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ANALYTIC EXPRESSION FOR THE EFFECTIVE PLASMA FREQUENCY IN ONE-DIMENSIONAL METALLIC-DIELECTRIC PHOTONIC CRYSTAL

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Abstract—In this work, an analytic expression to define the effective plasma frequency of an one-dimensional periodic system containing alternating dielectric and metallic slabs is proposed. Such metallic elements are considered to have a Drude dielectric function. The effective plasma frequency is obtained as a simple average of the constitutive materials, and its cutoff frequency for the propagating modes is compared with band structure calculations. We also explore the role of absorption in the transparency frequency cutoff.

1. INTRODUCTION

Optical properties of periodically modulated metallic-dielectric structures have attracted a great deal of interest since the pioneering work of Sievenpiper et al. [1] and Pendry et al. [2] where such systems where first discussed. When light interacts with a metal, the propagation is dominated by the free electrons which behave as a plasma. Using the Drude model, it is possible to define a metallic dielectric function in the form

$$\varepsilon_m(\omega) = 1 - \frac{\omega_p^2}{(\omega^2 + i\gamma\omega)} \tag{1}$$

with $\omega_p = ne^2/\epsilon_0 m$ as the plasma frequency with a typical 10^{15} Hz value for various bulk metals. Here ϵ_0 is the free space permittivity. n is the electron density. e is the charge. m is the electron mass. γ is a damping term representing the dissipative loses in the system. If we ignore the absorption effects, above ω_p the dielectric function is positive, and the medium is transparent to light. On the

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other hand, if the frequency is below ω_p the dielectric function is negative, and the metal becomes a mirror. However, if we consider light with $\omega < \omega_p$ impinging from a dielectric medium there always exists a small amount of penetration on the metal surface called skin dept. A consequence of this penetration is a coupling that allows the existence of electromagnetic modes bounding the dielectric-metal interface. These are the surface plasmons resonances (SPRs), responsible of unique phenomena for metals [3–10].

SPRs are electromagnetic waves that propagate parallel to the dielectric-metal interface. These waves are very sensitive to the presence of any other SPRs in its vicinity. Pendry et al. [2] introduced the idea that a geometrical configuration with multiple interfaces — such as a three dimensional array of thin metallic wires — is able to support collective oscillations of SPRs. The description of the composite structure and its interaction with electromagnetic waves was given in terms of a simple formula which has a great conceptual elegance because it unifies all the electromagnetic phenomena in a simple equation [2]. Ignoring absorption effects, the collective oscillations in the composite structure can be characterized in terms of an effective dielectric function of the form $\varepsilon_{eff} = 1 - \Omega_p^2/\omega^2$, where Ω_p is the effective plasma frequency. Such effective media have unusual properties difficult to find in other metalic solids. In close similitude with bulk metals, light of frequency below Ω_p is reflected because the composite medium behaves as an effective medium with negative dielectric function ($\varepsilon_{eff} < 0$), for which propagating modes can not exist. On the other hand, light of frequency above Ω_p is transmitted because the effective medium is positive ($\varepsilon_{eff} > 0$) and propagating modes are allowed. The interesting fact is that the cutoff of the propagating modes defined by Ω_p is now in the GHz regime, opening new possibilities for microwave metallo-dielectric photonic crystals (MDPC).

The derivation of an effective plasma frequency was first done for a three dimensional array of very thin metallic cylinders, and the theoretical analysis was made by considering the electromagnetic self-inductance of the wire structure as the predominant phenomena in the composite medium [2]. Recent approximations have also taken into account the spatial dispersion of the effective medium [11–14]. The effective plasma frequency for three-dimensional (3D) metallic-dielectric Photonic Crystals (3D-MDPC) have been experimentally verified in a number of works [15–17].

For two-dimensional (2D) geometries there is no unified theoretical approach to deal with this problem, and a number of alternative analytical attempts have been tried to deal with the determination of the effective plasma [2, 11–14, 18, 19]. However, these results are still controversial. For a recent review see the works by Brand et al. [18] and Markos et al. [13]. From the experimental side, the existence of the plasma frequency in 2D-MDPC is well documented [17, 20–23].

