LETTER TO THE EDITOR

Absorption in one-dimensional metallic–dielectric photonic crystals

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Abstract
We show theoretically that the absorption of one-dimensional metallic–dielectric photonic crystals can be enhanced considerably over the corresponding constituent metal. By properly choosing the structural and material parameters, the absorption of one-dimensional metallic–dielectric photonic crystals can be enhanced by one order of magnitude in the visible and in the near infrared regions. It is found that the absorptance of such photonic crystals increases with increasing number of periods. Rules on how to obtain a absorption enhancement in a certain frequency range are discussed.

Photonic crystals (PCs) represent a new kind of optical materials, which possess many interesting properties and render many novel applications possible as well [1–6]. The existence of photonic band gaps (PBGs) in PCs, owing to multiple Bragg scatterings, leads to many interesting phenomena: for example, the suppression of spontaneous emission [1] and photon localization [2]. Many physical properties can be modified with the presence of PBGs. It has been suggested theoretically that Planck blackbody radiation can be suppressed in the PBG regions of one-dimensional (1D) PCs [7]. Enhancement and suppression of thermal emission and absorption were reported experimentally in Si-based 3D PCs [8] and theoretically in 1D dielectric PCs [9], respectively.

Most PCs fabricated so far are made from two dielectric materials. Usually, PBGs of dielectric PCs are not large. Combinations of metallic and dielectric materials may lead to many interesting properties. The introduction of metal sheets into dielectric PCs can increase PBGs considerably [10, 11]. A theoretical study revealed that the reflection of bulk aluminium can be enhanced from 96% to approximately 98% over a narrow frequency range by inserting an air layer periodically [12]. If designed properly, 1D metallic–dielectric PCs, consisting of alternating metallic and dielectric layers, can be made transparent in the visible region [13, 14].
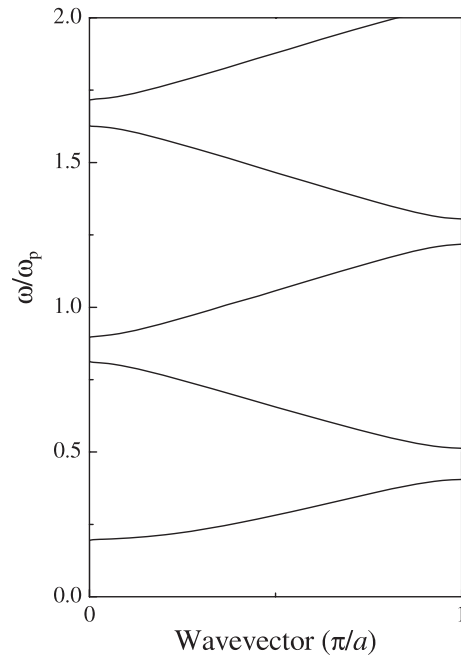
Figure 1. The photonic band structure of a 1D metallic–dielectric PC. The thicknesses of the metallic and dielectric layers are $0.5c/\omega_p$ and $5c/\omega_p$, respectively, where c is the speed of light in vacuum.

Metals are rather reflective over a wide range of frequencies. For frequencies above the visible region, there is a considerable power loss owing to absorption. Below the visible region, absorption is rather small: a few per cent in the visible and in the near infrared regions. However, we will show in the present work that the absorption of the bulk metal can be considerably enhanced by inserting a dielectric layer periodically to form 1D metallic–dielectric PCs. By a proper choice of the structural and material parameters, one can obtain a large absorption enhancement in the visible and in the infrared regions. Absorption enhancement could allow many potential applications in photothermal technology, thermophotovoltaics and blackbody emission.

