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Guided modes of surface plasmon polaritons in linear dielectric–metal–nonlinear dielectric waveguide

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ABSTRACT

We investigate the guided modes of the surface plasmon polaritons in metal waveguide with a nonlinear dielectric substrate and a linear dielectric cladding. It is shown that the nonlinear fundamental guided mode is always absent for any waveguide parameters. The exact dispersion relations of the surface plasmon polaritons are obtained in the form of the propagation constant versus the frequency and the waveguide thickness. We also investigate the slow-wave guided modes in the metal waveguide and show that only lowest-order mode can exist.

1. Introduction

Surface plasmon polaritons are propagating electromagnetic surface wave at the interface between dielectric and metal [1]. During the past decades, the study of surface plasmon polaritons in subwavelength metal-dielectric nanoscale structures, nanophotonics [1], has been a hot topic [2] since the extraordinary optical transmission through a two-dimensional metallic hole array was firstly reported in 1998 [3]. The developments and applications of surface plasmon polaritons have opened a new way to achieve optical nanoscale manipulations [4] and nano-optical devices [5,6]. Compared with the linear surface plasmon polaritons, recent studies have illustrated that the nonlinear surface plasmon polaritons becomes a more interesting subject, due to the case of electromagnetic field confinement and enhancement in metallic structure. Many works have investigated the nonlinear surface plasmon polartions in metal-electric based structures, including single interface [7–13] and superlattices [14–18], etc.

Nonlinear surface plasmon poalritons have also been studied in waveguide containing metal and nonlinear dielectric. Some novel phenomena and properties, such as plasmon solitons [19,20], second harmonics [21], directional coupler [22], long-range plasmonic [23], and nanofocusing [24], have been demonstrated in detail. Recently, the exact dispersion relations have also been studied [25–27]. The nonlinear plasmon polaritons was even studied in planar waveguide with metal nonlinearities [28,29]. Although the nonlinear surface plasmon polaritons have been investigated extensively in metal waveguide, the guided modes [30,31] of the nonlinear surface polartions have not drawn considerable attention. Especially, almost no people concentrate on the slow-wave nonlinear surface plasmon polaritons guided modes.

In this paper, we investigate the guided modes of the surface plasmon polaritons in linear dielectric–metal–nonlinear dielectric waveguide by using the plane wave approximation and the graphic method. It is shown that the nonlinear fundamental guided mode is always absent. The exact dispersion relations of the surface plasmon polaritons are obtained analytically. We also investigate the slow wave guided modes in such nonlinear metal waveguide and show only the lowest order slow-wave guided mode can exist. Our results may lead to the potential applications in nanophotonics and nonlinear plasmonics.

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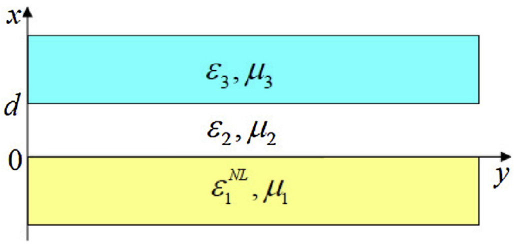

Fig. 1. Schematic structure of the metal waveguide with a nonlinear substrate and a linear caldding, the core thickness is d. (For interpretation of the references to color in text/this figure legend, the reader is referred to the web version of the article.)

2. Physical model and basic equations

Considering a thin slab of linear dielectric–metal–nonlinear dielectric waveguide structure, as shown in Fig. 1. It should be noted that the dispersion relation of the nonlinear surface plasmon polaritons has been studied analytically based on first integral approach in such a waveguide structure [32]. However, in Ref. [32], the guided modes and the slow-wave modes have not been obtained. In this paper, we use different methods to study the nonlinear surface plasmon polaritons, especially the guided modes and the slow-wave polaritons. We assume the core of the waveguide is metal with the thickness d, the permittivity and the permeability are ϵ_2 and μ_2. We also assume the linear dielectric of cladding is air with the permittivity and the permeability are $\epsilon_3 = \mu_3 = 1$. The substrate is the nonlinear medium with the permittivity and the permeability are $\epsilon_1^{\mathrm{NL}} = \epsilon_1^L + \alpha|E_1|^2$ and μ_1, where ϵ_1^L is the linear refractive index and α is the nonlinear coefficient index, $\alpha > 0$ ($\alpha < 0$) corresponding to self-focusing (self-defocusing) nonlinearity, E_1 is the transmitted electric field in substrate. In this paper, we focus on the self-trapping situation with $\alpha > 0$. We also make the assumption that all the material are nonmagnetic $\mu_1 = \mu_2 = \mu_3 = 1$.