In the case of the one-dimensional (1D) MDPC the effective plasma frequency has been much less studied. There are several reports where the transparency cutoff of a 1D-MDPC has been calculated or measured [24–27]. To the author's knowledge, only one work by Xu et al. [28] exists, where an explicit formula for the effective plasma frequency has been given. Xu and co-workers have reported three erroneous conclusions about the effective plasma frequency. First, these authors consider that the plasma frequency does not depend on the plasma frequency of the constituent metal. Second, in the case of low metallic filling fraction the effective plasma frequency is insensitive to the thickness of the metallic layer. Third, the effective plasma frequency is inversely proportional to thickness of the dielectric layer.

In this work, we have three objectives. First, to present an alternative way to Ref. [28] to determine the effective plasma frequency and the conditions that define the transparency in an 1D-MDPC. Second, to show that different from 2D-MDPC, in 1D-MDPC the cutoff frequency that defines the transparency condition is not related to sophisticated phenomena such as the induction of magnetic fields or the enhancement of the effective electron mass [2]. Third, to explore the role of absorption in the transparency cutoff frequency.

2. THEORY

We begin the analysis by considering an 1D-MDPC as shown in Fig. 1, panel (a). The unit cell is composed by two slabs of metallic and dielectric materials of dielectric functions $\varepsilon_m(\omega)$ and ε_d, respectively. The width of the unit cell is $d = d_m + d_d$, where the metallic and dielectric layers are d_m and d_d, respectively. In the unit cell, the position dependent dielectric function can be written as

$$\varepsilon(x, \omega) = \varepsilon_m(\omega) + [\varepsilon_d - \varepsilon_m(\omega)]\Theta(x - d_m) \tag{2}$$

where we have used the Heaviside function which is $\Theta(x) = 1$ if $x \geq 1$ and $\Theta(x) = 0$ if $x < 0$. The dielectric function is periodic in $x-$axis and can be expanded in Fourier series in the form

$$\varepsilon(x, \omega) = \sum_G \varepsilon(G)e^{iGx} = \varepsilon(0) + \sum_{G'} \varepsilon(G')e^{iG'x} \tag{3}$$

Here $G = 2\pi n/d$ is the reciprocal lattice vector, and n is an integer number. The primes indicate that the terms with $G = 0$ are excluded

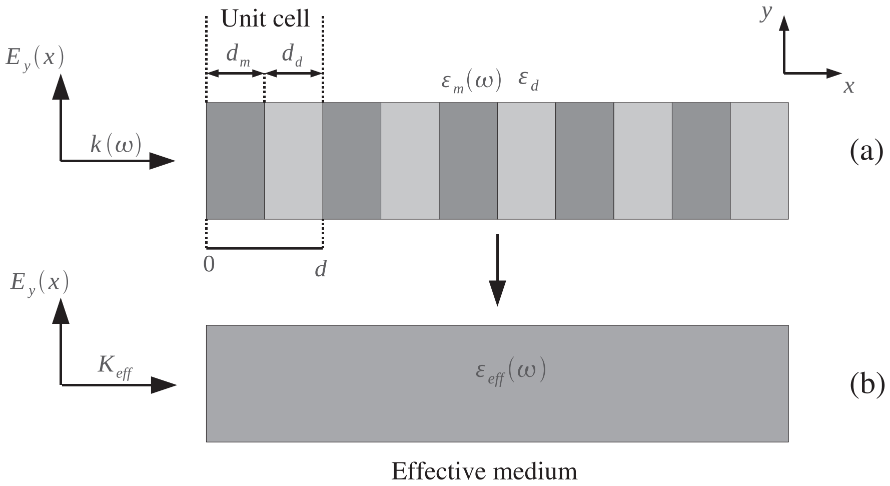

Figure 1. In panel (a), schematic of a metallic-dielectric one-dimensional photonic crystal where is illustrated the unit cell. In panel (b), the corresponding effective medium. In both panels we present the direction of the electric field and the wave vector.

from the sum. The Fourier coefficients $\varepsilon(G)$ can be found integrated in the unit cell

$$\varepsilon(G) = \frac{1}{d}\int_0^d \varepsilon(x)e^{-iGx}dx \tag{4}$$

The result of this integral is

$$\varepsilon(G) = \varepsilon(0)\delta_{G,0} + \varepsilon(G)(1-\delta_{G,0}) \tag{5}$$

