Finite-element analysis of Λ-wedge plasmon polariton guide

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Abstract: *The Λ-wedge plasmon polariton waveguide is analysed using a vector finite-element method. The mode appreance, propagation loss, and geometric dispersion of such waveguide are studied at both visible and near infrared wavelenghts. No modal cutoff is seen for increasing wedge angle at any wavelength.*

Introduction

A straight Λ-shaped metal corner [Fig. 1(a)] is able to guide plasmon polariton waves (so-called wedge plasmon polaritons, or WPPs) [1]. Using some noble metals (e.g. gold and silver) the guided mode can be at the near infrared and even visible light wavelength range. The electromagnetic field of the mode is coupled with the oscillating electrons in the metal and therefore is highly localized to the metal surface (laterally at Λ tip for the problem at hand). Such non-diffraction-limited wave guidance in (better yet) such a simple structure can be a very promising candidate for both optical integration as well as sensing applications.

Previous theoretical analysis was limited to the finite-difference time-domain (FDTD) method [1]. The traditional FDTD method interprets material interfaces (where mode field is at its maximum for plasmon polariton waveguides) cruelly owing to its use of orthogonal mesh. In this paper, we use a vector finite-element method (FEM) to study this class of waveguides. The FEM is based on the wave equation governing the transverse magnetic field. The Gauss's law for magnetic field, $\nabla \cdot \mathbf{H} = 0$, is explictly imposed for eliminating spurious modes [2]. Abilities in accurately defining material interfaces as well as in adaptive mesh resolution make FEM especially advantageous for deriving surface plasmon polariton (SPP) modes (a WPP is nothing but coupled SPPs). Second-order shape function is used for accelerating numerical convergence. At the same time, formulation in second-order shape function makes the computed mode field twice differentiable, which in turn allows us to derive the rest four field components (i.e. H_z, E_x, E_y, E_z fields). For certain waveguide structures, a triangle edge size as small as 2nm at the Λ tip is used to achieve convergence [Fig. 1(b)].

The studied Λ metal wedges are assumed to have infinite side walls. This is to mitigate the influence of other metal corners formed when the height of the wedge is finite. Numerically we enlarge the computation domain (around the wedge tip) until field amplitude decays by 30dB at the computational boundary. We point out that the field tends to be singular at a sharp wedge tip, a feature that is also present in pure-dielectric waveguides. Such field singularity in dielectric waveguides usually does not prevent a numerical method from converging. It however significantly affects the propagation constant of a mode guided by a metal corner (including the V-shaped channel plasmon polariton waveguide) when the numerical resolution is further refined. For this reason, all Λ corners are rounded with an arc of 10nm in radius in the current analysis.

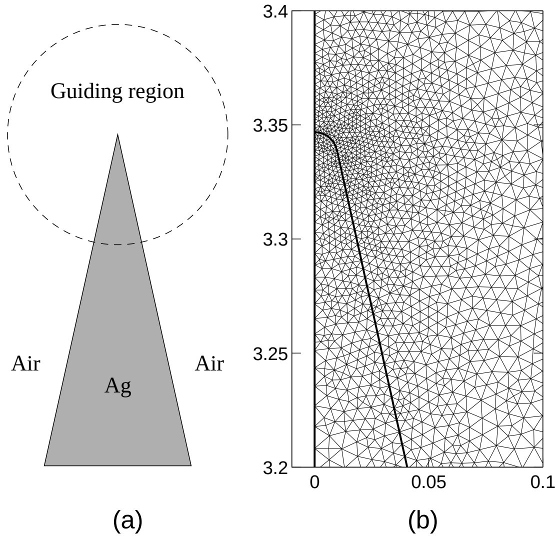

Fig. 1: (a) Schematic diagram of a metal wedge plasmon polariton waveguide. (b) Finite-element mesh of a metal wedge guide with Λ angle at 25 degree. Only half of the waveguide is used by using perfect magnetic conductor (PMC) condition at its symmetry line ($x = 0$). The tip is rounded with an arc with 10nm radius. Axis unit: μm.

