Complex Bloch-modes calculation of holey metal film for Extraordinary Optical Transmission

G.Parisi[1,2], P. Zilio[1,2], and F. Romanato[1,2]

[1]Department of Physics and Astronomy
University of Padova
Via Marzolo 8, 35131 Padova,Italy
Fax: +390498277102; email: giuseppe.parisi@unipd.it
[2]LaNN - Laboratory of Nanofabrication of Nanodevices
Corso Stati Uniti 4, 35127 Padova, Italy
Fax: +390498538857; email: giuseppe.parisi@venetonanotech.it

Abstract

We adopt a Finite Element Method (FEM) for calculating the complex valued $\mathbf{k}(\omega)$ dispersion curves of a holey metal slab. In particular the method allows retrieving the imaginary part of the dispersion curve even in presence of strong leakage radiation. Transmittance maps of the structure are compared to the Bloch bands clarifying the relationship between optical response of the structure and periodicity induced resonant modes.

1. Introduction

Periodic metallic nanostructures have received great attention in recent years due to their surprising optical properties. The interaction of electromagnetic fields with the free electron gas of metals gives rise to particular electromagnetic field waves which are known as Surface Plasmon Polaritons (SPPs) [1]. In particular, periodically nanostructured metal-dielectric interfaces have been subject of many researches due to their unexpected optical properties such as Extraordinary Optical Transmission [2] and negative refraction [3].

The description of Plasmonic Bloch waves propagating in a plasmonic crystal slab is typically a more challenging task with respect to the description of photonic Bloch waves in fully periodic dielectric systems. This is mainly for two reasons. First, metal optical properties are highly frequency dependent. This causes a nonlinearity in the Helmholtz's eigenvalue equation which is to be solved. Second, the analysis of Photonic Crystal *Slabs* (PCS) requires proper handling of not only truly bound modes but also of *leaky* modes, which is a non trivial task for standard numerical eigenvalue techniques.

In this work we tackle the problem of calculating the Bloch band structure of a holey metal film presenting the phenomenon of Extraordinary Optical Transmission. This kind of structure can be viewed as a dispersive lossy photonic crystal slab. We numerically solve the eigenvalue problem adopting the weak formulation of the Helmholtz's equation and discretizing the system by means of Finite Elements Method. In addition to the analysis presented in [4], we include Perfectly Matched Layers (PMLs) within the unit cell domain in order to properly deal with leaky modes radiation [Parisi, 2012 submitted].

2. 2D periodic array model

The structure (see Fig.1, left) consists of an array of squared nano-holes with sizes $a_x = a_y = a$ milled in a thin silver. Period and silver thickness are fixed to d = 940nm and h = 200nm respectively. Two PMLs are introduced in the unit cell in order to absorb the leakage radiation propagating toward open space. They are set at distance z_0 = ±1470nm from the origin (coinciding with the center of the slab) with thickness $L = 4d$.

