

Self-focusing of femtosecond surface plasmon polaritons

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Abstract: We study the propagation of femtosecond pulses in nonlinear metal-dielectric plasmonic waveguiding structures by employing the finite-difference time-domain numerical method. Self-focusing of plasmon pulses is observed for defocusing Kerr-like nonlinearity of the dielectric medium due to normal dispersion. We compare the nonlinear propagation of plasmon pulses along a single metal-dielectric interface with the propagation within a metal-dielectric-metal slot waveguide and observe that nonlinear effects are more pronounced for the single surface where longer propagation length may compensate for lower field confinement.

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1. Introduction

The study of pulse and beam propagation in plasmonic waveguides is of great interest for telecommunication, computing, and information processing [1]. It is expected that nonlinear effects may even further enhance the capabilities of plasmonic devices also opening the door to the observation of novel effects such as plasmon self-focusing, self-trapping, and frequency conversion.

Early pioneering studies of nonlinear propagation of surface plasmon polaritons employed simple approximations for the analysis of Kerr nonlinearities in a single metal-dielectric interface geometry [2–5], and in a metal film embedded into a nonlinear Kerr medium [6]. However, only very few works have considered so far nonlinear guided waves in metal-dielectric structures, reporting on the studies of temporal effects and the formation of *temporal surface-polariton solitons* [7]. More recently, several groups have analyzed spatial localization of plasmon beams and the formation of *spatial plasmon solitons* [8–10].

One of the main challenges associated with the study of nonlinear effects in plasmonic waveguides, such as self-focusing and the formation of optical spatial and temporal solitons [11], is the presence of strong characteristic losses in metals at optical frequencies. Indeed, such losses can even be much stronger than effects of nonlinearity and dispersion, and they may consequently overshadow any manifestation of nonlinear self-action effects. Notwithstanding, the study of strong self-focusing of nonlinear waves in lossy media is well documented in other fields such as magnetic spin waves [12]. In particular, it is well established that nonlinear evolution of magnetostatic spin waves in thin YIG magnetic films may demonstrate strong spatiotemporal self-focusing and the formation of localized waves in the form of spin-wave solitons and bullets [13]; the effects that can be readily observed even in the presence of relatively strong losses. Moreover, self-action manifests itself as a transient effect at the initial period of the pulse evolution when the attenuation is weaker than the nonlinearity.

In this paper, we study the propagation of femtosecond pulses in nonlinear metal-dielectric plasmonic waveguiding structures by employing the finite-difference time-domain numerical method. We demonstrate that in the presence of a *defocusing* Kerr-like nonlinear response of the dielectric medium, femtosecond plasmonic pulses undergo self-focusing similar to the pulses in optical fibres [11] but with a transient formation of temporal plasmon-solitons, and then experience broadening due to strong losses in metal. We consider two major types of plasmonic waveguides with a nonlinear dielectric, namely a single metal-dielectric interface and a metal-dielectric-metal (MDM) slot waveguide. We find that nonlinear effects are more pronounced for plasmon pulses propagating along a single metal-dielectric interface where longer propagation length may compensate for lower field confinement. Finally, we study the interaction of the plasmonic pulses with the counter-propagating continuous wave (CW) plasmons and show that, by changing the amplitude of incoming CW, one can control the phase of the pulses.

