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What is an epsilon-near-zero mode?

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Abstract: Thin metallic films support long-range surface plasmons. For thicknesses much smaller than the skin depth, the mode dispersion approaches the plasma frequency, giving rise to the so-called epsilon-near-zero mode, whose features and observation conditions are analyzed.

OCIS codes: (240.6680) Surface plasmons; (260.2030) Dispersion

1. Introduction

It has been known for years that thin films made of metals, doped semiconductors, or polar materials can support surface plasmon- or phonon-polaritons (SPPs) [1,2]. For deeply subwavelength film thicknesses, a so-called "epsilon-near-zero" (ENZ) mode has been observed [3]. This ENZ mode is confined to the film and its dispersion lies on the right of the light line. It was briefly shown that this mode corresponds to a long-range surface wave mode in the thin-film regime [4]. The goal of this work is to study the behavior and domain of existence of the ENZ mode, which have not been clearly investigated so far (see [5] for more details).

2. From long-range surface plasmon to epsilon-near-zero mode

We consider here the three-layer structure depicted in Fig. 1. A layer with thickness d and relative permittivity ε_2 is surrounded by two semi-infinite regions with dielectric constants ε_1 and ε_3. For the sake of simplicity, and in order to extract the essential physics of the ENZ mode, we will consider a plasmonic film, whose dielectric constant is described by a simple Drude model $\varepsilon_2(\omega) = 1 - \frac{\omega_P^2}{\omega^2 + i\gamma\omega}$, with ω_P depicting the plasma angular frequency and γ the damping, and surrounded by free space ($\varepsilon_1 = \varepsilon_3 = 1$). The dielectric constant of the film can vanish when the angular frequency is close to ω_P, leading to the possibility to observe an ENZ mode. For the same reasons of simplicity, we will not address the issue of non-local effects that could arise from very small film thicknesses.

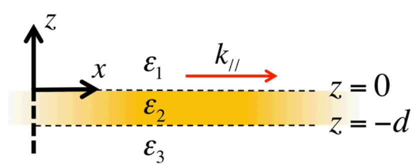

Fig. 1. Thin film geometry. The intermediate layer and the surrounding semi-infinite media are characterized by their dielectric constants ε_2, and ε_1 and ε_3, respectively.

A mode is characterized by its transverse component of the wave vector $k_{//}$ and its angular frequency ω that satisfy the equation

$$1 + \frac{\varepsilon_1 k_{z3}}{\varepsilon_3 k_{z1}} = i \tan(k_{z2} d)\left(\frac{\varepsilon_2 k_{z3}}{\varepsilon_3 k_{z2}} + \frac{\varepsilon_1 k_{z2}}{\varepsilon_2 k_{z1}}\right) \qquad (1)$$

where $k_{zi}^2 = \varepsilon_i \frac{\omega^2}{c^2} - k_{//}^2$, and k_{zi} is the longitudinal component of the wave vector in medium $i = 1,2,3$. We choose to solve the modes using real-valued $k_{//}$ and complex-valued ω as suggested in [1,3]. Two confined modes can exist for a thin film whose thickness is comparable to or smaller than the skin depth. These modes are well known as short- and long-range surface plasmons. Figure 2 shows the dispersion relation of these modes for two different thicknesses and for values $\omega_P = 10000\,\text{cm}^{-1}$ (corresponding to a plasma wavelength $\lambda_P = \frac{2\pi c}{\omega_P} = 1\ \mu\text{m}$, the wavelength for which the film dielectric constant vanishes) and $\gamma = 100\,\text{cm}^{-1}$. We can see that when the thickness is much lower than the skin depth (which is around 100 nm in our case), the long-range surface plasmon dispersion reaches the plasma frequency for which the dielectric constant vanishes. Around this frequency, the *z*-component of the electric field becomes dramatically large when compared to the in-plane components. Moreover, it presents also a constant value in the film. This peculiar behavior, which is due to the very small value of the dielectric constant, makes us refer to as ENZ mode the long-range surface plasmon in this dispersion region.

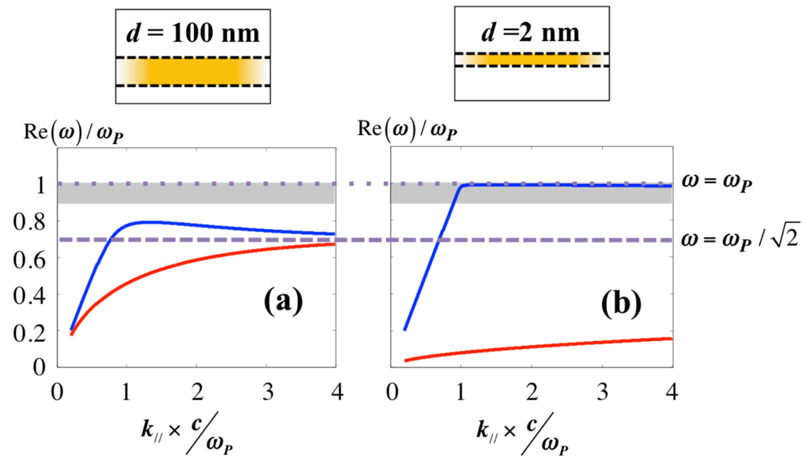

Fig. 2. Dispersion relation (real part only) for the short- (red) and long- (blue) range surface plasmon, for two different film thicknesses. When the film thickness is much smaller than the skin depth, the dispersion reaches the plasma frequency, for which the dielectric constant is close to zero. The gray area represents the frequency range where the mode presents a large, constant electric field inside the film. It is seen that the dispersion relation becomes linear in this region. Due to these peculiar properties, this part of the long-range surface plasmon mode is referred to as ENZ mode.