The Fourier coefficient for $G = 0$ is

$$\varepsilon(0) = f\varepsilon_m(\omega) + (1-f)\varepsilon_d \tag{6}$$

where we have taken $f = d_m/d$. The Fourier coefficient for $G \neq 0$ is

$$\varepsilon(G) = \frac{\varepsilon_m(\omega) - \varepsilon_d}{iGd}(1 - e^{-iGd_m}) \tag{7}$$

The effective index can be taken as the average over the unit cell in the form [29]

$$\varepsilon_{\mathit{eff}}(\omega) =< \varepsilon(x,\omega) >= \int dx' f(x')\varepsilon(x-x',\omega) \tag{8}$$

If we consider the simplest case where $f(x') = 1/d$ we obtain

$$\varepsilon_{\mathit{eff}}(\omega) = \varepsilon(0) + \frac{1}{d}\sum_{G'}\varepsilon(G')\int_0^d e^{iG'(x-x')}dx' \tag{9}$$

The integral of the second term is zero, then we only retain the term with $G = 0$

$$\varepsilon_{eff}(\omega) = f\varepsilon_m(\omega) + (1 - f)\varepsilon_d \tag{10}$$

Considering the metallic dielectric function in Eq. (1) we can write

$$\varepsilon_{eff}(\omega) = \varepsilon_0 - \frac{\Omega_p^2}{\omega^2 + i\gamma\omega} \tag{11}$$

where $\varepsilon_0 = \varepsilon_d + f(1 - \varepsilon_d)$ is an static dielectric constant for the composite structure. The effective plasma frequency is defined by

$$\Omega_p(f) = \sqrt{f}\omega_p \tag{12}$$

This result indicates that the effective plasma frequency is proportional to the metallic plasma frequency times the square root of the filling fraction.

Now we consider Fig. 1(b) where we illustrate how the metallic-dielectric composite can be switched into an effective medium. The wave equation for the electric field of the effective medium is

$$\frac{\partial^2}{\partial x^2}E_y(x) = -\frac{\omega^2}{c^2}\varepsilon_{eff}(\omega)E_y(x) \tag{13}$$

The solution of this equation is

$$E_y(x) = E_{y,0}^{+}e^{+iK_{eff}(\omega)x} + E_{y,0}^{-}e^{-iK_{eff}(\omega)x} \tag{14}$$

where we have defined

$$K_{eff}(\omega) = \sqrt{\varepsilon_{eff}(\omega)}\frac{\omega}{c} \tag{15}$$

Let us consider the case without absorption in Eq. (11) taking $\gamma = 0$. Propagating modes are possible in the effective medium when $\varepsilon_{eff}(\omega) > 0$, and therefore the multilayer medium is transparent. Conversely, evanescent modes exist when $\varepsilon_{eff}(\omega) < 0$ and the composite media block the impinging light. These restrictions allow to write a cutoff frequency for the propagating modes in the form

$$\omega_{cut}(f) = \frac{\Omega_p}{\sqrt{\varepsilon_0}} = \frac{\sqrt{f}\omega_p}{\sqrt{\varepsilon_d + f(1 - \varepsilon_d)}} \tag{16}$$

This equation defines, in a simple way, the conditions where the composite medium becomes transparent. This is the main result of this work. With this equation we are proposing — different from Ref. [28] — that the transparency can be determined as function of the structural parameters of the composite medium, such as the filling fraction (f), metallic plasma frequency (ω_p) and dielectric function of the dielectric medium (ε_d).

In [28], Xu et al. have reported an analytical expression for the effective dielectric function as follows

$$\tilde{\varepsilon}_{eff}(\omega) = \tilde{\varepsilon}_0 \left(1 - \frac{\tilde{\Omega}_p^2}{\omega^2}\right) \tag{17}$$

where $\tilde{\varepsilon}_0$ is defined as "the effective static dielectric constant of the 1D MDPC, simply taken as the geometric mean of the static dielectric constant of the metallic and dielectric layers" [28]. The effective plasma frequency was proposed as