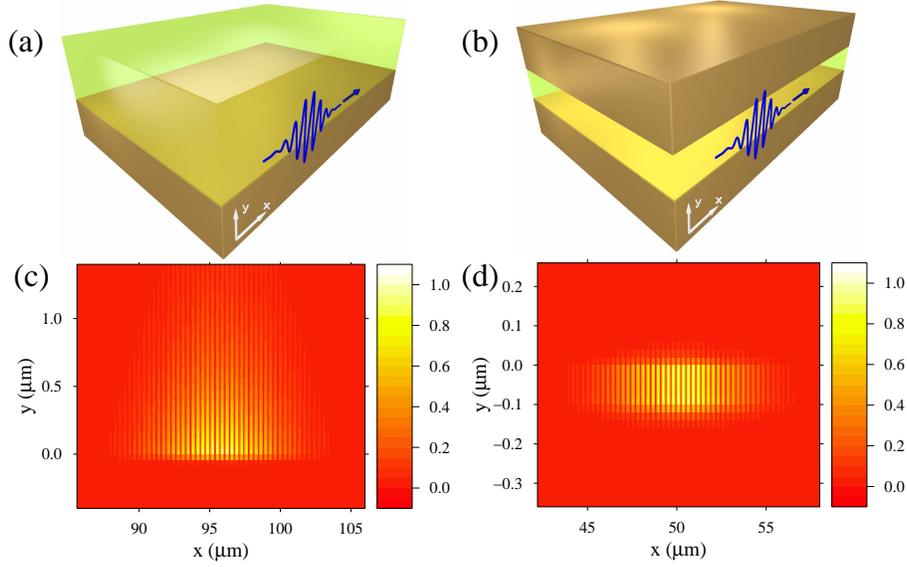


Fig. 1. Schematic of the pulse propagation along (a) metal-dielectric interface and in (b) metal-dielectric-metal slot waveguide. (c,d) Pulse profiles shown as squared magnetic field carried by the pulses.

2. Methods

To calculate the dynamics of the propagating TM polarized plasmon pulses we use a finite-difference time-domain (FDTD) numerical technique. For TM polarization, Maxwell's equations reduce to the following form,

$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -\mu_0 \frac{\partial H_z}{\partial t}, \quad \frac{\partial H_z}{\partial y} = \epsilon_0 \epsilon \frac{\partial E_x}{\partial t}, \quad -\frac{\partial H_z}{\partial x} = \epsilon_0 \epsilon \frac{\partial E_y}{\partial t}. \quad (1)$$

To model the metallic response of silver in the telecommunication regime we employ the Drude model

$$\epsilon_{Ag}(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\Gamma},$$

with $\omega_p = 1.39 \cdot 10^{16} \text{rad/s}$ and $\Gamma = 3.2 \cdot 10^{13} \text{rad/s}$, which fits the experimental data of Johnson and Christy [14].

The Kerr-type response of the nonlinear dielectric is calculated [15, 16] via a recursive application of the nonlinear material relation $\mathbf{E} = \mathbf{D}/(\epsilon_d + \epsilon_{NL}|\mathbf{E}|^2)$. As a result, the nonlinear permittivity is $\epsilon = \epsilon_d + \delta\epsilon = \epsilon_d + \epsilon_{NL}|E|^2$, where $|E|^2 = E_x^2 + E_y^2$, and we also take $\epsilon_d = 4.9$.

In our analysis we consider two structures. The first structure is a simple metal-dielectric interface [see Fig. 1(a)] supporting the propagation of a surface plasmon with the magnetic field distribution of the form,

$$H(x, y) = \begin{cases} A \exp(i\beta x) \exp(-k_d y), & \text{for } y > 0, \\ A \exp(i\beta x) \exp(k_m y), & \text{for } y < 0. \end{cases} \quad (2)$$

The complex propagation constant β can be found from the boundary conditions as

$$\beta = k_0 \left(\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d} \right)^{1/2}, \quad (3)$$

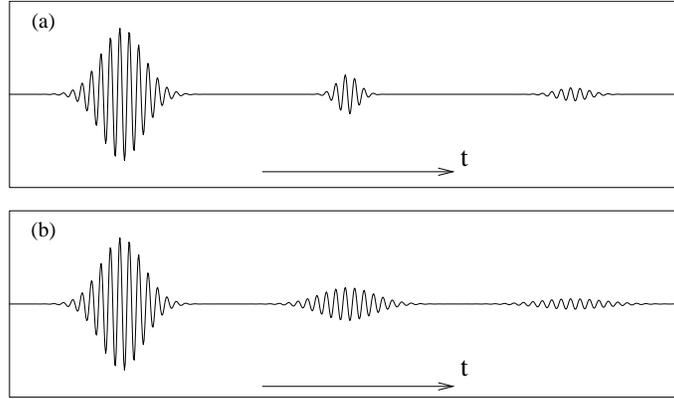


Fig. 2. Schematic of pulse propagation in (a) nonlinear and (b) linear case. The pulse energy always decreases during propagation. In the nonlinear case (a), the pulse width w first decreases before a linear propagation regime is reached, and then it increases again. In the linear regime (b), a steady increase of the pulse duration is observed.

where $k_{m,d}$ are transverse wavenumbers: $k_{m,d}^2 = \beta^2 - k_0^2 \epsilon_{m,d}^2$, and $k_0 = \omega/c$. The propagation length of the surface plasmon ($[2\text{Im}(\beta)]^{-1}$) at telecommunication wavelength ($\lambda_0 = 1550 \text{ nm}$) is evaluated to $105 \mu\text{m}$, and the corresponding imaginary part of the wavenumber is 4764 m^{-1} .