The reason for the absorption enhancement lies in the peculiar photonic band structures in PCs: the existence of PBGs and photonic bands. The photonic band structure of an 1D metallic–dielectric PC is shown in figure 1. Within a PBG there are no propagating modes. Those propagating states, which can exist in a homogenous medium, should move away from PBGs to photonic bands. As a result, more states are concentrated on the frequency ranges of photonic bands with respect to the homogenous medium due to the conservation of the total number of states. If the thickness of the metallic layer in 1D metallic–dielectric PCs is close to or smaller than the relevant skin depth of the corresponding metal, some portion of electromagnetic waves can traverse this metallic layer. Since PCs are periodic structures, multiple Bragg scatterings play an important role, leading to the formation of photonic bands and PBGs in infinite PCs and to considerable transmission for frequencies within photonic bands in finite PCs. These factors can give rise to an absorption enhancement for frequencies within photonic bands.

The photonic band structure shown in figure 1 is calculated from the dispersion relation for a 1D double-layer PC (ABAB . . . stack), namely

$$\cos qa = \cos k_1 d_1 \cos k_2 d_2 - \frac{1}{2}\left(\frac{k_1}{k_2} + \frac{k_2}{k_1}\right)\sin k_1 d_1 \sin k_2 d_2, \tag{1}$$

where d_i is the thickness of the ith constituent layer, $a = d_1 + d_2$ is the lattice constant, and q is the Bloch wavevector. The local wavevector is given by $k_i = \sqrt{\varepsilon_i}\omega/c$, where ε_i is the dielectric constant of the ith layer. In the above photonic band structure calculations, the dielectric constant of the metallic layer simply takes the form of the Drude model, i.e., $\varepsilon(\omega) = 1 - \omega_p^2/\omega^2$, where ω_p is the plasma frequency. For the metallic layer, the local wavevector should be imaginary for frequencies below ω_p. Consequently, the cosine and sine functions in the dispersion relation should be replaced, respectively, by the hyperbolic cosine and sine functions for frequencies below ω_p. It can be seen from figure 1 that there are series of PBGs and photonic bands. The position of a PBG or a photonic band can be carefully designed by a proper choice of the parameters ε, d, and ω_p.

Without loss of generality, 1D metallic–dielectric PCs considered in the present work are composed of Ag and MgF$_2$ layers stacking alternately. The refractive index of MgF$_2$ is assumed to be real and frequency independent in the frequency range considered, taken to be 1.38 [15]. The measured values of refractive index [16], which is frequency-dependent, are used for Ag.

A standard transfer matrix method [17, 18] is used to study the absorptive properties of finite 1D metallic–dielectric PCs. The complex transmission and reflection coefficients t and r are related to the total 2×2 transfer matrix **M** by

$$\begin{pmatrix} t \\ 0 \end{pmatrix} = \mathbf{M}\begin{pmatrix} 1 \\ r \end{pmatrix}. \tag{2}$$

From the above relation, the complex transmission and reflection coefficients can be derived from the elements of the transfer matrix, yielding

$$t = M_{11} - M_{12}M_{21}/M_{22}, \tag{3}$$
$$r = M_{21}/M_{22}. \tag{4}$$

The associated transmittance T and reflectance R are calculated from $T = |t|^2$ and $R = |r|^2$. Finally, the absorptance A can then be obtained from

$$A = 1 - T - R. \tag{5}$$

As is known, metals are highly reflective in the visible and infrared regions. Light waves are evanescent inside metals. However, light can actually penetrate a small distance inside a metal surface, known as the skin depth. The skin depth is related to the imaginary part of the refractive index, given by $\lambda/4\pi n_i$, where n_i is the imaginary refractive index of metal and λ the wavelength of light. Using the measured refractive index [16], the derived skin depth for Ag is about 12 nm in the visible region and 13 nm in the near-infrared region. If the thickness of an Ag film is much larger than the skin depth, transmission can be neglected and most of the light is reflected. Consequently, the absorption should be very small. For example, the absorptance for an 80 nm Ag film is about 4% in the visible region and about 2% in the near-infrared region. However, if a bulk Ag film is inserted by a dielectric layer periodically to form an 1D metallic–dielectric PC, its absorption can be enhanced considerably over the bulk metal, as can be shown below.

