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Abstract. We revisited the problem of the existence of plasmonic modes guided by metal-dielectric-metal slot waveguides. For the case of lossless slot waveguides, we classify the guided modes in the structure with the metal dispersion and found that, in a certain parameter range, *three different guided modes* coexist at a fixed frequency, two (symmetric and antisymmetric) forward propagating modes and the third, *backward* propagating antisymmetric mode. We study the properties of the forward and backward plasmonic guided modes in the presence of realistic losses, and discuss the importance of evanescent modes in lossy structures.

Keywords: surface plasmons, guided waves, losses

1 INTRODUCTION

One of the most recent activities of modern optics is associated with the manipulation of light at the nanoscale. It was shown that optical systems with metallic waveguides can allow miniaturizing optical components through excitation of surface plasmon polaritons, or plasmon modes. Metal-dielectric structures exhibit a wide range of novel physical phenomena which can be employed for various applications such as sensing, imaging, and waveguiding (for a general overview, see Refs. 1-3). Most importantly, plasmonic optical elements provide possibilities to overcome the diffraction limit, and they allow squeezing light to subwavelength dimensions. One may think of designing optical plasmonic integrated circuits which would allow miniaturizing devices to increase their functionalities in signal processing [4]. One of the key components of any integrated circuit is a waveguide, which transfers a signal between the circuit elements. Thus, the study of plasmonic waveguides is of a fundamental importance for the design of nanoscale structures and circuits, as well as their future applications.

Optical waveguides guiding surface plasmon polaritons have been a subject of extensive studies, and different types of metal-dielectric waveguides have been suggested theoretically and demonstrated experimentally (see, e.g., Refs. 5-8). The simplest plasmonic waveguide is an interface between metal and insulator which supports plasmon polaritons; however, due to losses in metal, an excited plasmon can propagate for only a very short distance [5, 9]. Introducing a heterostructure such as a three-layer system helps to increase the propagation distance due to the coupling of plasmons at the neighboring interfaces and the field localization in dielectric rather than metal [2]. Thus, two basic geometries are being explored for guiding plasmons, namely, dielectric-metal-dielectric and metal-dielectric-metal structures. In the past decades, rigorous analysis of these structures has been presented [9–11]. It was found that layered metal-dielectric structures support TM surface waves which have only one component of the magnetic field. Applying the continuity of the tangential field component, the dispersion relations were derived for both dielectric-metal-dielectric and metal-dielectric-metal structures.
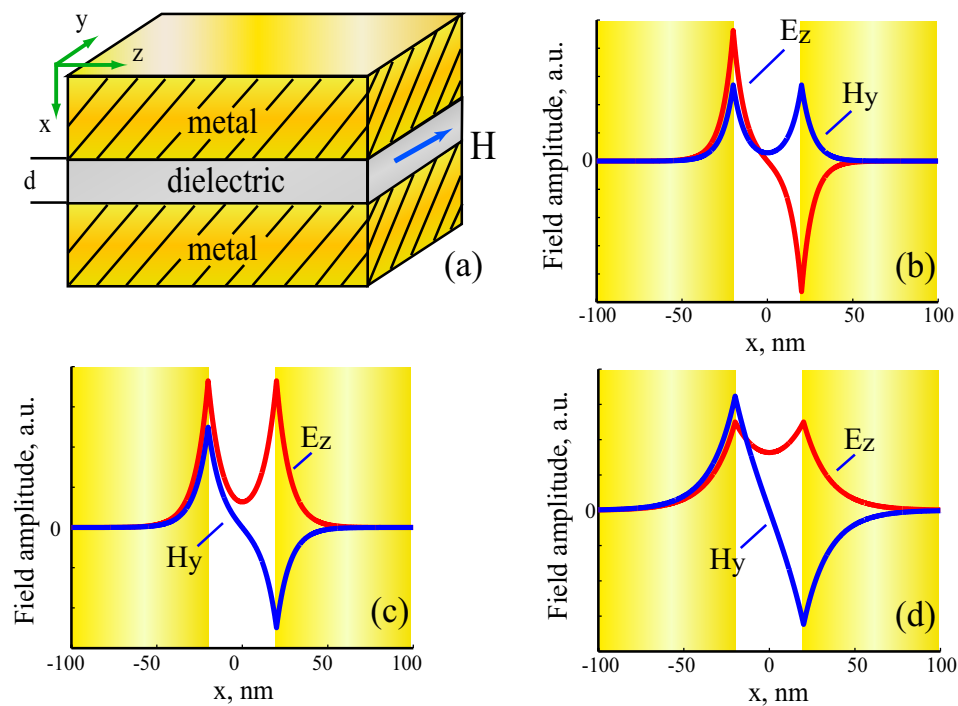
Fig. 1. (a) Schematic of a symmetric plasmonic slot waveguide; (b-d) Magnetic and electric field profiles calculated in a lossless 40 nm wide slot waveguide for the frequency corresponding to the free space wavelength of 465 nm for forward propagating (b) symmetric mode and (c) antisymmetric modes, and (d) backward antisymmetric mode