Using Eq. (1) and a normalization condition of the mode given in [6] for which the mode carries 1 Watt of power per meter of wavefront, we demonstrate that:

(i) The so-called ENZ mode is a part of the long-range surface plasmon mode, and is thus a transverse electromagnetic mode.

(ii) For thicknesses much smaller than the skin depth, the dispersion relation can reach the plasma frequency and can then be approximated by a linear relation between the angular frequency ω and the transverse component of the wave vector $k_{//}$.

(iii) The ENZ electric field inside the film increases when the thickness *d* decreases, and is proportional to *1/d*.

(iv) This behavior is not limited to the simple case of a Drude layer surrounded by free space, but available for a wide range of structures, as for example a thin glass layer deposited on gold [3]. In that work, the ENZ frequency is related to the longitudinal phonon frequency in the glass.

(v) The ENZ mode exists only for a given range of thicknesses; a good rule of thumb is $d < \lambda_P / 50$. This criterion gives trends on what materials can be used to observe/excite an ENZ mode and at which wavelength. We map in Fig. 3 the plasma wavelength λ_P versus thin layer thickness *d* for some (non-exhaustive) material systems, and overlap colored boxes for each material system representing the experimentally achievable thickness. This result shows that the ENZ modes can be observed mainly in oxides, doped semiconductors, and polar materials, but not in metals, due to the combination of values of plasma wavelength and experimentally achievable thicknesses.

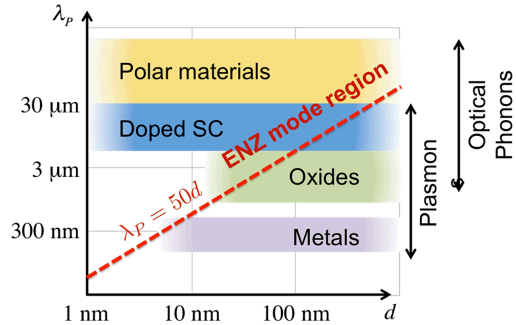

Fig. 3. Classification of some (non-exhaustive) material systems that may support ENZ modes, obtained by mapping the plasma wavelength λ_P versus thin layer thickness d. The color boxes for each material system extend horizontally and to the left to the minimum experimentally achievable thickness. The red dashed line defines the relation $\lambda_P = 50d$, which represents a boundary to determine if the structure supports an ENZ mode (left area).

3. Conclusion

The results shown in Sec. 2 allow us to understand which material systems can support an ENZ mode and under which conditions. This paves the way to very interesting possibilities, particularly in semiconductors, where very thin layers can be easily fabricated, and opens up possibilities in many applications, such as directional perfect absorption [7-9], ultrafast voltage-tunable strong coupling with metamaterials [10], electro-optical modulation [11], and ultrafast thermal emission [4,12].

References

[1] K. L. Kliewer and R. Fuchs, "Optical modes of vibration in an ionic crystal slab including retardation. II. Radiative region", Phys. Rev. 150, 573 (1966),

[2] D. Sarid, "Long-Range Surface-Plasma Waves on Very Thin Metal Films", Phys. Rev. Lett. 47, 1927 (1981)

[3] S. Vassant, J. P. Hugonin, F. Marquier, and J. J. Greffet, "Berreman mode and epsilon near zero mode", Opt Express 20, 23971 (2012)

[4] S. Vassant *et al.*, "Epsilon-Near-Zero Mode for Active Optoelectronic Devices", Phys. Rev. Lett. 109, 237401 (2012)

[5] S. Campione, I. Brener and F. Marquier, "Theory of epsilon-near-zero modes in ultrathin films", Phys. Rev. B Rapid Comm. To be published

[6] J. J. Burke, G. I. Stegeman, and T. Tamir, "Surface-polariton-like waves guided by thin, lossy metal films", Phys. Rev. B 33, 5186 (1986)

[7] T. S. Luk *et al.*, "Directional perfect absorption using deep subwavelength low-permittivity films", Phys. Rev. B 90, 085411 (2014)

[8] M. A. Badsha, Y. C. Jun, and C. K. Hwangbo, "Admittance matching analysis of perfect absorption in unpatterned thin films", Opt. Comm. 332, 206 (2014)

[9] S. Feng and K. Halterman, "Coherent perfect absorption in epsilon-near-zero metamaterials", Phys. Rev. B 86, 165103 (2012)

[10] Y. C. Jun *et al.*, "Epsilon-Near-Zero Strong Coupling in Metamaterial-Semiconductor Hybrid Structures", Nano Lett. 13, 5391 (2013)

[11] A. P. Vasudev, J.-H. Kang, J. Park, X. Liu, and M. L. Brongersma, "Electro-optical modulation of a silicon waveguide with an “epsilon-near-zero” material", Opt. Express 21, 26387 (2013)

[12] S. Vassant *et al.*, "Electrical modulation of emissivity", Appl. Phys. Lett. 102 (2013)