In figure 2 the calculated absorptance of 1D metallic–dielectric PCs with different periods is shown together with that of an 80 nm Ag film. The thickness of the Ag layer in the PCs is 12 nm and that of the dielectric layer is 120 nm. This choice of thickness can render a large absorption enhancement in the visible region. For the 80 nm Ag film, the absorptance is about 4% in the visible region. The thickness of 80 nm is much larger than the skin depth of Ag in
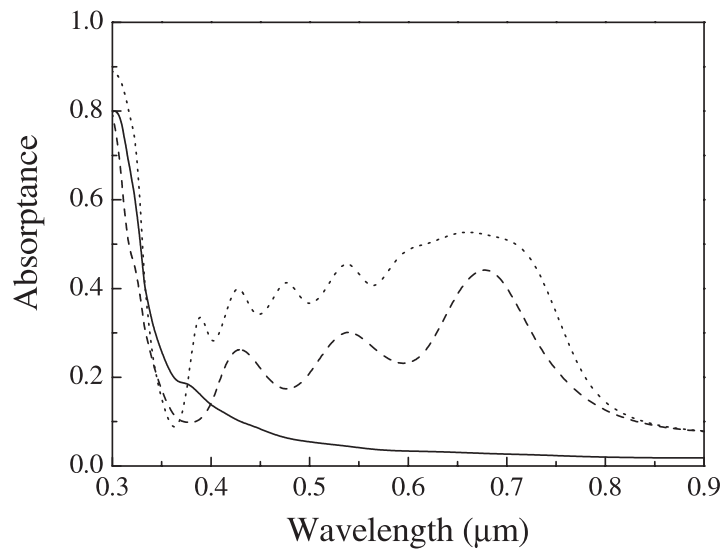
Figure 2. Calculated absorptance spectra of 1D Ag/MgF$_2$ PCs with 4 (dashed curve) and 8 periods (dotted curve). Thicknesses of Ag and MgF$_2$ layers in PCs are 12 and 120 nm, respectively. Solid curve stands for absorptance of an 80 nm Ag film.

the visible region. Therefore, the 80 nm Ag film can resemble bulk Ag. In the blue, green and yellow wavelength regions the absorptance is, on average, more than 20% for a 4-period PC and nearly 40% for an 8-period PC. In the red wavelength region the average absorptance is more than 30% for the 4-period PC and about 50% for the 8-period PC. For the 8-period PC the absorptance is higher by one order of magnitude than that of bulk Ag in the visible region. It can be seen that the absorption enhancement increases with increasing number of periods. The enhancement is larger in the red wavelength region than in the blue, green and yellow wavelength regions. Note that there exist some oscillations in the absorptance spectra of the visible region, which are due to interference.

To get an insight into the absorption enhancement, transmittance and reflectance spectra of a 4 period metallic–dielectric PC are shown in figure 3. By inspecting the corresponding photonic band structure, it is found that the frequency range of absorption enhancement corresponds just to one photonic band. As discussed earlier, for frequencies within this photonic band, strong transmission is expected. Multiple Bragg scatterings can lead to a large absorption enhancement. From figure 3 it can be seen that there is indeed significant transmission in the frequency range of absorptance enhancement, averagely being more than 40%, while reflectance is small, around 20% averagely. The transparency of 1D metallic–dielectric PCs in the visible region can be understood by tunnelling effects [13]. It is found that transmission in the visible region decreases with increasing number of periods.

