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We investigate numerically the properties of metallo-dielectric, one-dimensional, photonic band-gap structures. Our theory predicts that interference effects give rise to a new transparent metallic structure that permits the transmission of light over a tunable range of frequencies, for example, the ultraviolet, the visible, or the infrared wavelength range. The structure can be designed to block ultraviolet light, transmit in the visible range, and reflect all other electromagnetic waves of lower frequencies, from infrared to microwaves and beyond. The transparent metallic structure is composed of a stack of alternating layers of a metal and a dielectric material, such that the complex index of refraction alternates between a high and a low value. The structure remains transparent even if the total amount of metal is increased to hundreds of skin depths in net thickness. © *1998 American Institute of Physics.* [S0021-8979(98)02205-1]

I. INTRODUCTION

In recent years, advances in photonics technology have generated a trend toward the integration of electronic and photonic devices. Photonic devices offer an array of advantages over conventional electronic devices. For example, they can provide enhanced speed of operation, reduced size, robustness to temperature fluctuations and other environmental changes, increased lifetime, and the ability to handle high repetition rates. These structures can be made of semiconductor materials, ordinary dielectrics, or a combination of semiconductors and dielectrics materials.

The intense theoretical and experimental investigations of these structures in recent years, of photonic band-gap (PBG) structures in particular,[1–5] is evidence of the widely recognized potential that these new materials offer. In this regard, we cite the cases of the photonic band-edge nonlinear optical limiter and switch,[6] the nonlinear optical diode,[7] a high-gain, second-harmonic generation device,[8] and the band-edge delay line.[9] These optical devices, whose operating principles are based entirely on the physics of the photonic band edge, are all extremely compact in nature (only a few microns in length). Many of these devices have electronic analogs. The optical limiter, for example, allows the propagation of a low intensity beam of light, while it reflects a high intensity beam. When used in combination with a second reference beam, it has been shown that the limiter can operate as an optical transistor or switch.[6] In the case of the optical diode, a beam can either be reflected or transmitted through a device depending on the direction of approach: right propagating waves may be reflected, while a left propagating signal may be transmitted.[7] The second harmonic generator utilizes band-edge and nonlinear effects to provide the phase matching needed for efficient frequency up-conversion.[8] On the other hand, the delay line relies on linear interference effects at the band edge in order to drastically reduce by orders of magnitude, and control by electro-optic or mechanical means, the group velocity of short pulses with respect to free space or bulk medium.[9]

For simplicity, substances are usually characterized by the degree to which they conduct electricity. Hence a distinction is made between good conductors (such as metals), insulators (such as glasses), and semiconductors (such as gallium arsenide). Under the right conditions, semiconductors may display properties common to both metals and insulators. The propagation of light inside these substances strongly depends on their conductive properties: metals are highly reflective, as well as absorptive, at nearly all light frequencies of interest, from long radio waves to short-wavelength ultraviolet light; some dielectric materials may be transparent across the visible spectrum (a slab of window glass, for example).

For this reason, metals are routinely used for radiation shielding purposes, as in microwave oven cavities, or for their reflective properties, as in ordinary household mirrors. On the other hand, dielectric or semiconductor materials are used in integrated-circuit environments, in waveguides, and directional couplers, for example, because they allow the unimpeded propagation of light beams with minimal losses. Therefore, it would be highly desirable, under certain cir-

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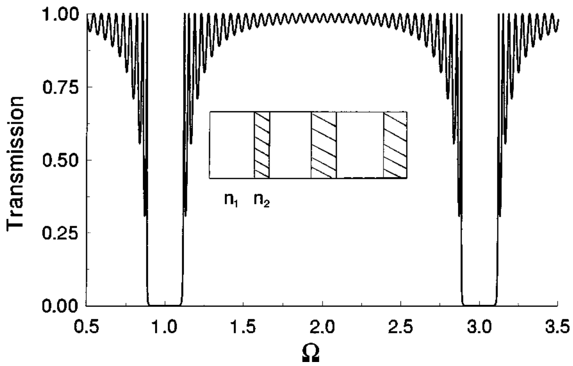

FIG. 1. Transmittance vs frequency for the generic PBG structure shown in the inset. Here, we show a series of transmission resonances, where the transmission is nearly unity, and two band gaps, where the transmission is nearly zero. These resonances and gaps repeat at higher frequencies ad infinitum. From a practical point of view, only the first few resonances and gaps are important. Inset: Truncated, three-period, generic PBG structure. The indices of refraction are n_1 and n_2 for each consecutive layer, with respective widths a and b. Each period is formed by the combination of two consecutive layers, and has width $d=a+b$.

cumstances, to have access to a substance which may act as a shield for a certain range of frequencies such as microwaves, and yet for it to be transparent in the visible portion of the spectrum, i.e., a transparent metallic structure.

