Slow Surface Plasmon-Polaritons in a Metal-Dielectric Structure Incorporating a Lorentzian Gain Medium

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Abstract: We investigate slow surface plasmons supported at the surface of a semi-infinite metal bound by a gain medium with Lorentzian lineshape and the induced slow light regime due to the active medium.

OCIS codes: (240.6680) Surface Plasmons; (060.4510) Optical communications; (230.7400) Waveguides, slab

1. Introduction.

Surface plasmon-polaritons (SPPs) are transverse-magnetic polarized optical surface waves that exist at the interface between two materials with the opposite permittivity real part. Such is the case for the Metal/Dielectric planar interface [1]. As it has been showed, due to its asymptotic behavior, SPPs can theoretically exhibit a slow group velocity region [2] in the vicinity of the SPP resonance frequency. Nevertheless, due to the metals intrinsic losses at the optical frequencies, as well as other loss mechanisms such as scattering produced by the surface roughness, the propagation length of SPPs degrades. Therefore, this proposal becomes, as its best, a limit for promising application and therein the need for an analysis in more realistic conditions.

An interesting property of SPPs is that they exhibit an asymptotic behavior in their dispersion curves at frequencies close to the SPP resonance. In this asymptotic region, the light group velocity slows down considerably, enabling modes with group indices as large as 5×10^4 in theory [2]. However, the intrinsic losses of metals at optical frequencies, and other loss mechanism, severely degrade the plasmonic mode performance in the structures for slow-light (SL) applications [3].

Recently, the use of gain media in plasmonic waveguides has been proposed to reduce the deleterious effects of losses [2,4,5] and specific analysis needs to be carried out to explore such proposal. In this work we will study the induced SL region far from the natural SL regime of SPPs when a finite gain model is used to describe the spectral gain response of a given gain medium.

2. Method of analysis

The structure under consideration is the simple planar metal/dielectric. The metal permittivity is modeled using the Drude model for silver and the dielectric is a generic material with refractive index of n_d. The SPP dispersion curve is $\beta = k_0\sqrt{\varepsilon\varepsilon_m/(\varepsilon+\varepsilon_m)}$, where β is the complex SPP propagation constant, k_0 the vacuum wavenumber, and ε and ε_m the wavelength dependent permittivities of the dielectric and metal, respectively. The SPP propagation mode group index n_g is computed from $\upsilon_g = (d\beta'/d\omega)^{-1} = c/n_g$, where υ_g is the group velocity, ω the frequency and c the speed of light in vacuum.

The susceptibility of the material hosting the gain medium is given by $\chi = \chi_d + \chi_g$, where χ_d corresponds to that of the dielectric itself and χ_g to that of the gain medium. Thus the complex dielectric permittivity of the gain medium becomes $\varepsilon = \varepsilon_0(n_d^2 + \chi_g) = n^2$. The refractive index can be approximated by $n = n_d + (\chi_g' + i\chi_g'')/2n_d$. In general for a wave propagating in an amplifying media the wavevector can be expressed as $k = k_0 n = \beta - i\gamma/2$ where γ must be positive. If we relate the last two equations, we can find that the imaginary part of the gain dielectric susceptibility medium is given by $\chi_g''(\nu) = -\gamma(\nu)\, n_d c/2\pi\nu$, where ν is the frequency and $\gamma(\nu)$ the response function that, in our case, it will be a Lorentzian function for the homogenous profile. Finally, the active nature of a dielectric propitiates a dispersive behavior, which are related by the Kramers-Kronig relations [6]. The complex refractive index is then

$$n = n_d - g_{\max}\frac{c}{2\pi^2}\int_0^\infty \frac{1}{s^2-\nu^2}\frac{(\Gamma/2)^2}{\left(s-\nu_0\right)^2+(\Gamma/2)^2}ds - i\frac{g_{\max}}{2k_0}\frac{(\Gamma/2)^2}{\left(\nu-\nu_0\right)^2+(\Gamma/2)^2} \tag{1.1}$$

