b). Generally, increasing tip radius results in decreasing sharpness (increasing width of the wedge near the tip) and therefore decreasing the coupling of plasmons across the wedge. Therefore the wave number should decrease with increasing tip radius as seen in Figs. 2(b) and 3(a) (which presents the wave number as a function of tip radius). As a result, increasing tip radius also generally leads to decreasing localization of the WP as shown in Fig. 3(b). All the three dependencies in Fig. 2(b) tend to merge when the wedge angle increases. This is because increasing $\theta$ results in reducing localization of the field that significantly extends to the flat regions (sides) of the wedge. In addition, the physical area of the rounded section of the tip at a given tip radius decreases with increasing wedge angle. Both these effects significantly decrease the contribution of the rounded section to the overall properties (e.g., dispersion) of the guided WP modes. On the contrary, if $\theta$ is small then the size of the localization region can be small compared to the size of the rounded tips, then the wave number is strongly affected by relatively small tip radii [Figs. 2(b) and 3(a)].

The dependence of the typical localization (beam diameter) of the guided WP fundamental mode on the radius of the wedge tip is shown in Fig. 3(b). As expected, the beam diameter rapidly increases with increasing tip radius.

It is important to understand that strong subwavelength localization of a plasmon is still insufficient for this plasmon to be useful for the development of efficient subwavelength waveguides. Another very important aspect that has to be taken into account is dissipation of the plasmon. If dissipation is large, so that the plasmon hardly propagates a few wavelengths, it may not be a good option for the development of subwavelength waveguides and interconnectors for integrated optics. The typical dependencies of the propagation distances of the fundamental WP mode on the tip radius...
are presented in Fig. 4 for the structure of a silver wedge of angle $\theta=40^\circ$. In the literature the dielectric permittivity of Ag is quite varied, and the experimental values can strongly depend on sample preparation techniques, etc. This is the reason for presenting the propagation distances for two different values of the permittivity at the same excitation wavelength (Fig. 4). As the tip radius $r$ is decreasing the propagation distance is decreasing (Fig. 4) while the wave number [Fig. 3(a)] and field localization [Fig. 3(b)] are increasing. Nevertheless, even in the case with strongest field localization and largest dissipation (i.e., at $r=0$ nm and $\varepsilon_m=-15.9+1.1i$), the propagation distance is $\approx2\ \mu$m, which is $\sim4\lambda_{WP}$ (where $\lambda_{WP}$ is the WP wavelength) while the diameter of the plasmon beam width is approximately tens of nanometers. This propagation distance is noticeably larger than the wavelength of the plasmon, and thus is sufficient for a range of nano-optics applications. Increasing wedge angle and/or tip radius results in increasing propagation distance and the number of plasmon wavelengths that fit within this propagation distance. However, this will also result in a simultaneous decrease in the localization (increased beam diameter). Physically, increasing dissipation with increasing plasmon localization (and wave number) is explained by the fact that the plasmon penetration depth into vacuum rapidly decreases with increasing localization (and wave number). As a result, a larger portion of the plasmon energy propagates in the dissipative metal, which naturally leads to increasing dissipation of WP and decreasing number of wavelengths that the plasmon can travel before the intensity of its field decreases $e$ times.

III. EXPERIMENTAL OBSERVATION OF EFFECT OF VARYING WEDGE TIP RADIUS

The experimental observation and investigation of WPs were undertaken in the structure shown in Fig. 5(a). An $\sim1.3$ $\mu$m silver film was evaporated onto a glass substrate. Three wedges with the height $\sim1$ $\mu$m were fabricated in this film using the focused-ion beam (FIB) lithography. The tip radii of these three wedges were $r=20$ nm [Fig. 6(a)], $r=85$ nm [Fig. 6(c)], and $r=125$ nm [Fig. 6(e)] [from the right to the left in Fig. 5(a)].

The end-fire excitation by red He–Ne laser ($\lambda=0.6328$ $\mu$m) was achieved through microholes fabricated in the silver film by means of FIB in front of the wedges with TE polarization [$E$ field in the $z$ axis, Fig. 5(b)]. A laser beam illuminated the holes from underneath the film [Fig. (a)] and its tight focusing was not required because the incident and WP fields were separated by the silver film. The detection of WPs in these structures was conducted by means of a near-field scanning optical microscope (NSOM). The distance between a metal coated NSOM probe tip (with $\sim100$ nm aperture) and the sample was maintained at $\approx10$ nm by shear force feedback. This experimental setup is similar to that used for the previous experimental observation of WPs on wedges under the assumption of nearly zero tip radius.\footnote{The near-field intensities of the generated WPs on the wedges [Fig. 5(a)] are shown in Fig. 5(b). It can be seen that the intensity of the optical signals registered by NSOM decays along the positive $x$ direction (direction of propagation) [Fig. 5(b)]. The solid curves in Figs. 6(b), 6(d), and 6(f) represent the exponential fit to the experimentally measured intensities of the NSOM signals along the direction of propagation ($x$ axis) for the wedges with the tip radii $r=20$ nm [Fig. 6(a)], $r=85$ nm [Fig. 6(c)], and $r=125$ nm [Fig. 6(e)].}