In this article we discuss a new transparent metallic structure such that it will have the properties of transparent glass in the visible portion of the spectrum, and yet be opaque for all longer wavelengths, or smaller frequencies, from infrared light to radio waves. This can be achieved with the utilization of a photonic band-gap structure.

II. GENERIC PHOTONIC BAND-GAP STRUCTURES

In one dimension, a photonic band-gap material is usually composed of alternating high and low index layers. We schematically depict the structure just described in the inset of Fig. 1. Each layer can be chosen such that its width is a fraction of the size of a reference wavelength, usually one quarter of the reference wavelength. This forms a quarter-wave stack. As a consequence of this arrangement of the dielectric layers, interference effects cause some wavelengths to be transmitted, while a range of wavelengths centered about the reference wavelength, often referred to as ''band-gap'' wavelengths, are completely reflected. Typical transmissive properties of the structure are depicted in Fig. 1, where we show a plot of the transmission of light as a function of wavelength from a quarter-wave stack composed of 20 periods, or 40 alternating high and low index layers. A transmission of unity corresponds to 100% of the signal being transmitted. For illustrative purposes, we have chosen two dielectric materials: a glass, with an index $n_2=1.41$, and air, with an index $n_1=1$.

Thus, a range of wavelengths about some reference wavelength cannot propagate inside this device. On the other hand, the structure may be transparent to other wavelengths, above and below the gap. It is the absence of those wavelengths from the transmitted spectrum that gives rise to the name ''band gap,'' in analogy to the electronic band gap of semiconductors, where electrons having a specific range of energies cannot propagate inside a semiconductor crystal.

At wavelengths outside the photonic band gap, in a range above and below the gap, the properties of the structures are such that a series of transmission resonances and gaps are obtained, as depicted in Fig. 1. The number of such resonances is equal to the number of periods that make up the structure.[10] The width of the resonances and gaps is a sensitive function of the total number of periods, the indices n_1 and n_2, and their difference $\delta n=|n_2-n_1|$, sometime referred to as index modulation depth.

Typically, the materials used in the fabrication of PBG structures are either dielectric or semiconductor substances, due to their low absorption characteristics. The choice of materials is most often dictated by a specific need, material properties, or by available fabrication techniques. The overriding concern is, however, that the materials used should not absorb light to any significant extent, so as not to compromise device operation. For this reason, metallic substances are almost exclusively used to enhance the reflective properties of dielectric or semiconductor materials by designing and incorporating within a particular device thick metallic films, such as silver, nickel, copper, aluminum, or gold.

III. METALLIC PHOTONIC BAND-GAP STRUCTURES

A. Background

A body of work on metallic PBG structures is already in existence.[11–15] However, most of that work stresses two-and three-dimensional structures in the microwave regime, where metals are present in the form of wire meshes, or micron thick metal disks that are strategically embedded inside a dielectric matrix to enhance the reflective properties of the structure in the band-gap region. Other work on one-dimensional PBG structures that include metals as at least one of the material components features calculations that show that the reflectivity of metallic structures can be enhanced with respect to bulk if the metal is arranged to form a periodic structure.[16] In Ref. 16, for example, a 256-period aluminum and air structure was designed so that the reflection from such a structure increased when compared to bulk aluminum from 96% to approximately 98% for a narrow frequency range. Each metal film was assumed to be approximately 2.5 nm in thickness, less than the skin depth. Even if a 256-period structure could be realized with aluminum or other metals, such a structure would be opaque to electromagnetic waves of all wavelengths, as calculations show. The traditional method to enhance the reflectivity of a metal is to grow a dielectric distributed Bragg reflector on the metal film. The combined dielectric DBR and metal film provide enhanced reflectivity with just a few periods.[17] Therefore, while it may be possible to make better mirrors by introducing and combining metals with periodic PBG structures, we attempt to answer what we believe is a fundamentally more difficult question: is it possible to propagate light through thick metal films, and render them transparent to visible light? This means focusing specifically on the transmissive properties of PBG structures where thick metal films may be a major component.