The second structure investigated here [see Fig. 1(b)] is a metal-dielectric-metal (MDM) slot waveguide. Here the permittivities are given as

$$\epsilon = \begin{cases} \epsilon_m, & |y| > a/2 \\ \epsilon_d, & |y| \leq a/2, \end{cases} \quad (4)$$

where we use the thickness of the dielectric layer $a = 100 \text{ nm}$. The dispersion equation for the propagation constant is then given as

$$\tanh(k_d a) [\epsilon_m^2 k_d^2 + \epsilon_d^2 k_m^2] + \epsilon_m \epsilon_d k_d k_m = 0. \quad (5)$$

We calculate the propagation length for the slot waveguide as $20 \mu\text{m}$, substantially shorter than the propagation length of the surface plasmon at a single interface. Both structures show normal dispersion at telecommunication wavelengths, so that a negative ϵ_{NL} is necessary to achieve the effective pulse compression [11].

To inject the correct pulse form into the FDTD computation domain, the profile of the linear mode is first calculated and then used as input for a total-field/scattered-field plane [15], in which both electric and magnetic fields are staggered with a phase difference corresponding to the propagation constant of the mode. For the study of the propagation of a single surface plasmon, we use a grid cell size of $\Delta x = 20 \text{ nm}$ and a total length of the computation domain along x-axis of $L = 400 \mu\text{m}$. The dielectric extends for $3 \mu\text{m}$ in the y-direction to minimize the effects of the boundaries, whereas the metal extends for $1 \mu\text{m}$.

In the calculation of the MDM slot waveguide the resolution is increased to $\Delta x = 10 \text{ nm}$ in order to sufficiently resolve the large field gradients across the structure. As a consequence of that, the computational domain has to be smaller with $L = 220 \mu\text{m}$, which corresponds to more than 10 times the propagation length, and thus it is long enough to capture all nonlinear effects. In both the cases perfectly matched layer boundary conditions are used at the boundaries of the simulation domains. Using the above resolutions in a two-dimensional FDTD simulation

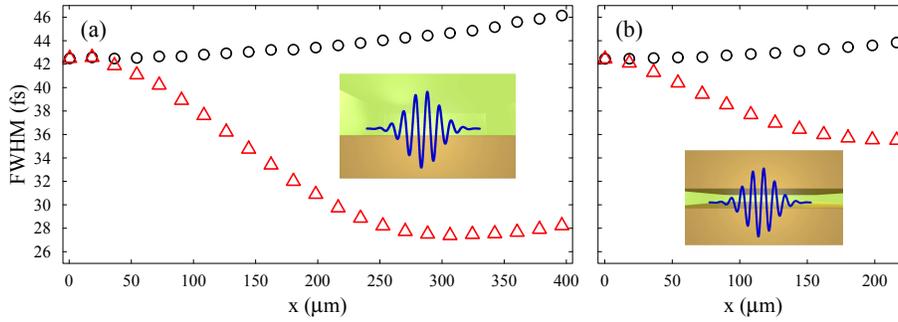


Fig. 3. Evolution of the pulse widths for Gaussian pulses with propagation distance for (a) single interface for the nonlinear (red triangles) and linear (black circles) dielectrics, and (b) in the slot waveguide with nonlinear (red triangles) and linear (black circles) dielectrics in the slot. The maximum nonlinear change of the dielectric permittivity at $x = 0$ is found as $\delta\epsilon_{\max} = -\epsilon_{NL}E_0^2 = 0.03$.

results in some numerical dispersion that is, however, still much smaller than the dispersion introduced by the Drude model of free electrons in the metal and the wave-guiding geometry.

Note that throughout this work, the intensities are normalized to $\epsilon_{NL}^{-1/2}$, and we monitored the maximum nonlinear correction to the dielectric permittivity $\delta\epsilon_{\max}$ that is reached in the nonlinear medium. We use this parametrization since the nonlinear effects that can be achieved in plasmonic systems are ultimately limited by the saturation of the nonlinearities.

3. Results

Figures 2(a) and 2(b) show schematically the propagation dynamics of nonlinear and linear pulses in lossy metal-dielectric plasmonic structures studied numerically. In the nonlinear case, the pulses are first compressed (or self-focused) until dissipation has reduced the pulse amplitude into the linear regime and dispersive pulse broadening takes over [see Fig. 2 (a)]. In the linear regime pulses experience continuous broadening [see Fig. 2(b)], as also observed in experiment [17].