Detailed analysis of eigenmodes, including radiative waves, in thin metallic films sandwiched between two semi-infinite dielectrics was presented in Ref. 10. Later, Prade *et al.* [11] developed a comprehensive analysis of dispersion relations for three-layer structures and studied possible plasmonic modes in the slot waveguide geometry (metal-dielectric-metal) as well as in a thin metal film (dielectric-metal-dielectric). In particular, their analysis suggests that a symmetric slot waveguide should support only two guided modes for various parameters: symmetric and antisymmetric forward propagating modes. However, the losses in metallic layers were not studied rigorously in early works, and the dispersive nature of dissipation in metals was not addressed either. Only recent studies provided analysis of waveguides with real metal losses in the waveguides, see Refs. 5,12 and 13.

Our recent study of guided modes in a nonlinear slot waveguide [14] suggested that not all regimes of the plasmon propagation were analyzed previously even in the linear case. In particular, in the lossless regime it was found that the asymmetric mode degeneracy may occur for some particular values In this paper, we elaborate on this finding further and show that for certain parameters and at a fixed frequency, a symmetric slot waveguide can support simultaneously *three guided plasmonic modes*, that is in contradiction to the accepted knowledge and the results obtained earlier by Prade and coauthors [11]. We demonstrate that in addition to the forward propagating symmetric and antisymmetric modes in a symmetric slot waveguide, there exists *a backward propagating antisymmetric guided mode*. Backward modes in plasmonic waveguides are of a particular interest due to their key role played for negative refraction at optical frequencies [15, 16]. The studies of negative index and backward waves was presented
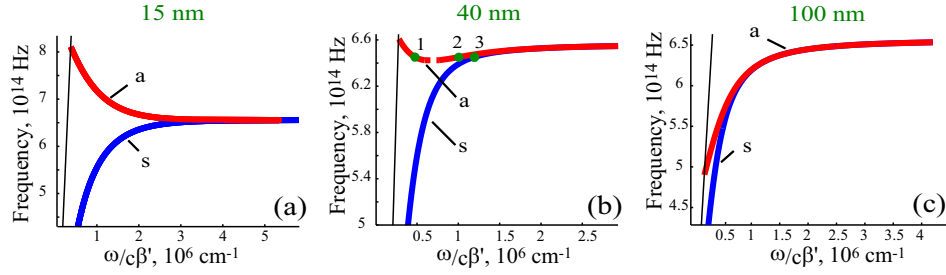
Fig. 2. Dispersion diagrams for slot waveguides: (a) $d = 15$ nm, (b) $d = 40$ nm, (c) $d = 100 nm$. Symmetric and antisymmetric modes are marked on the figures with "a" and "s", respectively. Numbered dots on the plot (b) indicate the modes which will be studied further in the paper: (1) backward antisymmetric mode with index of 4.43, (2)- forward antisymmetric mode with effective index 9.34, and (3) - symmetric mode with effective index 11.07. Modes (1-3) co-exist at the same frequency.

in Ref. 13, where authors showed the regions where the backward modes may exist. However, the mechanism of losses and the regime of three simultaneous guided waves was not studied.