To our knowledge, no previous work addresses the possibility of rendering a layered, metallic structure transparent to visible light, while at the same time maintaining its reflective properties for low-frequency radiation, i.e., those of a metal shield. The reason for this is that it is generally thought that either an increase in thickness, or the presence of additional metal layers, can drastically reduce the transmission of visible light. In fact, in this paper we predict that the transmission at visible wavelengths does not change appreciably, and can be controlled more effectively, with a metallo-dielectric, periodic structures that has more than two metal layers. In addition to the transparency region, the reflective properties of the resulting structure are as good as those of a metal shield for very-low-frequency (VLF) and extremely-low-frequency (ELF) radiation.

B. Skin depth

As is well known, light can actually propagate a small distance δ inside a metal before it is mostly reflected. A small amount of light, on the order of 1% or less, is typically absorbed, and reappears as heat given off by the metal. This characteristic length δ depends on the wavelength of the incident light, and it is referred to as ''skin depth.'' It is arbitrarily defined as the distance at which the value of the field intensity has decreased to approximately $1/e$ of its value at the input surface of the metal.[18] It can be expressed in terms of the imaginary component of the index of refraction n_i and the frequency ω, or wavelength λ, as follows: $\delta = c/2n_i\omega = \lambda/4\pi n_i$, where c is the speed of light in vacuum. For example, consider silver metal. Taking $\lambda = 5\times10^{-7}$ m, then $n_i = 3$ (Ref. 19); consequently, δ is approximately 10 nm. On the other hand, n_i is of order 10^4 for centimeter, microwave wavelengths; the skin depth is then on the order of microns. This implies that externally incident waves will propagate approximately these respective distances inside the metal, depending on the incident wavelength, before being reflected, for the most part.

A metal film whose thickness is in excess of 10 or 15 nm is usually considered a thick film for visible light, and extremely thin for microwave radiation and radio waves. Both the real and the imaginary components of the index of refraction of a good metal have magnitudes of order 10^4 for GHz, centimeter radiation. At GHz frequencies, the wavelength inside the metal is $\lambda = \lambda_0/n = 10^{-6}$. Then, the optical path of our 10-nm-thick film is 10^{-4} m, or about 100 λ, i.e., it is a bulk material for all intents and purposes. This provides a nearly insurmountable potential barrier to the incoming microwave field. Therefore, a 10 nm silver film is completely opaque to microwave radiation, as a simple calculation will show.

The skin depth δ that we have described above is a useful concept, as long as light is incident on uniform, thick, highly reflective, metal films. However, we find that the concept of skin depth looses its meaning in the case of a periodic structure, where the presence of closely spaced boundaries, i.e., spatial discontinuities of the index of refraction, alters the physical properties of the structure as a whole. Some of these properties include modification of (a) the effective group velocity near the band edge, (b) transmission and reflection coefficients, and more importantly, (c) the suppression of absorption as the field propagates inside the metal.

C. Layered metallic structures

The layered, metallic PBG structures that we discuss are typically composed of a metal; such as gold, silver, or copper; and a dielectric or semiconductor material. We presently use the metal silver and the glass magnesium fluoride, as an example to illustrate our device and its operation.

Each metal layer may be as thin as 10 nm (or thinner, as long as the properties of the layer are smooth and uniform throughout). The total net thickness of Ag across each structure may be hundreds of skin depths in length. As we will see below, the thickness of the MgF_2 layers can also vary. For the moment, we focus our attention on the transmissive properties of a structure composed of several alternating Ag and MgF_2 layers deposited on a glass substrate. Our calculations were performed using the matrix transfer method,[20] and the beam propagation method.[21] We calculated the transmissive properties of such a structure as a function of a number of parameters that included the incident wavelength or frequency, the number of layers, and layer thickness. We used the data for the refractive index and the absorption of these materials, as measured and reported in the book by Palik.[19] We modeled the substrate with a type of glass whose index of refraction is approximately 1.5 for a wide range of incident wavelengths. The purpose of the substrate is, in general, to hold the material components in place, and its exact physical properties may also vary.