$$\tilde{\Omega}_p = \frac{\pi c}{n_d d_d} \tag{18}$$

where $n_d = \sqrt{\varepsilon_d}$ and d_d are the refractive index and the thickness of the dielectric layer, respectively. However, it is easy to see that Eq. (18) is not a good approximation for the effective plasma frequency. For example, it fails in the limit of the homogeneous bulk metal where it is expected that $\Omega_p = \omega_p$. In Eq. (18), the limit where the dielectric layer goes to zero is

$$\lim_{d_d \to 0} \tilde{\Omega}_p = \infty \tag{19}$$

In contrast, in our Eq. (16) in the limit of the homogeneous bulk metal we have

$$\lim_{f \to 1} \Omega_p = \omega_p \tag{20}$$

In order to determine the accuracy of our cutoff frequency in Eq. (16), we calculate the photonic band structure of the composite structure using the well-known formula [30]

$$\begin{aligned} \cos[k(\omega)d] &= \cos(k_d d_d)\cos[k_m(\omega)d_m] \\ &\quad -\frac{1}{2}\left[\frac{k_d}{k_m(\omega)} + \frac{k_m(\omega)}{k_d}\right]\sin(k_d d_d)\sin[k_m(\omega)d_m] \end{aligned} \tag{21}$$

Here $k(\omega)$ is the Bloch wave vector. $k_d = \sqrt{\varepsilon_d}\omega/c$ and $k_m(\omega) = \sqrt{\varepsilon_m(\omega)}\omega/c$ are the wave vector for the dielectric and metallic medium, respectively.

3. THE CASE WITHOUT ABSORPTION

Let us start by presenting the case without absorption, $\gamma = 0$ in the metallic component of Eq. (1). For simplicity, we consider that the dielectric medium is vacuum, $\varepsilon_d = 1$. The effective plasma frequency of Eq. (11) is reduced to the expression

$$\varepsilon_{eff}(\omega) = 1 - f\frac{\omega_p^2}{\omega^2} \tag{22}$$

In Fig. 2, we present the effective plasma frequency for three values of the filling fraction. From right to left, we present the cases of filling fraction $f = 0.95$, $f = 0.5$ and $f = 0.05$ with blue, green and red lines, respectively. We observe that the effective dielectric function shifts to lower frequencies as the filling fraction decreases. The cutoff is the point where $\varepsilon_{\mathit{eff}}(\omega) = 0$. We observe how the cutoff also shifts to lower frequencies as the filling fraction decreases.

In Fig. 3, we present the dispersion relation of a 1D-MDPC with a period of $d = 0.5(2\pi c/\omega_p)$. The wave vectors $k(\omega)$ and K_{eff} of Eqs. (20) and (15) are presented with solid and dashed lines, respectively. In both panels the cases of filling fraction $f = 0.95$, $f = 0.5$ and $f = 0.05$ are plotted with blue, green and red lines. We present in panels (a) and (b) the real and imaginary parts of the wave vector. We observe in panel (a) that $k(\omega)$ is limited to the First Brillouin Zone (FBZ). In change, K_{eff} extends beyond the FBZ. We observe that in both panels, the cases of $f = 0.95$ and $f = 0.05$, the dispersion relations are similar. Conversely, for the case of $f = 0.5$ the dispersion relation presents a slight difference. Transparency exists in 1D-MDPC where the real part of the wave vector is positive or in an equivalent manner, when zero component of the imaginary part of the wave vector exists.

In order to determine the variation of the transparency as a function of the filling fraction we consider the cutoff condition of

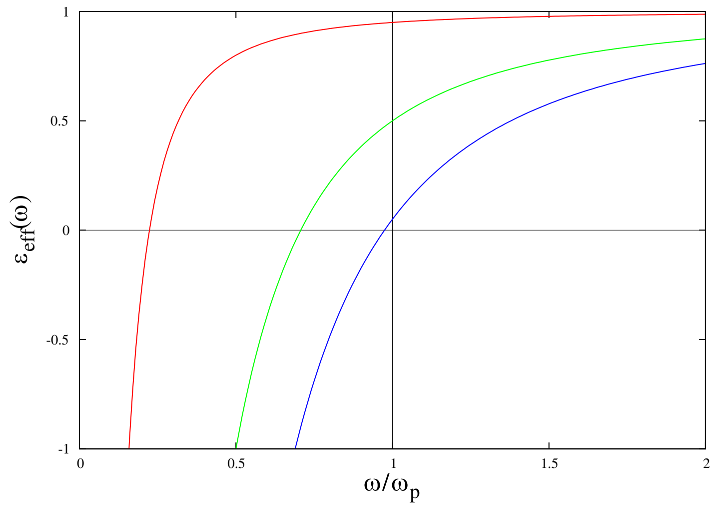

Figure 2. Effective dielectric function as a function of the frequency. We plot three cases of filling fraction, $f = 0.95$, $f = 0.5$, and $f = 0.05$ with blue, green and red colors, respectively.