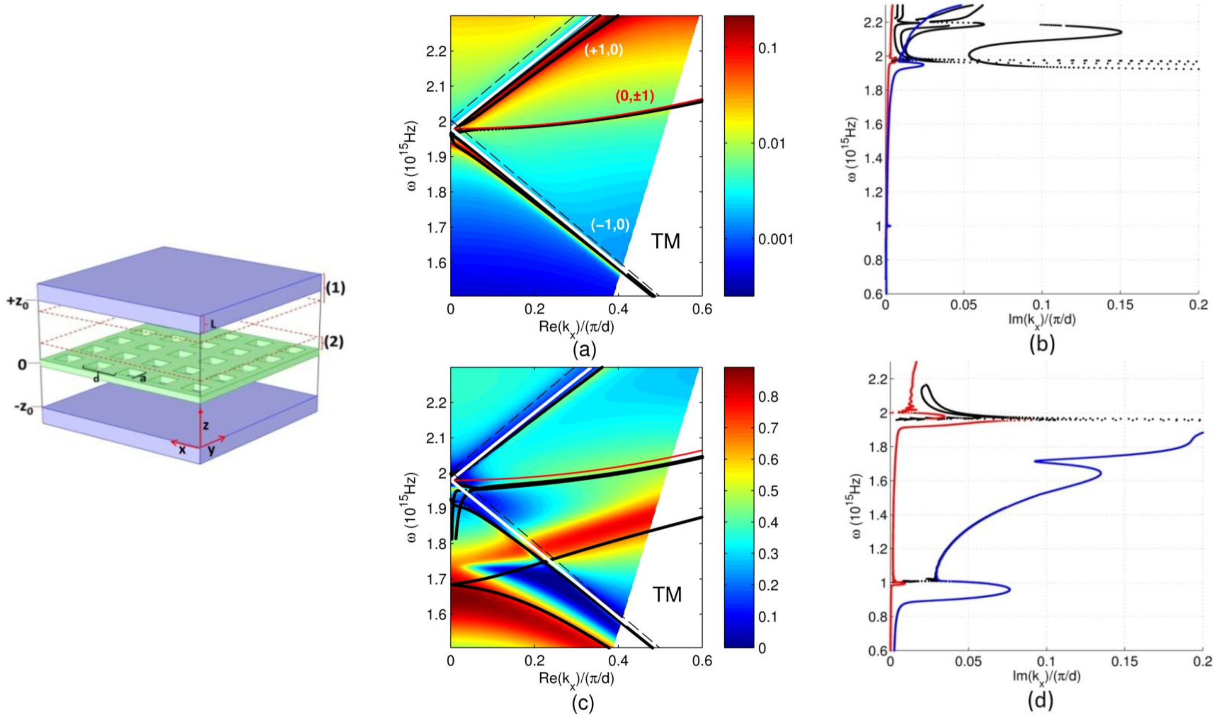

Figure 1. Left: Scheme of plasmonic crystal slab (green) with PMLs (violet) truncating the cladding domains. Right: Transmittance maps compared with the calculated dispersion curves (black lines). (a) and (b) refer to a 250nm holes array, (c) and (d) to a 500nm holes array. The black dashed line marks the light line, white and red solid lines mark the flat SPP dispersions, (±1,0) and (0,±1) respectively for all maps.

3. Results

Typically, what is usually omitted in literature is the detailed visualization of both the real and imaginary dispersions of the SPP modes of the structure. This is due the strong leakage radiation damping that affects the plasmonic modes for large hole-sizes and periods, which is hardly handled by standard numerical techniques. We performed two simulations: the first for a small hole size, a=250nm, the second for a wider hole, a = 500nm. We focus on modes along x-direction.

In Fig. 1(a),(c) we report the transmittance maps obtained by FEM scattering simulations in case of grating with holes size, a, of 250nm and 500nm for TM polarized impinging plane waves, respectively. The superimposed black lines (±1,0) are the real parts of the SPP Bloch modes of the structure calculated with the modal analysis. As can be seen, they directly correlate to the transmittance of the structure. The calculated Bloch modes (black curves) belong to two categories: symmetric (at higher frequencies) and anti-symmetric (at lower frequencies) modes depending on the distribution of the y-component of the magnetic field with respect to the two air-metal interfaces. This is a consequence of the mirror symmetry of the plasmonic slab with respect to the z=0 plane. Both of them are related to transmission resonances. The symmetric mode corresponds to the excitation of SPPs at the two horizontal metal-dielectric interfaces, weakly coupled via evanescent fields inside the hole. We see that it is only weakly perturbed by the increased holes size and exactly matches the corresponding transmittance peak visible in the map. The anti-symmetric mode, instead, corresponds to the excitation of SPPs strongly coupled via a Fabry-Pérot resonance inside the hole. Remarkably, the anti-symmetric mode for large hole (*a*=500) and $\omega < 1.8\text{x}10^{15}$Hz does not exactly follow the wide transmittance maxima observed. This mismatch is ascribed to the interplay between SPPs at horizontal interfaces and vertical Fabry-Pérot resonances. The latter mechanism, as the hole gets larger, becomes the dominant mechanism for enhanced transmission [5]. However, since it does not involve only the periodicity of the structure, but also a localized resonant mechanism, its contribution to transmittance is not purely related to Bloch modes and thus it is reasonably not caught by an in-plane modal analysis.

In Fig. 1(b),(d) we report the real and imaginary parts of the complete band structure within the first Brillouin along the Γ-X direction for both cases at *a*=250nm and *a*=500nm. The colored bands refer to the TM symmetric (red) and anti-symmetric (blue) modes. The most striking effect of increasing the hole size is found looking at the imaginary parts of the modes. In particular, as can be expected, the anti-symmetric mode, being related to the vertical Fabry-Pérot resonance, is the most sensitive to the hole size and shows a huge increasing of imaginary part. On the other hand, the imaginary part of the symmetric mode is almost the same for a=250nm and 500nm. At frequencies close to $1\text{x}10^{15}$Hz the small first order frequency gap found for a=250nm is much wider at a=500nm. The variation of the hole-size corresponds to a variation of the metal filling fraction along the mode direction of propagation which in turn affects the frequency gap-size.

4. Conclusion

In conclusion we have employed a full-vectorial Finite Elements based numerical method for the modal analysis of a plasmonic crystal consisting in a holey metal film for EOT. The method offers the possibility of retrieving both the real and imaginary part of Bloch-modes giving rise to the opportunity to study plasmonic nano-structures in terms of their surface resonances. The role played by Bloch-modes in the EOT phenomenon is elucidated, confirming that for small hole-sizes they are directly involved in EOT, while for larger hole sizes the transmission enhancement results from an interplay between horizontal surface modes and vertical resonances.

References

1. H. Rather, *Surface Plasmons* (Springer-Verlag, 1988).
2. F. J. Garcia-Vidal, L. Martin-Moreno, T. W. Ebbesen, L. Kuipers, “Light passing through subwavelength apertures,” Rev. Mod. Phys. **82**, 729-282 (2010).
3. A. Mary, Sergio G. Rodrigo, L Martin-Moreno and F. J.Garcia-Vidal, “Plasmonic metamaterials based on holey metallic films,” J. Phys. Condens. Mat. **20** , 304215 (2008).
4. C. Fietz, Y. Urzhumov, and G. Shvets, “Complex k band diagrams of 3D metamaterials/photonic crystals,” Opt. Express, **19**, No. 20, 19027-19041 (2011).
5. J. Bravo-Abad, L. Martín-Moreno, F. J. García-Vidal, E. Hendry, and J. Gómez Rivas “Transmission of light through periodic arrays of square holes: From a metallic wire mesh to an array of tiny holes,” Phys. Rev. B **76,** 241102 (2007).