2 WAVEGUIDING STRUCTURES AND BASIC EQUATIONS

We study the guided modes in a symmetric metal-dielectric-metal plasmonic waveguide of the width d, which is schematically shown on Fig. 1(a). The variation of the dielectric permittivity across the structure can be presented in the form,

$$\varepsilon(x) = \begin{cases} \varepsilon_m(\omega) = \varepsilon'_m + j\varepsilon''_m, & |x| > d/2, \\ \varepsilon_d, & |x| < d/2, \end{cases}$$

where d is the slot width, $\varepsilon_m(\omega)$ and ε_d are dielectric permittivities of metal and insulator, respectively. In our work we use the Drude-Lorentz model to describe dielectric constant of metal, $\varepsilon_m(\omega) \simeq \varepsilon_\infty + \Sigma[\alpha_i/(\omega^2 - 2j\gamma_i\omega - \omega_i^2)]$, that agrees well with the experimental data [2, 17, 18]. We take into account 6 resonant terms $(i = 1, ..., 6)$, with resonant frequencies ω_i and collision frequencies γ_i.

It is known that planar metal-dielectric structures support surface TM waves, with the field structure $\mathbf{H} = (0, H_y, 0)$ and $\mathbf{E} = (E_x, 0, E_z)$ [2, 10, 11]. Applying boundary conditions of continuity of the tangential field components, H_y and E_z, at the interfaces, we obtain the following well-known dispersion relation [10, 11]:

$$\tanh\left(\frac{1}{2}\kappa_d d\right) = - \begin{cases} \dfrac{\varepsilon_d}{\varepsilon_m} \dfrac{\kappa_m}{\kappa_d}, & (symmetric), \\ \dfrac{\varepsilon_m}{\varepsilon_d} \dfrac{\kappa_d}{\kappa_m}, & (antisymmetric), \end{cases} \tag{1}$$

where $\kappa_m = \sqrt{\beta^2 - \varepsilon_m}$ and $\kappa_d = \sqrt{\beta^2 - \varepsilon_d}$, β - guide index. Note that we use the coordinates normalized to ω/c.

The dispersion relation (1) splits into two separate equations describing symmetric and antisymmetric modes with respect to the magnetic field, due to the symmetry of the structure.

Since in general case the permittivity is complex, $\varepsilon_m = \varepsilon'_m + j\varepsilon''_m$, with the imaginary part describing losses in metal, the solutions of dispersion relation (1) would be complex as well, $\beta = \beta' + j\beta''$. However, for simple analysis of modes and their propagation, the losses are usually neglected [11, 14], $\varepsilon''_m, \gamma_i \to 0$, and only real value propagation constants, $\beta = \beta'$, are
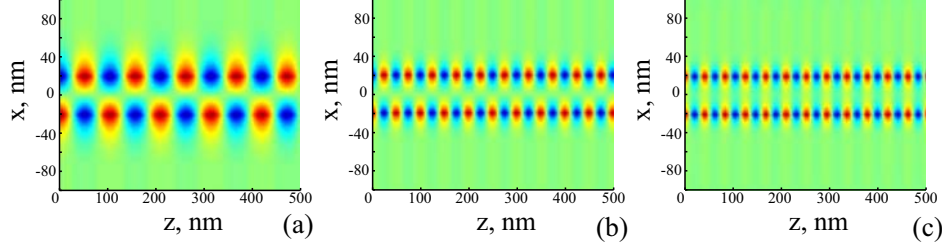
Fig. 3. Magnetic field distribution in lossless case for 40 nm slot waveguide for the free space wavelength $\lambda = 465nm$: (a) backward antisymmetric mode,(b) forward antisymmetric, and (c) symmetric modes.

taken into account corresponding to the guided or propagating modes of the waveguide. This analysis has quite limited applicability due to high losses in metals.

Our study is based on the reciprocity of the system. We consider that fields are represented as $\mathbf{F} = 1/2(\hat{\mathbf{F}}exp[-j(\omega t - \beta' z)]exp(-\beta'' z) + c.c.)$, and guide index β' is assumed to be always positive, for the simplicity of our analysis. In this case, the Poynting vector $\mathbf{S} = \hat{\mathbf{S}}exp(-2\beta'' z)$ should decay along the propagation direction, thus the imaginary part of the guide index β'' should be positive for forward waves, $\mathbf{z} \cdot \mathbf{S} > 0$, and negative, for backward waves, $\mathbf{z} \cdot \mathbf{S} < 0$; this formalism differs slightly from the approach employed in Ref. 13, however the physical meaning of the obtained results does not change.