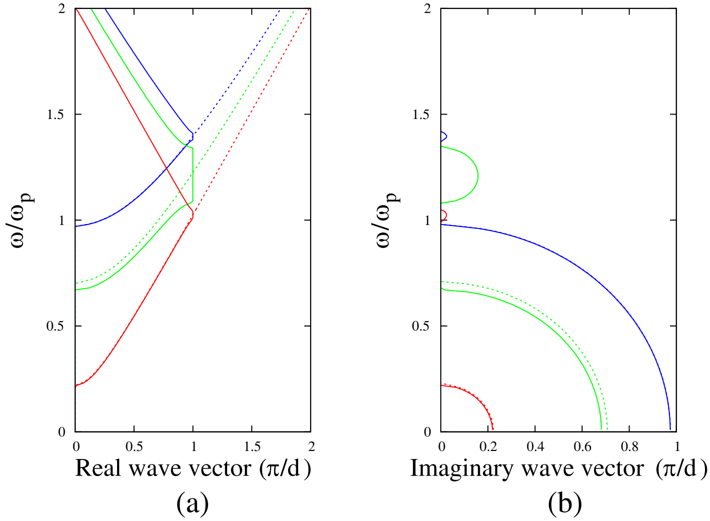

Figure 3. Relation dispersion for a 1D-MDPC of period $d = 0.5(2\pi c/\omega_p)$. The wave vectors $k(\omega)$ and K_{eff} are presented with solid and dashed lines, respectively. In panels (a) and (b) we have the real and imaginary parts of the wave vector. In both panels the cases of filling fraction $f = 0.95$, $f = 0.5$, and $f = 0.05$ are plotted with blue, green and red lines, respectively.

Eq. (16) in the case $\varepsilon_d = 1$,

$$\omega_{cut}(f) = \sqrt{f}\omega_p \tag{23}$$

In Fig. 4, this cutoff frequency is plotted with black line. As comparison, we present the condition of propagating modes where the real wave vectors become positive, $\Re[K_{\mathit{eff}}(\omega)] > 0$ and $\Re[k(\omega)] > 0$, using gray and orange lines, respectively. We observe that for low ($f < 0.1$) and high ($f > 0.9$) filling fraction the three cutoff conditions agree well. In the regime of $0.5 < f < 0.9$ the cutoff frequency defined by $\Re[k(\omega)] > 0$ has a lower value than the $\omega_{cut}(f)$ and the condition $\Re[K_{\mathit{eff}}] > 0$. The disagreement becomes more pronounced at the filling fraction $f = 0.5$.

In Eq. (21) it is established that $\Re[k(\omega)] > 0$ is a function of the variation of the magnitude of lattice period d. In contrast, $\Re[K_{\mathit{eff}}]$ and $\omega_{cut}(f)$ defined in Eqs. (15) and (16) are invariant for any d. In order to sketch the cutoff dependence on the condition $\Re[k(\omega)] > 0$ we consider a 1D-MDPC with a filling fraction of $f = 0.5$. We consider a variation of the lattice period in the form $d = \alpha(2\pi c/\omega_p)$, where α takes values between the interval $[0 : 2]$. In Fig. 5, we present the variation of

