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# Two-dimensional metallo-dielectric photonic crystals embedded in anodic porous alumina for optical wavelengths

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A theoretical study is presented for hexagonal lattice metallic pillar photonic crystals in anodic porous alumina with a lattice constant of 500 nm. The objective of the investigation is to design a two-dimensional metallo-dielectric photonic crystal with an anodic porous alumina template. Optical responses are calculated for silver pillars of radii 100 nm, and 200 nm in porous alumina. The nature of their stop bands and attenuation in the near-infrared region is investigated. Calculations reveal that two-dimensional photonic band gaps for the TM polarization exist at visible wavelengths when the radius is 200 nm. © *2004 American Institute of Physics*.
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There has been extensive theoretical and experimental research on photonic crystal structures incorporating metals due to their high negative dielectric constants in the optical region.[1–9] Such periodic configurations are sometimes referred to as metallo-dielectric photonic crystals since they are composed of metals and dielectrics.[2] However, in the near-infrared and visible wavelength regions, absorption caused by metals is no longer negligible and careful analysis should be undertaken for each metal.[3,6,7,9] van der Lem and Moroz studied two-dimensional metallic pillar structures in silica and showed that two-dimensional photonic band gaps exist at visible wavelengths, although the absorption of metals was neglected.[4] Such metal-infiltrated structures can also be realized in anodic porous alumina.[10,11]

Anodic porous alumina has a highly ordered hexagonal orientation of hollow cylinders as depicted in Fig. 1. It has been investigated as a two-dimensional photonic crystal for visible[1,2] and near-infrared wavelengths.[13–15] Anodic porous alumina provides a template of pillar structures in a hexagonal arrangement for infiltration with metal nano-wires by electrodeposition technique[16,17] because of its high uniformity, aspect ratio, and controllability of structural constants.

In this letter, we report the numerical analysis of two-dimensional metallic pillar structures arranged in a hexagonal orientation within a template of anodic porous alumina, including the effects of metal absorption, in order to analyze their optical properties in the near-infrared and the visible regions. The presented detailed analysis is based on our initial work.[18]

The calculations were performed using TRANSLIGHT PACKAGE,[19] which employs the transfer matrix method applied to photonic crystals.[20] In calculations, the unit cell of the photonic crystal is divided into small meshes so as to discretize Maxwell's equations throughout the unit cell. A plane wave is assumed to enter one side of the mesh, and, by computing the transfer matrix that represents each mesh, the electromagnetic fields are obtained at the other side of the mesh. The fields are coupled to the next mesh and repetition of this procedure over the whole structure yields the transmission and reflection coefficients of the finite periodic structure. The TM polarization has a magnetic field perpendicular to the pillar axis, and the TE polarization has an electric field perpendicular to the pillar axis, as defined in Fig. 1.

The lattice constant is chosen to be 500 nm,[13–15,17] and the refractive index of anodic porous alumina is assumed to be 1.67,[12] with no loss. The metal under investigation is silver for its low refractive index, ranging from 0.12 to 0.65 at a wavelength interval of 400–2000 nm,[21] which creates a high refractive index contrast when combined with the porous alumina. Moreover, silver has the lowest absorption among other metals in the optical region. For our calculations, we used experimentally measured optical constants taken from Ref. 21. In the case of porous alumina with a lattice constant 500 nm, it is reported that the radius to the lattice constant ratio, given by $r/a$, is controllable from 0.18 to 0.42 through appropriate chemical processes.[14,15] Thus,

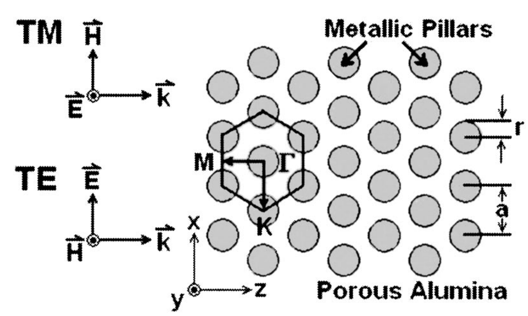


FIG. 1. Schematic illustration of a two-dimensional metallic pillar photonic crystal in anodic porous alumina. The directions of wave propagation under investigation are denoted as $\Gamma-M$ and $\Gamma-K$. $r$ and $a$ are the radius of the metal pillars and the lattice constant of the porous alumina, respectively.