In order to study the TM-modes surface plasmon polaritons, a plane wave approximation is firstly applied [33] which was previously used to study the nonlinear surface plasmons in thin metal films. The nonlinear coefficient α of the substrate is connected to the optical Kerr constant n_2 through the relation $\alpha = \epsilon_1^L\epsilon_0 c n_2$. Under the plane wave approximation, the electric field intensity $|E_1|^2$ can be represented as $|E_1|^2 = \mu_1/\epsilon_1\epsilon_0^2c^2|H_1|^2$, where H_1 is the corresponding magnetic field [33]. Since $\alpha|E_1|^2$ is relatively small compared with ϵ_1^L, ϵ_1 can be approximately expressed as $\epsilon_1 = \epsilon_1^L + \alpha'|H_1|^2$, with $\alpha' = n_2\mu_1/\epsilon_0 c$. Thus the magnetic fields in three regions of the metal waveguide can be written as

$$\psi(x) = \begin{cases} \frac{k_1}{k_0}\sqrt{\frac{2}{\alpha'\mu_1}}\,\mathrm{sech}[k_1(x-x_0)], & x<0, \\ Ae^{\mathrm{i}k_2(x-d)} + \mathrm{B}e^{-\mathrm{i}k_2(x-d)}, & 0<x<d, \\ \mathrm{C}e^{-k_3(x-d)}, & x>d, \end{cases} \tag{1}$$

where $k_1^2 = \beta^2 - k_0^2\epsilon_1^L\mu_1$ and $k_3^2 = \beta^2 - k_0^2\epsilon_3\mu_3$ are the transverse decay indexes in substrate and cladding, $k_2^2 = k_0^2|\epsilon_2\mu_2| - \beta^2$ is the transverse wave vector of the guided modes in core and it is real, β is the propagation constant of guided modes. The phase velocity of this waveguide is $v_p = \omega/\beta$, which indicates that $v_p > \omega/(k_0\sqrt{|\epsilon_2\mu_2|})$ (ω and k_0 are the angular frequency of the guided mode and its wavenumber in vacuum). This type of guided waves are called as fast-wave guided modes.

Applying the continuity of wave function at the interfaces $x = 0$ and $x = d$, we obtain the corresponding dispersion equation as follow:

$$\tan(k_2 d) = \frac{\epsilon_1^L\epsilon_2 k_2 k_3 - \epsilon_2\epsilon_3 k_1 k_2\tanh(-k_1x_0)}{\epsilon_1^L\epsilon_3 k_2^2 + \epsilon_2^2 k_1 k_3\tanh(-k_1x_0)}, \tag{2}$$

where $x_0 = -\frac{1}{k_1}\mathrm{sech}^{-1}\left[\frac{k_0}{k_1}\sqrt{\frac{\alpha'\mu_1}{2}}(\cos k_2 d + \frac{\epsilon_2 k_3}{\epsilon_3 k_2}\sin k_2 d)C\right]$ is the position of the maximum of the amplitude in nonlinear substrate, C being the amplitude of the magnetic field at the interface $x = d$.

3. Fast-wave guided modes

We assume the linear part of the nonlinear permittivity is $\epsilon_1^L = 1.2$ and the optical Kerr index is $n_2 = 2\times10^{-9}$ [34]. The metal is considered as silver for which the permittivity is chosen as Drude model, $\epsilon_2 = 1 - \omega_p^2/(\omega^2 + i\omega\omega_c)$, where ω, ω_p and ω_c are angular frequency, plasma frequency and collision frequency, respectively. For convenience, in this paper, we also neglect the loss of the metal. For silver, we take the plasma frequency $\omega_p = 1.37\times10^{16}$ rad/s (about 2.18×10^{15} Hz) [35]. We use the graphic method to obtain the guided modes of the nonlinear surface plasmon polaritons [36]. As shown in Fig. 2, we plot the guided modes in metal waveguide when the angular frequency is $\omega = 0.5\omega_p$. We find that the fundamental TM_0 mode is absent for any parameters of the nonlinear metal waveguide. The lowest mode is TM_1 guided mode. The unique property is very different from the case of conventional nonlinear waveguide where the lowest-order TM_0 guided mode is always exist [37]. The reason that TM_0 mode does not exist can be explained in waveguide phase method. In fact, when $\omega < \omega_p$, $\epsilon_2 < 0$, the metal waveguide can be treated as a single negative metamaterial waveguide, where the lowest guided modes are not supported [38–40]. Since the magnetic magnitude has a peak in the nonlinear media, the guided modes not only have mode energy in the core, but also a peak mode energy in the nonlinear substrate