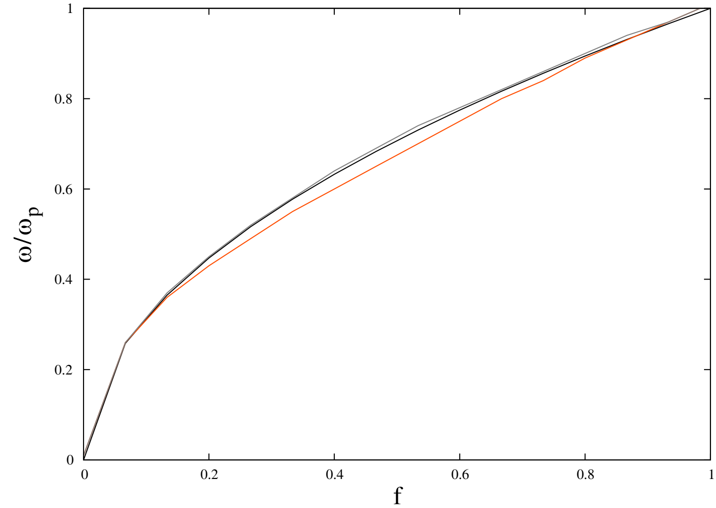

Figure 4. Variation of the cutoff frequency as a function of the filling fraction, f. $\omega_{cut}(f)$ and the conditions $\Re(K_{\mathit{eff}})(\omega) > 0$ and $\Re[k(\omega)] > 0$ are plotted with black, gray and orange lines, respectively.

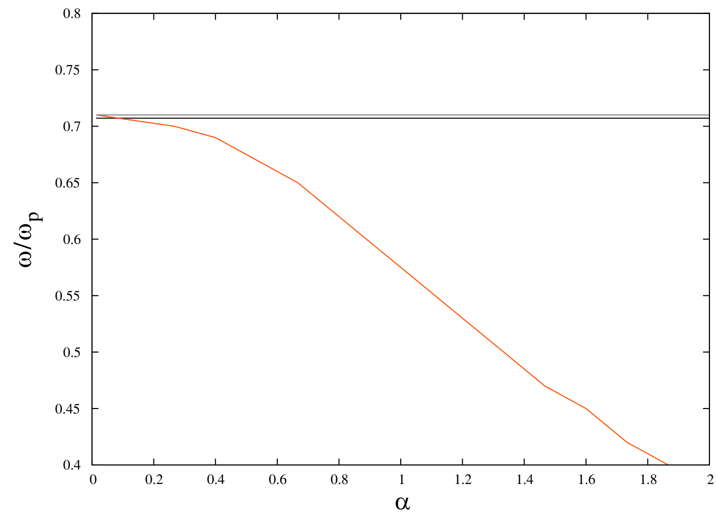

Figure 5. Variation of the cutoff condition as a function of the lattice period $d = \alpha(2\pi c/\omega_p)$ in the case of a filling fraction $f = 0.5$. The cases of $\omega_{cut}(f)$, $\Re[K_{\mathit{eff}}] > 0$ and $\Re[k(\omega)] > 0$ are presented with black, gray and orange lines, respectively.

$\Re[k(\omega)] > 0$ with an orange line. We also plot the conditions $\omega_{cut}(f)$ and $\Re[K_{eff}] > 0$ with black and gray lines, respectively. We find that better agreement among the three cutoff conditions is for the cases when $\alpha < 0.2$.

4. THE CASE WITH ABSORPTION

Now we consider the case with absorption, where $\gamma \neq 0$. For simplicity, here we also consider that the dielectric function is the air, $\varepsilon_d = 1$. The effective plasma frequency in this case is

$$\varepsilon_{eff}(\omega) = 1 - f\frac{\omega_p^2}{\omega^2 + i\gamma\omega} \tag{24}$$

We present in Fig. 6 the complex effective dielectric function as a function of the frequency for a lossless parameter of $\gamma = 0.1\omega_p$. The real and imaginary parts are plotted with solid and dashed lines, respectively. We present the cases of filling fraction $f = 0.95$, $f = 0.5$ and $f = 0.05$ with blue, green and red lines.