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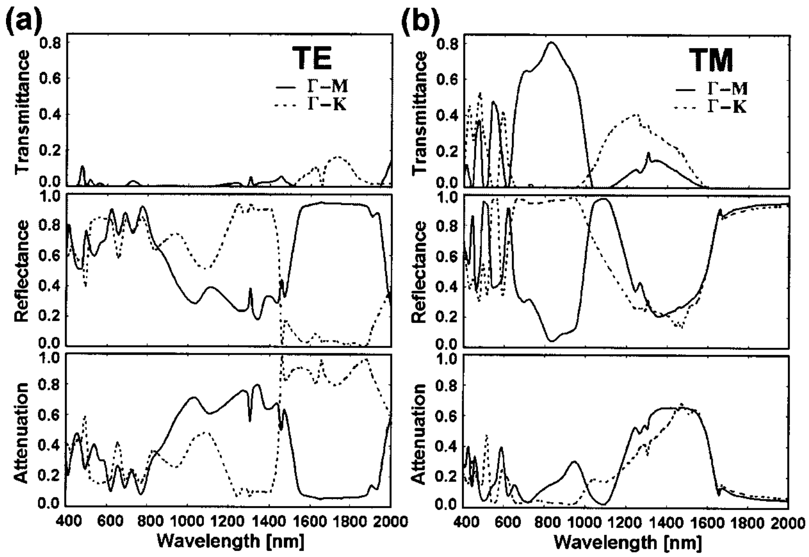


FIG. 2. Calculated transmittance, reflectance, and attenuation of (a) TE- and (b) TM-polarized incident light along the $\Gamma - M$ (solid lines) and the $\Gamma - K$ (dotted lines) directions for anodic porous alumina with silver pillars. The lattice constant, the ratio $r/a$, and the number of layers are assumed to be 500 nm, 0.2, and 17, respectively.

we start our analysis from a silver pillar structure with $r/a = 0.20$, namely, radius 100 nm. It can be seen from Fig. 2(a) that the stop band for TE polarization appears between 1550 and 1940 nm along $\Gamma - M$ direction, and between 1240 and 1410 nm along $\Gamma - K$ direction. In the case of TM-polarized incident light as shown in Fig. 2(b), the stop band extends from 1030 to 1110 nm and from 650 to 950 nm along $\Gamma - M$ and $\Gamma - K$ directions, respectively. Those stop band intervals are wider than those of porous alumina photonic crystals with air holes.[15] The highest attenuation for the TM polarization is seen at the upper edges of the stop bands. Furthermore, for the TM polarization, a wide stop band extends from a cut-off wavelength of 1650 nm to longer wavelengths for light propagating along $\Gamma - M$ and $\Gamma - K$ directions. Such a broad stop band occurs for only TM polarization, and is the characteristic of two-dimensional metallic pillar photonic crystals.[1] The cut-off wavelength is tunable by varying the radius of metal pillars.[1] It is observed that attenuation of TE-polarized incident light is higher than that of TM-polarized light. This higher attenuation is associated with interactions with surface plasmon in the silver pillars.[5,9] Hence, taking this factor into account, we focus on the TM-polarization in the following analysis (Fig. 3).

We also examined the optical response of the metallic pillar structures with a radius of 200 nm. A wide stop band is present starting at 660 nm in this configuration, as shown in Fig. 4. Calculations reveal that two-dimensional photonic band gaps for TM-polarized light are obtainable in the visible region, which is shown using a logarithmic scale. TM-polarized light incident along both the $\Gamma - M$ and the $\Gamma - K$ directions experiences a significant decrease in transmittance between 475 and 550 nm for the silver pillar structures. This wavelength interval corresponds to a normalized frequency, given by $\omega a / 2\pi c$, of 0.91 to 1.05. The gap to midgap ratio in this case is 14.6%. This is comparable to a result of calculations conducted by van der Lem and Moroz based on the photon version of the Korringa–Kohn–Rostocker method, although the lattice constant in their calculation was 650 nm.[4] Within the band gap, the reflectance is approximately 95%, and the attenuation is about 5%. At the lower and higher band edges, the attenuation is 0.3 and 0.38, respectively. Attenuation peaks decrease in comparison with those for the structure with a 100 nm pillar radii. This can be attributed to the fact that the absorption of silver pillars is higher in the near-infrared region than in the visible region.[21]

In order to investigate the effect of the metal's absorption within the photonic band gap, we calculated transmittances of the structure with a single defect. Silver pillars with the same radii and lattice constant were defined in such a way that light propagating along both the $\Gamma - M$ and the $\Gamma - K$ directions experience eight layers of silver pillars and a single defect, as shown in the inset of Fig. 4. The figure shows the transmittances on a logarithmic scale when TM-polarized light propagates along the $\Gamma - M$ and the $\Gamma - K$ directions. Without absorption of the metal, transmission peaks are observed at 490 nm and 527 nm in the photonic band gap for both the $\Gamma - M$ and the $\Gamma - K$ directions. Those peaks are