From photonic band structures we can determine the positions of photonic bands and PBGs. If one intends to enhance the absorption in a certain frequency range, one can properly choose the structural and material parameters to find a target photonic band whose frequency range is just the desired frequency range of absorption enhancement. In figure 4 the absorption spectra around 1.5 μm are shown as another example. In the metallic–dielectric PCs the thickness of the Ag layer is 20 nm and that of the dielectric layer is 450 nm. Again, the absorptance increases with increasing number of periods. The absorptance is on average above 25% for a 4-period PC and above 30% for an 8-period PC for wavelengths ranging from 1.3 to 1.6 μm. The absorption is enhanced by more than one order of magnitude over bulk Ag.
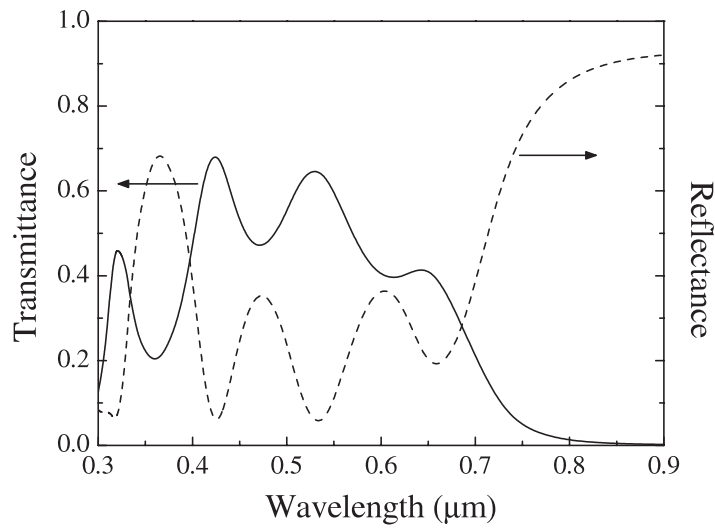
Figure 3. Calculated transmittance (solid curve) and reflectance (dashed curve) spectra for a 1D Ag/MgF$_2$ PC of 4 periods. Thicknesses of Ag and MgF$_2$ layers in PCs are 12 and 120 nm, respectively.
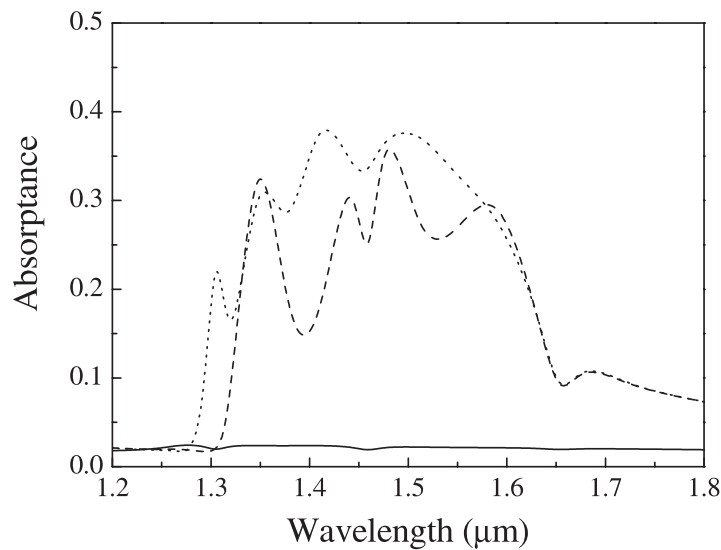

Figure 4. Calculated absorptance spectra of 1D Ag/MgF$_2$ PCs with 4 (dashed curve) and 8 periods (dotted curve). The thicknesses of Ag and MgF$_2$ layers are 20 and 450 nm, respectively. The solid curve represents the absorptance of an 80 nm Ag film.

In summary, we have presented theoretical studies on the absorption of 1D metallic–dielectric PCs. It was found that the absorption of 1D metallic–dielectric PCs can be enhanced considerably over the corresponding metal. We have shown two examples of absorption enhancement, one in the visible region and the other in the near-infrared region. In both cases the absorptance in PCs can be enhanced by one order of magnitude over the corresponding metal. Absorption enhancement increases with increasing number of periods of such PCs.

We can properly choose the structural and material parameters in order to obtain absorption enhancement in the desired frequency range.

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