D. Examples

As a first example, we consider a single Ag layer 40 nm in thickness suspended in air. We show the sample in the inset (a) of Fig. 2. Our calculations show that this sample transmits 2.5% of the incident red light, 8% of green light, and about 15% of blue light (Fig. 2, dotted line). Thus, this film is fairly opaque to visible light. However, if we now imagine we could slice the original 40 nm film into four films each about 10 nm in thickness, and space each Ag layer with approximately 110 nm of MgF_2 [Fig. 2, inset (b)] then the total transmission of visible light increases to an average of 70% (Fig. 2, solid line).

As another example, a silver film 200 nm in thickness [Fig. 3, inset (a)] is completely opaque to nearly all frequencies. We calculate that only 10^{-7} of the incident visible light will be transmitted. (Fig. 3, dotted line). On the other hand, if we once again slice the original Ag film into 20 layers of Silver, each about 10 nm thick, and place a thickness of about 140 nm of MgF_2 as the intervening medium between the silver layers [Fig. 3, inset (b)], then the average transmission in the visible range of frequencies increases to about 35% (Fig. 3, solid line), or about seven orders of magnitude better transmission than for the single 200 nm silver film case. At the same time, the periodicity of the structure also ensures better suppression of the transmitted light at longer wavelengths, and also for part of the ultraviolet frequency range.

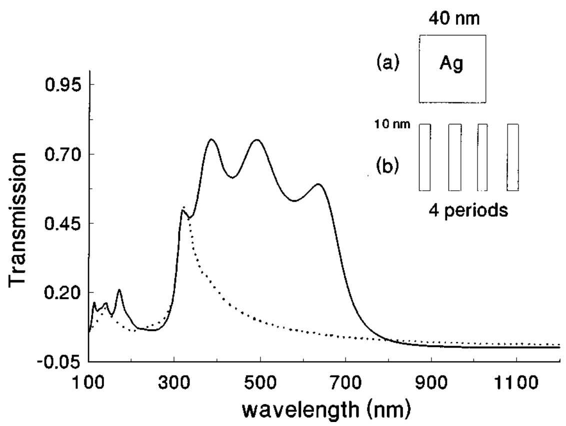

FIG. 2. Transmission vs wavelength for a four-period PBG sample (solid line) and a solid silver film 40 nm thick (dotted line). Silver layers are 10 nm thick, while the MgF_2 layers are 110 nm thick. Inset: (a) bulk and (b) PBG samples.

Generally, adding more Ag and MgF_2 periods to the structure causes a decrease in the transmitted light intensity. For example, although we do not show this, our calculations suggest that a 40-period Ag and MgF_2 structure, where each silver layer is 10 nm in thickness, and each MgF_2 layer is approximately 200 nm thick, causes the average transmission in the visible range to decrease to approximately 10%. At the same time, the transmission at all longer wavelengths, beginning in the near infrared at about 800 nm, is well below 10^{-20} for this example. This is an extremely high degree of isolation, with essentially zero transmission.

Our calculations also suggest that decreasing the number of periods and increasing metal layer thickness leads to much the same results. Therefore, in the examples that follow, we will use structures that contain three periods, but where the thickness of each metal layer is approximately 30 nm. As we have illustrated in Fig. 2, this is considered a thick metal film at visible wavelengths; ordinarily, it would be considered counterintuitive to add more, and perhaps thicker metal layers in order to improve the transmissive properties of the structure.

In Fig. 4, we show a structure composed of a glass substrate, and a three-period, Ag and MgF_2 metallic PBG structure [Fig. 4(a)]. We compare the properties of this structure with those of a single thick metallic film that contains the same amount of silver on the same substrate [Fig. 4(b)]. Each silver layer in Fig. 4(a) is taken to be 30 nm thick. MgF_2 layers are about 140 nm thick. In Fig. 5, we show the results of the calculated transmission of light as a function of incident wavelength for the two structures shown in Fig. 4. We note that the transmission from the solid metal film (dotted line) is approximately 10^{-3} in the visible range of wavelengths. On the other hand, the maximum transmission through the periodic structure is nearly 50% of the incident radiation, or four order of magnitude greater compared to the solid metal film, with a peak in the green, around 520 nm. This transmissive range extends over a good portion of the visible range. As in Figs. 2 and 3, a transmission resonance also appears at about 320 nm, in the ultraviolet frequency range. This transparency is not due to the periodicity of the