3 LOSSLESS SLOT WAVEGUIDES

First, we start with the simplest case of nonabsorbing metal, i.e. $\varepsilon''_m \equiv 0$, and discuss only propagating waves $\beta = \beta'$. Prade *et al*. [11] have presented a detailed study of the dispersion relation (1) in this case. It was shown that for $\delta = \varepsilon_d/|\varepsilon_m| \geq 1$ ($\omega \geq \omega_{spp}$) there exists only one antisymmetric mode, and this mode has a cutoff for larger slot widths. For $\delta < 1$ two modes were found, one symmetric without cutoff and one antisymmetric with lower width cutoff. However, the analysis of the dispersion relation (1) for different slot widths shows novel features not discussed in the previous works.

To be more specific, we consider dielectric with refractive index $n = 2.5$ sandwiched between thick silver plates, described by Drude-Lorentz model for metal permittivity, ε_m, with zero losses, $\varepsilon''_m, \gamma_i \rightarrow 0$. We solve dispersion relation taking into account only propagating waves, $\beta'' = 0$, and plot dispersion curves for this structure, see Fig. 2(a-c). For very narrow slot widths, $d = 15nm$, we observe the regime predicted by Prade et. al., where for $\delta > 1$ only one antisymmetric mode exists and for $\delta < 1$ only symmetric mode is observed, see Fig. 2(a). For relatively wide slot waveguides, e.g. for $100nm$, we found symmetric and antisymmetric modes [see Fig. 2(c)] which exist only for $|\varepsilon_m| > \varepsilon_d$, as it was predicted earlier [11]. Note that for all slot widths, in case of lossless metal, when the $|\varepsilon_m| = \varepsilon_d$ the plasmon propagation constant for both modes becomes infinitely large, $\beta \rightarrow \infty$, corresponding to surface plasmon-polariton resonance, $\omega = \omega_{spp}$, [2].

In the case of a waveguides with the slot width varying in range $35 \lesssim d \lesssim 50nm$ we reveal a new regime where three modes, symmetric, antisymmetric and *backward antisymmetric*, coexist as shown in Fig. 2(b), for frequencies below surface plasmon resonance, $\delta > 1$. The backward mode is characterized by a negative slope of the corresponding dispersion curve. The minimum on the dispersion curve corresponds to the region where the plasmon group velocity, conventionally defined in the structure without dissipation $v_g = \partial\omega/\partial k$, approaches zero. The profiles of all three modes, for the frequency corresponding to the free-space wavelength $\lambda = 465$ nm, are presented on the Figs. 1(b-d). We also have presented the field profiles of various modes in the system, see Fig. 3. The backward antisymmetric mode is less confined to
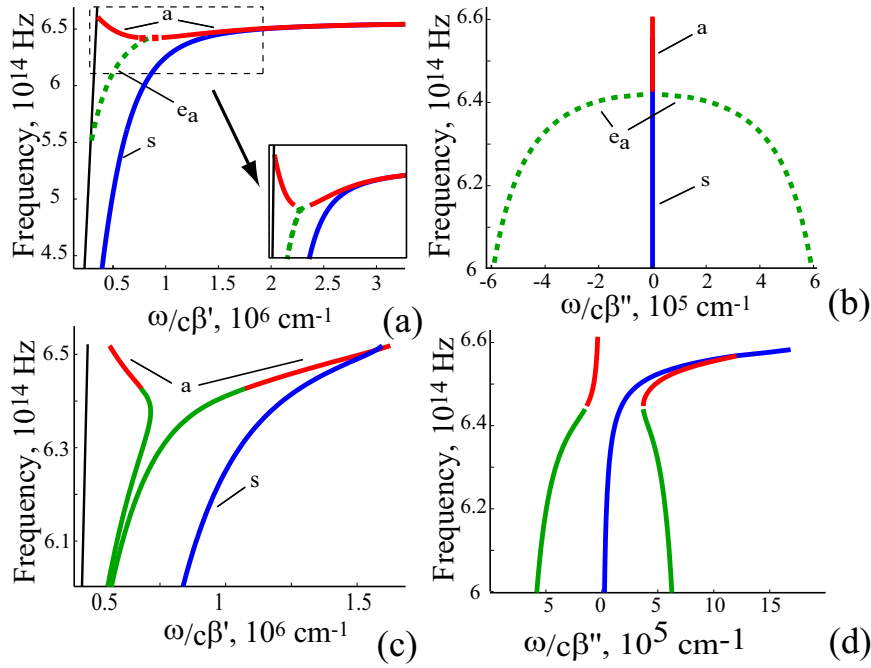
Fig. 4. Dispersion diagrams for 40nm slot waveguide: (a) Dispersion of real part of propagation constant in lossless case, $\varepsilon_m'' = 0$. Dashed line corresponds to evanescent mode marked e_a. Inset shows the magnified dashed region with merging propagating and evanescent modes; (b) Decay factor (imaginary part of wavenumber) dispersion, $\varepsilon_m'' = 0$; (c,d) Same as (a) and (b) but with small losses described by reduced collision frequencies $\gamma_i/10$.