In Figs. 3(a) and 3(b) the qualitative behaviour indicated in Figs. 2(a) and 2(b) is quantified for both the single interface and slot waveguide. The initial Gaussian pulses are given by $E(t) = E_0 \cos[\omega(t - t_0)] \exp[-(t - t_0)^2/\tau^2]$ with $\tau = 36$ fs.

We can see that the pulses are compressed more quickly in the slot waveguide because of the higher field confinement. The high losses (short propagation length) in the slot waveguide, however, lead to the plasmon pulse quickly reaching the linear regime, where it starts to broaden again. Thus the surface plasmon can, when excited with the same maximal field amplitude, experience substantially stronger compression, as can be seen in Fig. 3(a). Here, the compression only slows down considerably after about $200 \mu\text{m}$ (twice the propagation length).

One of the fascinating properties of optical solitons is their ability to interact during collisions [18]. The inherent weakness of the Kerr nonlinearity, however, limits the effective interaction strength for short pulses, unlike, e.g., in self-induced transparency solitons where even femtosecond pulses can interact very strongly and induce soliton birth or breakup [19]. Therefore, we now analyse the effect that a counter-propagating quasi-CW excitation has on a short femtosecond pulse.

Figure 4 shows the maximum phase shift that can be accumulated by a pulse subjected to the interaction with a counter-propagating CW excitation on the surface (black triangles) or the slot waveguide (red diamonds). The achievable phase shift depends mainly on the maximum

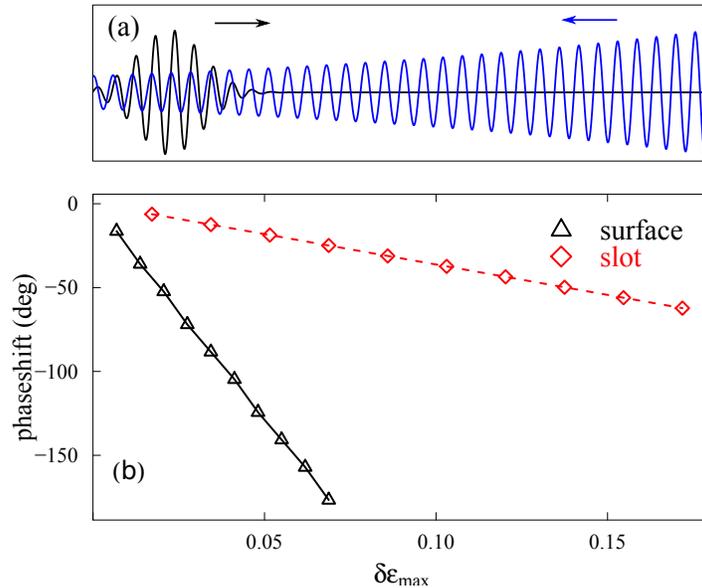


Fig. 4. (a) Schematic of the nonlinear soliton collision. A pulse coming from the left (black line) collides with a quasi-CW excitation coming from the right (light blue line). Note that the CW excitation loses energy during propagation. (b) Maximum phase-shifts attainable for a pulse colliding with a CW excitation evaluated for various initial nonlinear permittivity changes $\delta\epsilon_{max}$ due to the CW field. Black triangles denote the data for a single interface, and red diamonds – the data for the MDM slot waveguide.

change in the permittivity before nonlinearity saturation sets in. A CW plasmon entering from the right [see Fig. 4(a) for a schematic view] attenuates upon propagation and ultimately it is too weak to induce a phase shift. Again, it is the shorter propagation lengths in the slot waveguide that limit the nonlinear effect. The phase shift is thus larger for the surface plasmon on a single surface. Here, the same (but sign-reversed) effect could be achieved with a positive values of the third order susceptibility. Such a nonlinear interaction setup can be employed for controlling the phase of the plasmonic pulses. We note that for the plasmon propagating distances and characteristic times that it takes for the plasmons to propagate these distances, we didn't observe any onsets of modulational instability of the CW.

4. Conclusions

We have studied self-focusing of plasmonic pulses in two major types of nonlinear metal-dielectric waveguiding structures by employing the finite-difference time-domain numerical methods. We have demonstrated that, even in spite of significant influence of characteristic losses in metal, the plasmonic pulses may undergo self-focusing with a transiting formation of (transient) temporal plasmon solitons. We have also revealed that nonlinear effects are more pronounced for the propagation along a single metal-dielectric interface than for a slot waveguide. Further enhancement of nonlinear interactions is expected to be achieved in tapered plasmonic structures [20], but this problem is beyond the scope of the current paper and will be addressed in further studies.

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