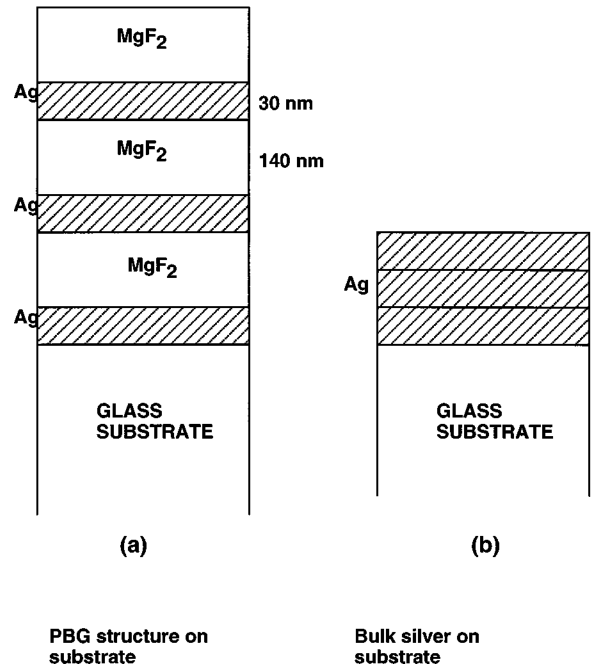

FIG. 4. Schematic representation of (a) three-period PBG and (b) 90-nm-thick silver film on substrate.

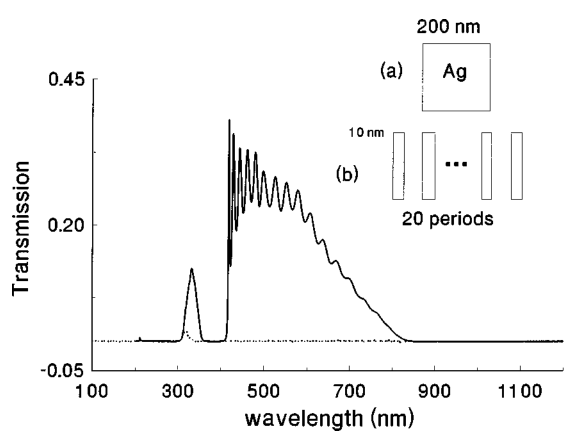

FIG. 3. Same as Fig. 2, except that for the PBG sample MgF_2 layers are 140 nm thick, and the solid silver film is 200 nm thick.

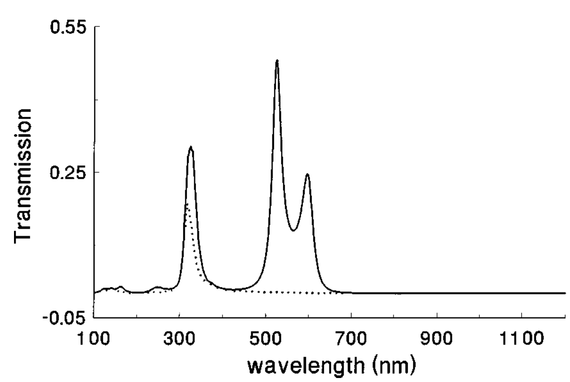

FIG. 5. Transmission vs wavelength for a Ag/MgF_2 PBG (solid line) and the continuous silver film (dotted line) shown schematically in Fig. 4.

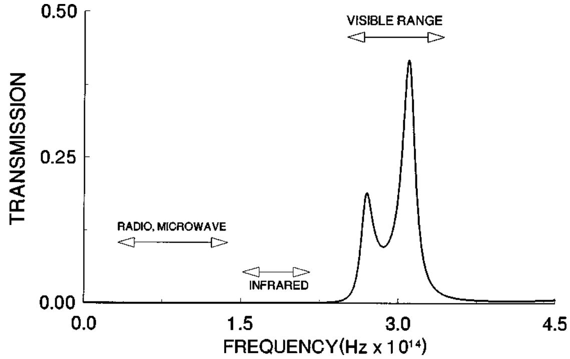

FIG. 6. Drude model calculation of transmission vs frequency. Theory predicts a transparency region at visible wavelengths, a band gap at ultraviolet frequencies, and nearly complete rejection of all lower frequencies, including infrared, microwave, and radio waves.