the interfaces, since it has smaller propagation constants, β, and its field is concentrated mainly in metal, rather than in dielectric. The backward nature of this mode is due to the fact that the energy flow in metallic slabs is dominant in relation to dielectric layer energy flow. This condition gives the region of existence of such solutions:

$$\frac{<\mathbf{z}\cdot\mathbf{S}_{diel}>_{|x|<d/2}}{|<\mathbf{z}\cdot\mathbf{S}_{metal}>_{|x|>d/2}|} = \frac{A^2\beta\varepsilon_d\kappa_d^{-3}\left[\sinh(\kappa_d d) - \kappa_d d\right]/2}{|\varepsilon_m|\beta\kappa_m^{-3}\exp(-\kappa_m d)} = \frac{\kappa_m^2}{\kappa_d^2}\left(1 - \frac{\kappa_d d}{\sinh(\kappa_d d)}\right) < 1$$

where $< \cdot >_x$ stands for averaging across the structure, $A = e^{-\kappa_m d/2}\cosh^{-1}(\kappa_d d/2)$.

In this case the total energy of the mode is transferred in the direction opposite to the propagation direction of the phase fronts, the analogous condition was discussed in Ref. 13.

Even for zero losses, $\varepsilon_m'' = 0$, the dispersion relation for guided modes generally has not only propagating mode solutions, but also solutions corresponding to *evanescent modes* with $\beta'' \neq 0$ (thus exponentially decaying from the source). Due to a rapid decay of these solutions in lossless structures, corresponding modes are usually not taken into account in the mode analysis of plasmonic waveguides [19], however such modes are well known in classical electrodynamics being important for the problem of waveguide excitation. In plasmonic systems, on the other hand, such modes may play a significant role since their decay rate may become comparable to the decay of the 'main' modes.

As an example, on the Figs. 4(a,b) we present the real and imaginary wavenumbers of the plasmons as a function of frequency for several lower order evanescent modes for the case of
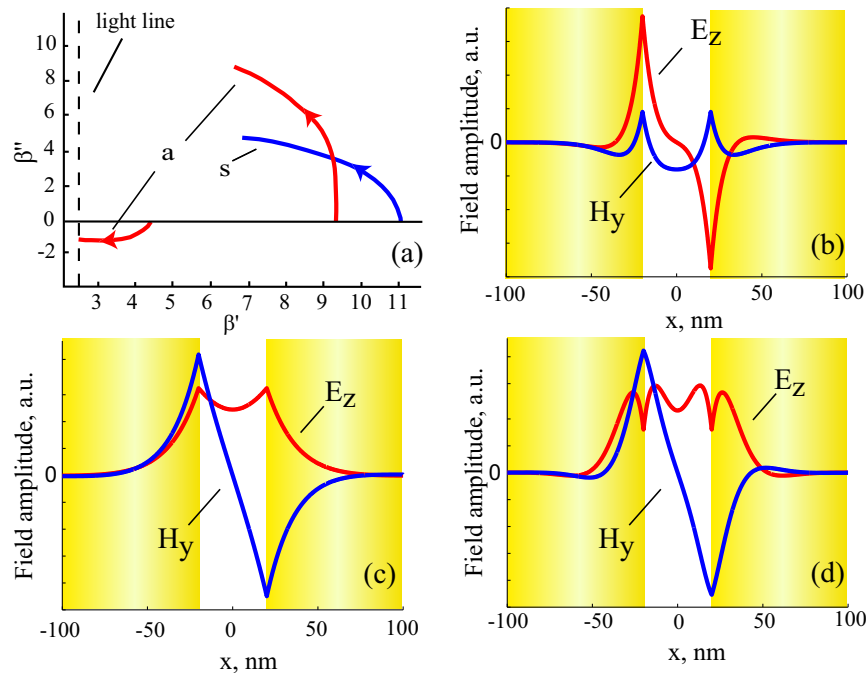
Fig. 5. (a) Motion of the guide indices of the propagating waves on the complex plane (β', β'') for increasing losses (for $\lambda = 465$ nm and the slot width of 40 nm). Increasing of the absorption of metals leads to a shift of the wavenumbers in the direction indicated by arrows. (b-d) Magnetic and electric field profiles in lossy 40 nm waveguide at $\lambda = 475$ nm: forward propagating symmetric (b), and antisymmetric modes (c), and (d) backward antisymmetric mode.