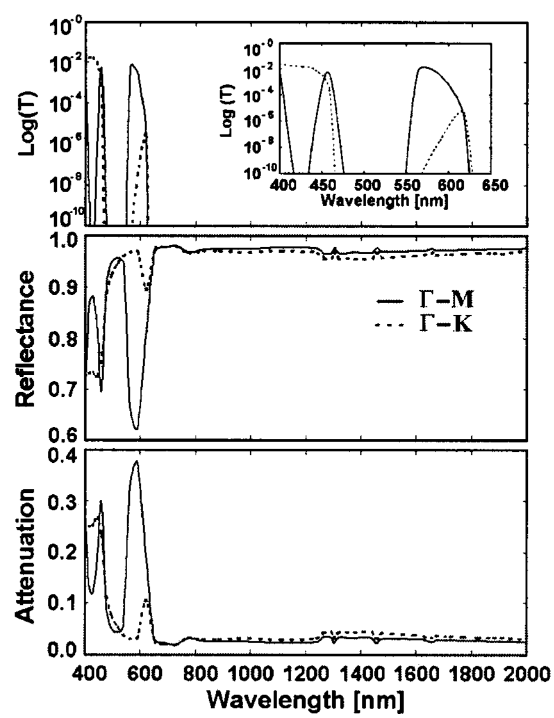


FIG. 3. Calculated transmittance on a logarithmic scale, reflectance, and attenuation of TM-polarized incident light for anodic porous alumina with 17 layers of silver pillars. The lattice constant and the ratio $r/a$ are 500 nm and 0.4, respectively. The inset shows the transmittance on a logarithmic scale for the visible wavelengths.

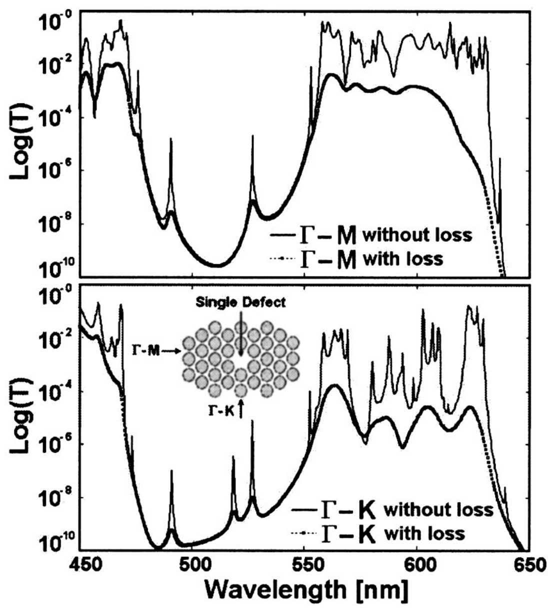


FIG. 4. Calculated transmittance on a logarithmic scale of TM-polarized incident light for anodic porous alumina with eight layers of silver pillars and a single defect. A silver pillar is removed and replaced by alumina. The lattice constant and the ratio $r/a$ are 500 nm and 0.4, respectively. The inset defines $\Gamma-M$ and $\Gamma-K$ directions.

considered to be defect modes induced by the single defect.[22] However, it is estimated that inclusion of silver's absorption significantly decreases the transmittances of the defect modes by $10^{-2}-10^{-3}$. Those high attenuations can be circumvented by reducing the number of metal layers.[23]

There are several advantages of metallic pillar photonic crystal structures hosted in porous alumina. First of all, anodic porous alumina provides an excellent template for metal infiltration thanks to its high uniformity and aspect ratio.[16,17] Although it has been proven that a hexagonal arrangement of metallic pillars in air does not possess a complete photonic band gap,[1] metallic pillars embedded in dielectrics do exhibit a complete photonic band gap.[4] Moreover, wide photonic band gaps for the TM polarization in metallic pillar structures exist from the cut-off wavelength, which is tunable. Finally, metallic photonic crystals tend to possess sufficient stop bands with fewer number of periodic layers than the dielectric ones.[24]

In conclusion, we investigated the possibility of a photonic band gap in a hexagonal metallic pillar structure in anodic porous alumina infiltrated with silver, by means of the transfer matrix method. Absorption of the metal was taken into account to study the behavior of such photonic crystal structures in the optical region. The calculations showed that broad stop bands are present in the near-infrared region when the radius of metal pillars is 100 nm. By enlarging the radius to 200 nm, the cut-off wavelength can be tuned to the visible wavelengths, and two-dimensional photonic band gaps for the TM polarization occur at wavelengths between 475 and 550 nm.

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