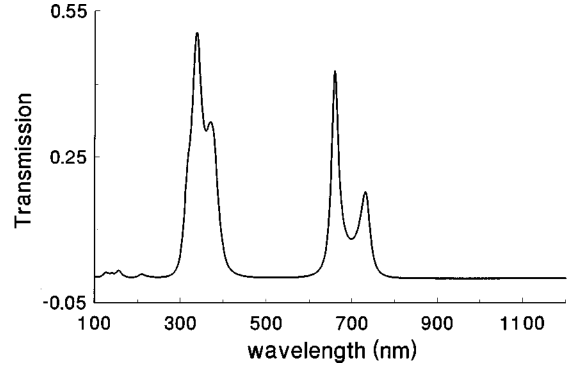

FIG. 7. Same as Fig. 5, but the magnesium fluoride layers are 200 nm thick.

structure, since it can be identified for both samples shown in Fig. 4. It is an intrinsic property of silver, which becomes slightly transparent at the plasma frequency, in the ultraviolet range, provided metal films are not too thick.

E. The drude model and the low-frequency limit

We would now like to extend our predictions to include low frequency, GHz radiation. This part of the spectrum is routinely used for communication purposes. The available data for most ordinary metals extends from the mid- to far-infrared frequency range, i.e., 1–30 μm. Therefore, we use the Drude model[18] for metals in order to numerically calculate (at very low frequencies) the characteristic transmission spectra for our periodic PBG structures. The model provides a good theoretical representation of the dielectric constant (or index of refraction and absorption characteristics) for most metals, including silver, for a range of frequencies that includes low-frequency, radio waves, and high-frequency, near-ultraviolet light. The dielectric function can easily be derived, and it can be written as[16,18]

$$\epsilon(\omega)=1-[\omega_p^2/(\omega^2+i\gamma\omega)],$$

where ω_p is the plasma frequency, and γ is the damping coefficient. We choose to depict our results as a function of frequency so that it will be simple to extrapolate to zero frequency (or infinite wavelength) without ambiguity. For silver, we use $\omega_p=7.2$ eV, and $\gamma=0.05$ eV, which are typical values for metals such as copper, gold, silver, and aluminum.

In Fig. 6, we plot the transmission versus frequency for our three-period metallic PBG depicted in Fig. 4. The figure shows that the transmission of light is suppressed for all frequencies up to the visible range, where a maximum of about 50% is transmitted through the sample; this agrees well with the results of Fig. 5. Of course, the Drude model is quite simplistic in that it cannot predict the transparency region found at about 320 nm (in Fig. 5, this would occur slightly to the right of visible range, around 4×10^{14} Hz), where the silver plasma frequency occurs. We see that a band-gap characterizes a good portion of the ultraviolet frequency range, which as a result is also suppressed. More importantly, the small-frequency range depicted in Fig. 6 includes all communication frequency bands, microwave, and infrared light. The calculation also suggests that in the limit of zero frequency, i.e., ELF and VLF radiation, the transmission is suppressed down to levels better than 1 part in 10 000 of the incident values. Therefore, the results in Fig. 6 represent the theoretical realization of what we referred to as a transparent metallic structure: it is transparent in the visible range, and it acts like a good metal reflector at all lower frequencies.

We note that this particular realization of transparent metals is not unique, in that different metals and dielectric (or semiconductor) thicknesses may be used. For example, our calculations suggest that it is also possible to use a combination of two or more metals, or two or more types of dielectric or semiconductor materials within the same structure, without any significant departure from the basic characteristics that we have described. The frequency range where light is transmitted can be changed by either increasing or decreasing the thickness of the magnesium fluoride layers. Increasing (decreasing) the thickness of the dielectric material cause a shift of the band structure toward longer (shorter) wavelengths. In Fig. 7 we show an example of this: we plot the transmission from a structure similar to that of Fig. 4, except that each MgF_2 layer is now about 200 nm in thickness (see inset of Fig. 7). Note that a band gap now characterizes the visible range. By the same token, it may be possible to make better far-ultraviolet and soft x-ray reflectors by judiciously choosing the contents and the periodicity of the structure.