$40nm$ wide slot waveguide. The behavior of higher order evanescent modes is also an important problem which will be studied elsewhere. In our case, lower order evanescent antisymmetric modes exist in the frequency domain between the light line and the point where propagating antisymmetric modes merge, see Fig. 4(a). It is clearly seen that both backward and forward antisymmetric modes have solutions continuing into the complex space of propagation constants. Moreover, the solutions are complex conjugates, and the imaginary propagation constant is negative for backward antisymmetric branch and positive for forward branch, which as discussed below defines backward and forward nature of evanescent waves, see Fig. 4(b). We also observe the increase of decay factors, $|\beta''|$, of evanescent plasmons with the decrease of frequency. Introduction of small losses in the structure clearly shows evolution of corresponding modes, as can be seen in Figs. 4(c,d). All modes now have complex wavenumbers, and antisymmetric mode dispersion curves merge with corresponding evanescent modes.

Already in this example we can see that the propagation length $(1/|\beta''|)$ of the modes, which are normally not considered in lossless mode analysis, becomes comparable to that of the 'main' modes of the lossy structure. This is in sharp contrast to optical waveguides, where the effect of losses is usually considered as a small perturbation to the lossless dispersion properties of the mode, which manifests itself mainly in slow mode attenuation. Thus, we conclude that the standard approach to the study of the optical modes is not convenient in plasmonics, and the full analysis of the dispersion properties of the lossy waveguide modes should be considered.

4 PLASMONIC SLOT WAVEGUIDES WITH REALISTIC LOSSES

In the previous section, we have discussed the solutions of the dispersion relation (1) in lossless and low-loss slot waveguides. Continuing our analysis, we consider realistic losses in the structure. In this case all solutions of the dispersion relation become complex, $\beta = \beta' + j\beta''$, and thus we cannot distinguish the propagating and evanescent modes.

As discussed above, introduction of small losses leads to the merging of the propagating mode solutions with the evanescent branches. One of the antisymmetric branches of evanescent modes has negative β'', see Fig. 4(d). In our convention, negative β'' corresponds to the wave decaying in (and thus the energy flowing to) negative-z direction. Since the corresponding real part of the wavenumber is positive, we come to the conclusion that the whole corresponding mode is backward, despite the fact that the dispersion curve slope is positive for lower frequencies [13, 20]. We note that in lossy systems the backward waves can be observed in considerably lower frequency ranges. The other antisymmetric branch remains forward with loss increase. At surface plasmon resonance frequencies, $\omega = \omega_{spp}$, the wavevector does not tend to infinity, as in lossless structures, and this feature was widely discussed in literature [2, 5]. For frequencies approaching the surface plasmon resonance the decay factors of forward waves increase dramatically, whereas the losses for backward modes decrease. In frequency domain above ω_{spp} the formation of quasi-bound modes [5] occurs due to the merge between corresponding propagating and evanescent solutions. The detailed analysis of mode behavior in this frequency domain will be discussed in further publications.