In the presence of absorption, the effective dielectric function is a complex number, thus is not possible to define a simple analytical

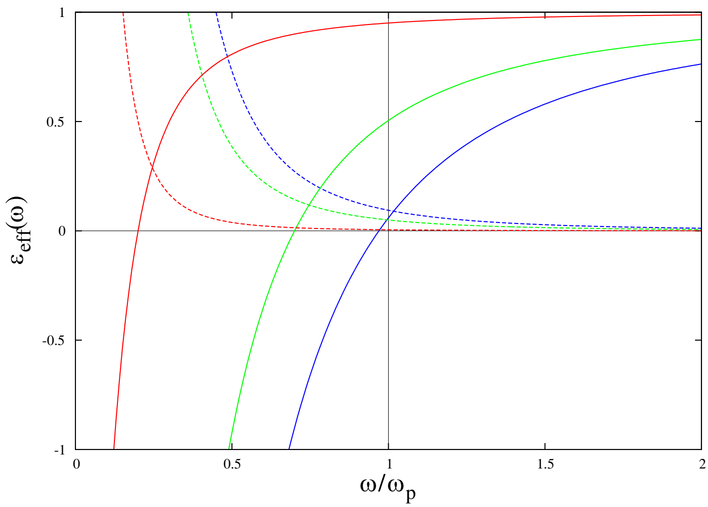

Figure 6. Effective dielectric function in presence of absorption. We consider that the lossless parameter is $\gamma = 0.1\omega_p$. We present the real and imaginary part of the dielectric function with solid and dashed lines. We plot three cases of filling fraction, $f = 0.95$, $f = 0.5$, and $f = 0.05$ with blue, green and red colors, respectively.

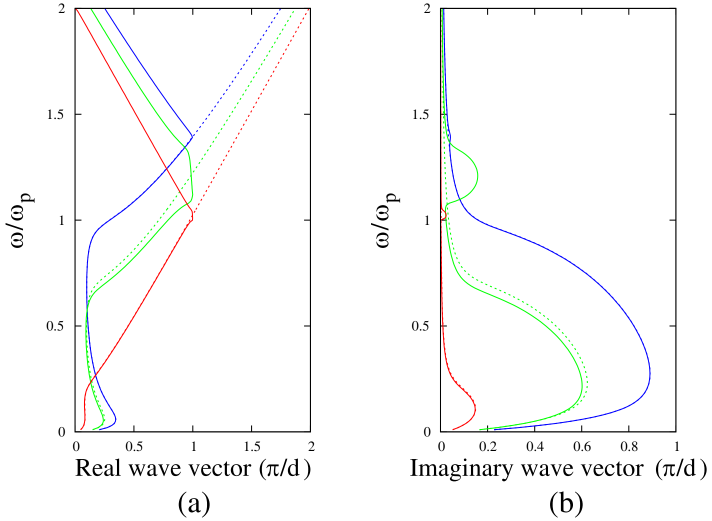

Figure 7. Relation dispersion for a 1D-MDPC of period $d = 0.5(2\pi c/\omega_p)$ in presence of absorption, $\gamma = 0.1\omega_p$.

condition to determine the propagating modes, as we have done in Eq. (16) for the case without absorption

In order to illustrate the complex propagation in 1D-MDPC in the presence of absorption, we present in Fig. 7 the complex dispersion relation for the case of a period $d = 0.5(2\pi c/\omega_p)$ taking an absorption of $\gamma = 0.1\omega_p$. The wave vectors $k(\omega)$ and K_{eff} are presented with solid and dashed lines, respectively. In panels (a) and (b) we have the real and imaginary parts of the wave vector. In both panels the cases of filling fraction $f = 0.95$, $f = 0.5$ and $f = 0.05$ are plotted with blue, green and red lines.

We conclude that in the presence of absorption, it is not possible to define an analytical expression for the cutoff to predict the transparency in 1D-MDPC. However, it is possible to define some numerical restriction for the imaginary part of the wave vector, such as $\Im(K_{\mathit{eff}}(\omega)) < 0.01$ in a similar manner as recently proposed by Bergmair et al. [31]. Nevertheless, this procedure does not allow to define an analytical cutoff frequency for the transparency region in the case with absorption.

5. CONCLUSION

In conclusion, in the case of absence of absorption we have given an analytical expression to define the cutoff frequency for the propagating modes. We have found that the transparency condition is a function of the filling fraction and the dielectric functions of the dielectric and metallic component. We have also explored the conditions of filling fraction and lattice period where our formula is suitable.

In the case of presence of absorption, we have found that it is not possible to define a simple analytical rule to determine the cutoff frequency.

We have demonstrate that different from the case of 2D-MDPC, the transparency condition in 1D-MDPC is a function of the constitutive parameters of the composite medium. We expect that these results may be of help to have a deeper understanding of the physical properties of metalo-dielectric photonic crystals.

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