IV. METALLIC FABRY–PÉROT CAVITY

In order to provide some physical insight into our results, we consider the following system: two silver films 40 nm in thickness, separated by a distance L, to form a Fabry–Pérot cavity with metallic mirrors of finite thickness. We depict this simple structure in the inset of Fig. 8. We assume an incident wavelength of approximately 1000 nm, such that the index of refraction is approximately $n=0.2+7i$.[19] We let the field be incident form the left. Assuming continuous boundary conditions on the field and its derivatives, we solve for the transmission coefficient through this structure as a function of L. The calculation is equivalent to solving a double barrier problem with five regions of interest, and can easily be carried out analytically. We plot the results in Fig.

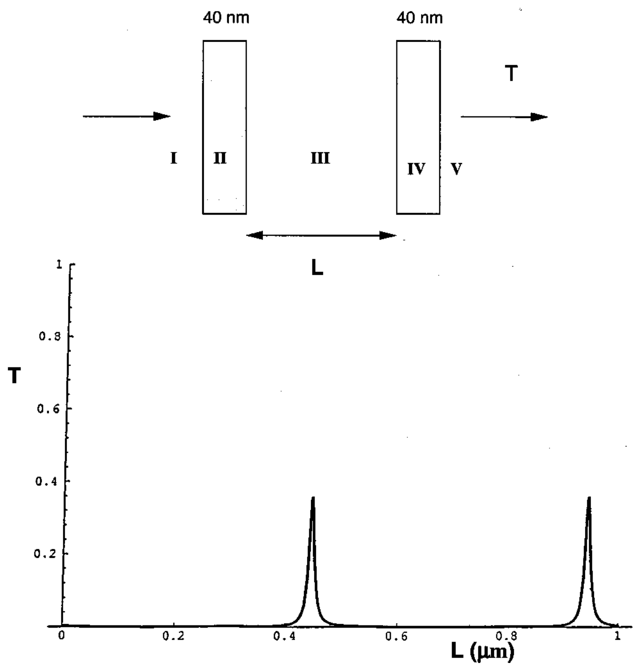

FIG. 8. Transmission coefficient vs cavity length calculated for a simple metallic Fabry–Pérot cavity having 40-nm-thick metal walls. A transmission resonance occurs when the condition $mL=2\lambda$ is approximately satisfied, as expected, where m is an integer. Adding more periods generates the band structure, with as many resonances within a pass band as there are periods. Inset: schematic representation of the structure, and the regions where we seek solutions for the wave equation.

8. The figure suggests that a transmission resonance occurs whenever film separation is almost a multiple of the $\lambda/2$, as expected. However, it is not exactly a multiple of $\lambda/2$ due to the finite thickness of the metal walls. It was surprising, however, to find that the transmission from a compound structure that contains 80 nm of silver is still a remarkable 40% of the incident value.

The effect that we observe in our simulations amounts to resonance enhanced tunneling of electromagnetic waves. The optical path of the 40 nm silver film that we consider is only approximately $10^{-3}\lambda$, where λ is the wavelength of light in silver. The introduction of a second metal layer, and hence additional boundary conditions, can create the right set of circumstances that lead to a kind of induced transparency such that the effective absorption coefficient inside the metal is also suppressed. This suggests that boundary conditions cause a significant redefinition of skin depth for metals, and as a consequence, its meaning cannot be taken at face value.

V. CONCLUSION

Finally, we simply point out that our discovery amounts to the fact that light can be transmitted through thick, periodic, metallic structures, and by controlling the thickness of the dielectric or semiconductor sandwiched between the metal films, as well as the thickness of each metal film, the transparency regions can be tuned. Just as significantly, the structure acts like a good metal reflector for all lower frequencies. In our discussion, we have highlighted the importance of boundary conditions and optical path. One cannot overstate their importance when interference effects dominate the dynamics, as in the case of a periodic, PBG structure. Even more so in the case of a metallo-dielectric PBG structures, which by virtue of their induced transparency and shielding abilities can lead to new types of devices. For example, one can envision the use of a transparent metal film device in a microwave oven door cavity, solar heat shields, laser safety goggles, sunglasses for protection from ultraviolet light, and other applications where transparent conductor oxides (such as indium tin oxide) are required to ensure good transmission of light and good conductivity at the same time.

For completeness, we point out that we have grown samples similar to those shown in Fig. 4; our preliminary experimental results, which will be fully reported elsewhere, show that the predictions we have made above are indeed correct; that is, thick metal layers can be rendered transparent by arranging them in a periodic metallo-dielectric structure.

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