FEM analysis

Our study concentrates on silver-air structure. The dielectric constant of silver is described in Drude model as $\epsilon = \epsilon_\infty - \frac{(\epsilon_0-\epsilon_\infty)\omega_p^2}{\omega^2+i\omega\gamma}$, with $\epsilon_\infty = 4.017$, $\epsilon_0 = 4.896$, $\omega_p = 1.419 \times 10^{16}$rad/s, and $\gamma = 1.117 \times 10^{14}$rad/s. This drude model is fitted according to the measured data from Palik's handbook [3]. In Fig. 2(a), we show the dispersion curve of the guided WPP mode as the Λ angle is varied, at 633nm and 1550nm wavelengths. The effective index value (related to propagation constant as $n_{\text{eff}} = \beta/k_0$) decreases as the angle increases, and it asymptotically approaches to the value corresponding to the SPP mode guided by a single Ag-air interface. It is obvious to see that such waveguide in general does not experience a cutoff as the Λ angle in-

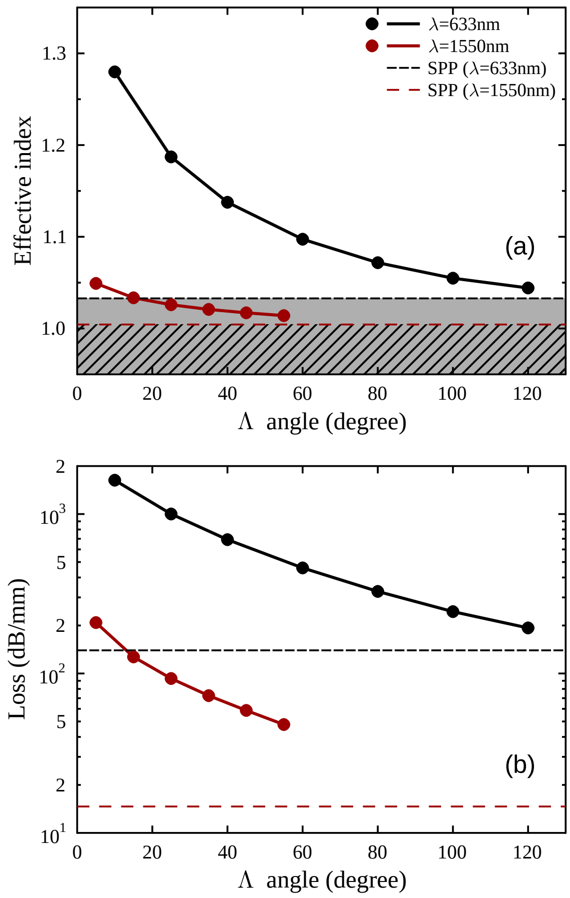

Fig. 2: (Color online) Dispersion (a) and loss (b) curves of the guided WPP mode as Λ angle changes. Gray (line-shaded) region in (a) is the allowed states by an Ag-air interface at λ = 633nm (1550nm).

creases, opposed to what was concluded in [1]. At a small angle, the mode field highly concentrates at the Λ tip. At larger angles, the field extends further away from the tip. Eventually, when the Λ angle is infinitesimally close to 180° (the Λ wedge becomes almost a flat surface), the mode will extend for the whole Ag-air interface, and becomes a SPP mode.

The transverse decay constant of the overall mode field along the surface and in the air can be estimated using

$$k_t^s = k_0\sqrt{n_{\text{eff}}^2 - n_{\text{SPP}}^2}, \quad (1)$$

$$k_t^a = k_0\sqrt{n_{\text{eff}}^2 - n_{\text{air}}^2}, \quad (2)$$

respetively. As n_{SPP} is always larger than n_{air}, field tends to strech longer along the two side interfaces. Note that the decay is highly polarization-dependent at the metal interface. Figure 3 shows the mode guided by a wedge with a 25° angle. Notice the Ag-air interfaces at two sides are close to vertical. As the x-component of the magnetic field [Fig. 3(a)] is not supported by a vertical Ag-air surface, it decays more quickly along the side interfaces, compared to the y field component [Fig. 3(b)]. The maximum of H_x is at the tip top, where, if examined in great detail, the field is parallel to the Ag-air interface. In contrast, the y component tends to extend more along the two side interfaces. And it is anti-symmetric about the $x = 0$ symmetry line. Notice at a very large Λ angle, the opposite attenuation behaviors along side interfaces are expected for the two polarizations. The maximum of the y component is not at the tip top, but at two sides near to the top. The H_y fields at two sides of the tip are coupled through the metal. The H_z field component [Fig. 3(c)] has a very similar appearance as compared to the H_y field component. This is due to the two fields are both parallel to (or close parallel to) the metal surface.

The propagation loss of the guided mode is shown in Fig. 2(b). In general, the mode experiences a higher loss at a smaller Λ angle, and at a smaller wavelength. A smaller angle induces stronger field coupling, and therefore a larger percent of the field is located in the metal, which results in higher loss. At a longer wavelength, silver has a larger negative dielectric constant (a more perfect conductor), therefore field tends to be expelled out of metal region. The loss value is close to that of the SPP mode as the Λ angle is approaching to 180°.