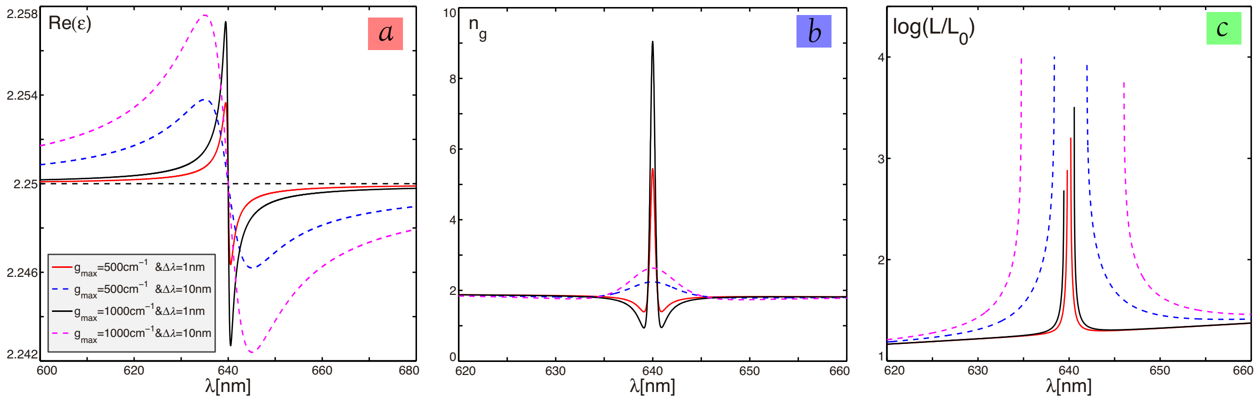

Figure 1. We plot the permittivity real part of the dielectric medium, the SPP group index and the SPP propagation length as function of the wavelength. The calculations were made for four cases, two maximum gains and two spectral widths. The solid red and dashed blue lines correspond to a maximum gain of *500cm^{-1}* with a spectral width of *1nm* and *10nm* respectively. The solid black and dashed pink lines correspond to a maximum gain of *1kcm^{-1}* with a spectral width of *1nm* and *10nm* respectively. The center wavelength at maximum gain is *640nm*. a) – Real permittivity part displays a dispersive behavior induced by the gain response. b) – Induced group index in the SPP dispersion curve is far from the natural SL region, about 350 nm in this particular case. The maximum group index is at the center wavelength of maximum gain. c) – Propagation length in a logarithmic scale normalized to $L_o = 1\mu m$.

where $g_{\max}$ is the maximum gain in cm^{-1} at a center frequency ν_0, Γ the FWHM value of the spectral width. This integral is carried out numerically using MATLAB where we have paid a special attention on the principal value computation.

3. Results and discussion.

In our analysis we use the Drude model for silver adjusted to experimental values [7], and used equation (1.1) to calculate the refractive index of the gain medium assuming *n = 1.5*. Numerically we calculate the dielectric refractive index and use it to find the SPP propagation constant for four different cases with a center wavelength of *640nm*: two maximum gains, *500cm^{-1}* and *1kcm^{-1}*, and two spectral widths, *1nm* and *10nm*, for each one. Knowing beta, we calculate the SPP group index and propagation distance $L=1/(2Im(\beta))$.

Fig 1a shows the real part of the gain medium's permittivity, which exhibits dispersion due to the Lorentzian lineshape of the gain spectrum. The large dispersion around ν_0 results in an increment of the SPP group index [8] that can be as large as 9, see Fig 1b. In addition, the imaginary part of the SPP propagation constant is negative; it means that in these region there is, theoretically, infinite propagation since the SPP mode is experiencing amplification due to the active dielectric.

4. Summary

We have considered a simple planar metal/dielectric waveguide with an optical gain modeled by a Lorentzian function, the homogenous profile case. We observed that a SL region is induced in the SPP mode dispersion curve, far from the natural SPP SL region, a result that is not predicted when the dielectric medium considers a constant gain value in the model. The induced maximum group index, that the SPP mode can experience, depends on the maximum gain and the spectral width and this will become latter the most important factor. In addition, the ensuing results for other gain function models will be considered and published elsewhere. Thanks to CONACyT through the projects CB-2010-01/157866 and CB-2008/101378.

5. References

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