To further demonstrate the importance of the evanescent modes in the lossy case, we study the behavior of the plasmon guide indices on the complex plain (β', β'') with increase of losses for the free space wavelength of $\lambda = 465nm$, see Fig. 5(a). As it follows from the graph the roots of dispersion relation, being real lossless case, become complex with loss increase. It is also clear that backward mode has negative decay factors, which corresponds to the negative energy flow, discussed in Ref. 13. Note that with loss increase the guide indices of all modes become smaller, and since the backward antisymmetric is close to light-line in lossless case, it disappears in some frequency domain in lossy case.

Figure 6 shows the dispersion curves for the structure with realistic losses. Only lower order modes with smaller imaginary parts of the wavenumber are shown. In contrast to lossless case, when the propagating waves existed either below or above the surface plasmon resonance frequency ω_{spp}, the modes are now spread across the whole frequency domain. In narrow waveguides, i.e. $d < \sim 35nm$, for lossy systems two coexisting modes are observed - forward symmetric and backward antisymmetric. For relatively wide slot waveguides, with $d \sim 100nm$, forward symmetric and antisymmetric modes coexist. For moderate slot widths [Fig. 6(b)], three coexisting modes can be excited: forward symmetric and antisymmetric and backward antisymmetric waves. Note that at lower frequencies counter-propagating antisymmetric waves have similar real parts of wavenumbers, β', which may be used in plasmonic couplers.

For forward waves above the surface plasmon resonance frequency the losses increase dramatically, the inverse behavior is observed for backward antisymmetric wave - losses are higher at low frequencies, see insets on the Figs. 6(a-c).

We study the mode profiles for lossy system for the free space wavelength $\lambda = 475$ nm; the results are presented on the Figs. 5(b-d). Due to losses the propagation constant becomes complex and thus the mode profiles obtain oscillatory nature, which is clearly observed on the Fig. 5(d). Also due to decrease of guide indices the modes become less localized compared to the modes in lossless case.
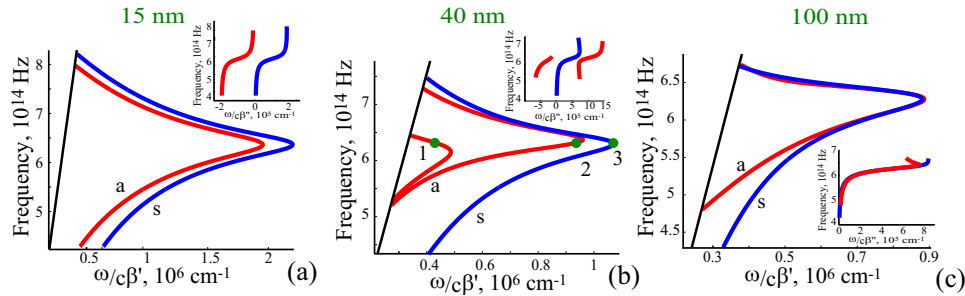
Fig. 6. Dispersion diagrams for slot waveguides in real systems: (a) $d = 15$ nm, (b) $d = 40$ nm, (c) $d = 100 nm$. Symmetric and antisymmetric modes are marked on the figures with 's' and 'a', respectively. Numbered dots on the figure (b) indicate modes which will be studied further in the paper: (1) backward antisymmetric mode with effective index 3.2-1.55j, (2)- forward antisymmetric mode with effective index 6.8+7j, and (3) - symmetric mode with effective index 7.8+3.5j. Modes (1-3) coexist at the same frequency. Insets show the imaginary part of effective index.

5 CONCLUSIONS

We have revisited the problem of the existence of plasmonic modes guided by symmetric metal-dielectric-metal slot waveguides. In addition to the well-known symmetric and antisymmetric forward propagating guided modes discussed in textbooks, we have revealed that, in a certain parameter range, three guided modes may exist simultaneously at the frequencies below the surface plasmon resonance; this includes an additional backward propagating antisymmetric mode. The new waveguiding regime is interesting not only for the future studies of nonlinear interactions and phase-matching between the plasmonic modes in slot waveguides, but also for the realization of the negative refraction regime in planar metal-dielectric structures operating in visible and at the nanoscale. We have demonstrated that losses may change dramatically the properties of guided plasmonic modes in slot waveguides, and we have discussed mutual the transformation of propagating and evanescent modes in lossy waveguides.

6 ACKNOWLEDGMENTS

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