Discussion and Conclusion

Two points should be addressed for better understanding such metal wedge waveguide. First, although group theory allows a mode with symmetric reflection symmetry (whose transverse magnetic field is parallel to y axis at $x = 0$ symmetry line), it however has a n_{eff} value in the shaded region in Fig. 2(a), and therefore will radiate away. Due to this fact, we have only used the PMC condition on the $x = 0$ symmetry line. Second, the physical problem is divergent with respect to sharpness of the Λ tip. Field tends to be more trapped into the corner if the tip becomes sharper (smaller curvature radius there). And correspondingly, the propagation constant becomes larger. This peculiar property of WPP waveguides though imposes great difficulties for theoreticians, it, however, indicates that we can achieve better confinement (and therefore denser integration) with sharper wedges. On the other hand, we should also expect that sharp irregularities on fabricated waveguides involving metals would affect the waveguides' performance greatly.

In conclusion, using the finite-element method, we have studied the modal properties of plasmon polariton modes guided by Λ-shaped metal wedges. Such waveguides are promising for nanoscaled integrated optical circuits and sensing applications. At the same time, such metal corners are most often present in other plasmon polariton waveguides (e.g. metal strip waveguides, and V-shaped channel waveguides), therefore knowing the modal behavior of such Λ-wedge waveguide is important for designing more complex waveguides.

Acknowledgments

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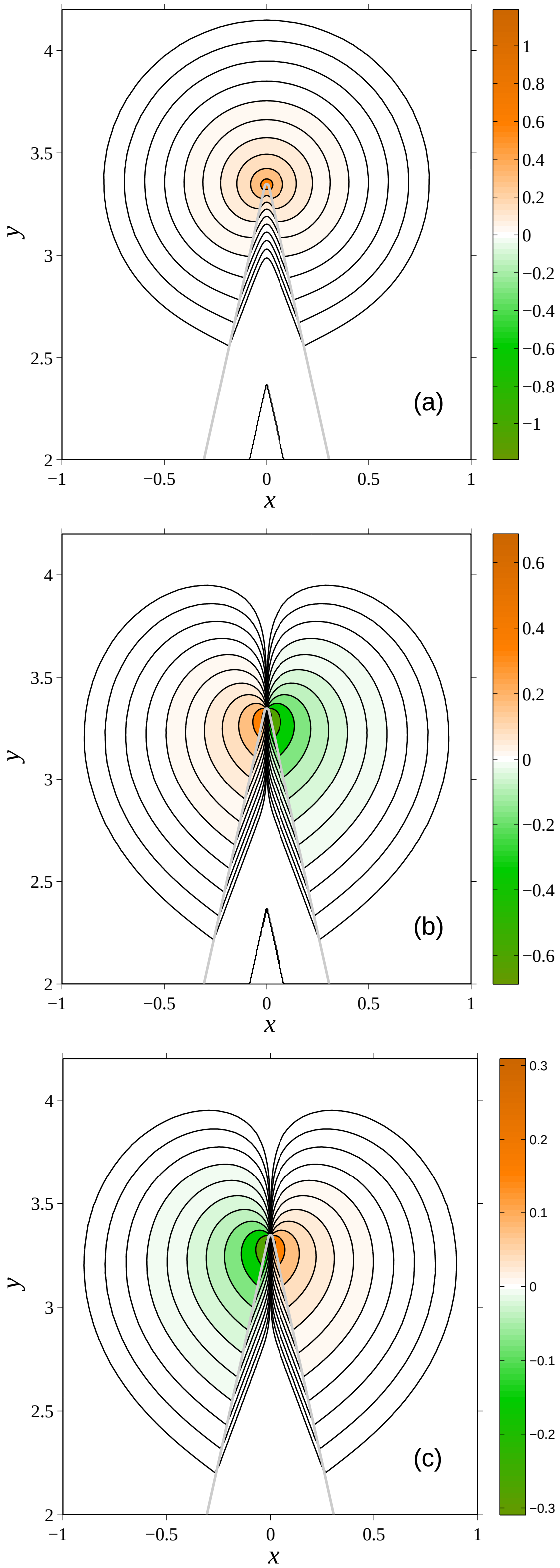

Fig. 3: (Color online) H field components of a mode guided by a wedge with a 25° angle. (a) H_x component; (b) H_y component; (c) H_z component. Orange for positive, and green for negativ. Contour lines (except the first one, which is at 90% of the maximum value) are in 3dB separation. The void regions within the metal wedge as appeared in (a) and (b) are not computed as the field there can be safely treated as zero.