The experimental propagation distances for WPs (at the $1/e$ level of its intensity) are $L=2.2$ $\mu$m, $L=2.5$ $\mu$m, and $L=3.1$ $\mu$m for the tip radii $r=20$ nm, $r=85$ nm, and $r=125$ nm, respectively, and generally are smaller than the predicted theoretical values (Fig. 4). In addition, as can be seen from Figs. 6(b), 6(d), and 6(f), intensity maxima at the distances from the point of the end-fire excitation ranging
from \( \sim 1.6 \) to \( \sim 2.3 \) \( \mu \text{m} \) are consistently displayed. It is clear that such maxima cannot be explained by dissipation of WP modes in the metal wedge.

One of the major reasons for such discrepancies between the experimental results and the predicted theoretical curves (Fig. 4) is probably related to additional contribution to the measured NSOM signal from scattered bulk and surface waves generated near the microholes in the silver film. For example, surface plasmons can be generated on the sides of the wedges near the holes used for the end-fire excitation [Fig. 5(a)]. These plasmons propagate up the wedge toward the tip and contribute to the overall resultant NSOM signal. It is quite possible to expect that the resultant interference pattern may have an intensity maximum at some distance from the point of the end-fire excitation [Figs. 6(b), 6(d), and 6(f)]. A similar situation and interference with the resultant NSOM signal may be expected if bulk scattered waves are also generated near the point of the end-fire excitation. Yet another confirmation of this mechanism is the observed tendency toward oscillations of the registered NSOM signal when the distance from the point of the end-fire excitation is increased. This tendency is especially clear in Fig. 6(f).

Because scattered bulk and surface waves generated near the microholes experience strong diffractional divergence, their contribution to the NSOM signal should rapidly decrease with increasing distance from the end-fire excitation, which is an explanation for more rapid than expected decay of the NSOM intensity along the wedges [Figs. 5(b), 6(b), 6(d), and 6(f)]. Therefore, it is concluded that these are the scattered bulk waves and surface plasmons generated on the sides of the wedges and their interference with the NSOM signals, which are primarily responsible for the artificially decreased experimentally observed propagation distances of WP fundamental modes [Figs. 6(b), 6(d), and 6(f)]. This also suggests that the used method of the end-fire excitation through the microholes in the metal film (to separate the scattered and WP signals) may not be efficient in terms of the suppression of interference with the generated WP modes. It seems to require further optimization and/or modification in order to effectively separate the generated guided WP modes from the scattered bulk and surface waves.

In addition, there can be other possible reasons for the observed discrepancies between the experimental and theoretical results. First, the aperture of the NSOM probe was \( \sim 100 \) nm, which is quite large compared to the expected localization region for the guided WP mode. Therefore, the NSOM probe is expected to efficiently collect additional interference signals (from bulk and surface waves), which will also contribute to a rapid decrease in intensity with increasing distance from the excitation point and artificial decrease in the seeming propagation distance. Second, surface roughness and nonuniformities of the wedge can result in additional radiative experimental energy losses (though this mechanism is not expected to be as essential in the conducted experiments). The fact that the combined aperture and metal coating of the NSOM probe, \( \sim 300 \) nm (\( \sim 100 \) nm aperture and \( \sim 100 \) nm Al coating), is significantly larger than the predicted beam diameter [Fig. 3(b)] makes the experimental dependencies of the beam diameter unreliable (see also Ref. 21) due to smearing by the probe-sample interaction. However, that the NSOM gave the region of lateral localization of the field near the tip of the wedge (several microns from the excitation area) between \( \sim 200 \) and \( \sim 450 \) nm (for \( r \) ranging between \( \sim 25 \) and \( \sim 125 \) nm, respectively) constitutes a demonstration that WP modes have been successfully detected. This is because such strong field localization cannot be achieved by bulk and surface waves at several microns from the point of the end-fire excitation because of the strong diffraction divergence of these waves.

IV. CONCLUSIONS

This paper has reported the numerical analysis of strongly localized plasmons propagating along the tips of sharp and smooth metal wedges by means of the compact-2D FDTD formulation. Detailed numerical analysis has been conducted for the WP fundamental mode, including its field structure, dispersion, dissipation, typical propagation distances, and the dependencies of the wave parameters on the radius of the wedge tip. WPs were experimentally excited and detected and physical reasons for the observed quantitative discrepancies with the theoretical predictions are suggested.

It has been demonstrated that the WP modes on smooth tipped wedges can be used for the design of effective subwavelength waveguides because their localization can be far beyond the diffraction limit of light, and they can normally
propagate at least several wavelengths. Increasing tip radius and/or wedge angles results in decreasing localization and increasing propagation distance. Further increase in the propagation distances could be achieved by means of gain-assisted propagation (which could be achieved by surrounding the metal wedges by a medium with gain, as was proposed for surface plasmons\(^{27,28}\)). The analysis has been conducted for the fundamental WP mode. At the same time, the major findings are also applicable for higher WP modes if their existence conditions for these modes are satisfied.

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