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Absorption enhancement in 1D Ag/SiO_2 metallic-dielectric photonic crystals

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The one-dimensional Ag/SiO_2 metallic-dielectric photonic crystals (PCs) have been prepared. The absorption enhancement effect over the corresponding metal of 1D Ag/SiO_2 metallic-dielectric multi-layer structures has been measured. The enhancement effect increases with the number of layers increasing. The origin of this phenomenon and its effect on the transmittance and reflectance have been discussed.

Keywords: photonic crystal, metallic-dielectric, absorption enhancement.

1. Introduction

Photonic crystals (PCs) have recently been found to possess many interesting properties and render many novel applications, offering a rich ground for both theoretical and experimental research [1–8]. In PC materials with any number of dimensions, the dispersion relations (frequency versus wave vector) have a number of branches. These branches form energy bands that might be separated by frequency gaps owing to the periodic dielectric modulation, analogous to the electronic band gaps in semiconductors due to the periodic potentials. Within a frequency band gap, electromagnetic (EM) waves cannot propagate. Since 1D, 2D, and 3D periodic dielectric lattices can be designed to create photonic band gaps, which is of significance as regards applications, PCs have attracted wide interest.

So far, most PCs are made of two kinds of dielectrics. However, some groups have utilized metals to alter the photonic crystal structures and generate odd properties. Consequently, some metals play an important role in the optical design and applications. In general, light cannot penetrate most of the metals, so that metals are hardly taken as a candidate material in 1D PCs. But when the thickness of metals is smaller enough, it will not block off some lights. If metals and dielectric materials are combined to form a multi-layer structure, some significant characteristics can be obtained [9, 10]. Recent result shows that the metallic-dielectric PCs can be transparent in the visible light region through a reasonable design [11], and the absorption of bulk metals in visible light region can be modulated by inserting dielectrics periodically to form a 1D PC, which has been proved by theoretical calculation [12].

In this paper, the one-dimensional Ag/SiO_2 metallic-dielectric multi-layer structures have been prepared and the absorption enhancing of 1D metallic-dielectric multi-layer structures has been experimentally observed, not only in visible light but also in infrared waveband. Moreover, we calculate the corresponding transmittance and reflectance spectra theoretically for comparison purposes. We have explained the principle of this phenomenon and its effect to the transmittance and reflectance have been discussed.

2. Model

In general, silver and silicon chosen here as the typical metallic and dielectric materials stack as ABAB… forming a one-dimensional metallic-dielectric multi-layer structure. We assume that the refractive index of SiO_2 is real and frequency independent, taken to be 1.45. The frequency-dependent refractive indexes of Ag are calculated by the Drude model, *i.e.*, $\varepsilon(\omega) = 1 - \omega_p^2/\omega^2$.

The transfer matrix method is used to study the absorptive properties of finite 1D metallic-dielectric PCs [13]. Let us consider the transmission and reflection of EM waves incident on a single dielectric layer separately from the right and from the left. The propagation through a single low and high index thin film can be expressed by 2×2 matrices M_1 and M_2, respectively. The properties of the whole structure can be described by [14]

$$M = (M_1 M_2)^n = \begin{pmatrix} A & B \\ C & D \end{pmatrix}^n \tag{1}$$

where n is the repetition period number, and:

$$M_1 = \begin{pmatrix} \cos(\delta_1) & i\sin\left(\dfrac{\delta_1}{n_1}\right) \\ in_1\sin(\delta_1) & \cos(\delta_1) \end{pmatrix} \tag{2}$$

$$M_2 = \begin{pmatrix} \cos(\delta_2) & i\sin\left(\dfrac{\delta_2}{n_2}\right) \\ in_2\sin(\delta_2) & \cos(\delta_2) \end{pmatrix} \tag{3}$$

where n_1 and n_2 are the refractive indexes of high refractive index and low refractive index materials; d_1 and d_2 are the phase thicknesses of low and high layers with $\delta_1 = 2\pi n_1 d_1/k_0$ and $\delta_2 = 2\pi n_2 d_2/k_0$, and k_0 is the wavelength of incoming light.

Let $\eta_i = \sqrt{\dfrac{\varepsilon_0 \varepsilon_i}{\mu_0}}$, the complex transmission and reflection coefficients can be derived from the elements of the transfer matrix, yielding

$$t = \frac{A\eta_0 + B\eta_0\eta_{n+1} - C - D\eta_{n+1}}{A\eta_0 + B\eta_0\eta_{n+1} + C + D\eta_{n+1}} \tag{4}$$

$$r = \frac{2\eta_0}{A\eta_0 + B\eta_0\eta_{n+1} + C + D\eta_{n+1}} \tag{5}$$

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

$$A = 1 - T - R \tag{6}$$

3. Experiment

Silicon and silver are deposited on the substrate periodically, so that the 1D PCs are formed. Since the skin depth for visible light of Ag is 12–15 nm and the thicker films will block off the light transportation, the thickness of Ag films is chosen here as 10 nm. Meanwhile, the thickness of silicon is taken as 100 nm. The samples formed by Ag and silicon film, with 2 layers, 6 layers and 12 layers, are prepared respectively by the method of ultrahigh vacuum electron beam evaporation (Fig. 1).

In addition, we prepare the Ag film and the SiO$_2$/TiO$_2$ photonic crystals to compare with the results of the metallic-dielectric multi-layer film. The thickness of Ag film is 70 nm, and the SiO$_2$ and TiO$_2$ layers are both 67 nm in the photonic crystals.

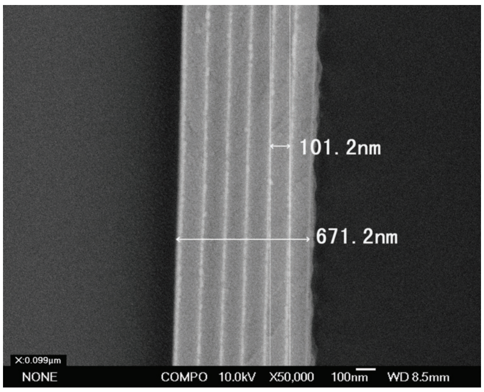
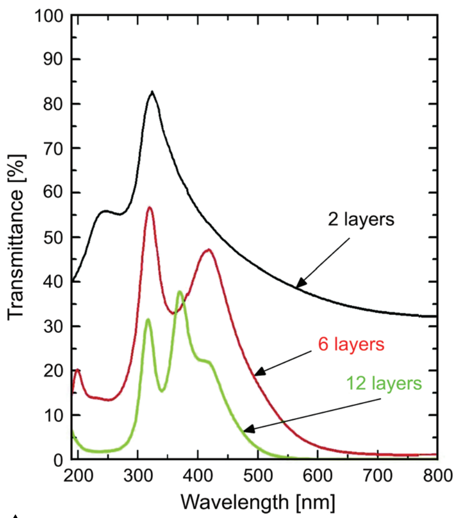


Fig. 1. SEM photo of a 12 layer Ag/SiO$_2$ sample. The thickness of every pair of Ag/SiO$_2$ layers is 101.2 nm, and the total thickness of 12 layers is about 671.2 nm.

4. Results and discussion

The transmittance spectra of the Ag/SiO_2 PCs with different number of layers have been measured, as shown in Fig. 2. The transmittance maintains more than 40% at a very wide range of wavelength for the two layer structures, because the thickness of the Ag film is less than the skin depth. Even in the 6 and 12 layer PCs, the transmittance is still at a considerably high level in the short wavelength range. It is worth noticing that the transmittance of the bulk Ag is nearly zero. Therefore, the transmittance



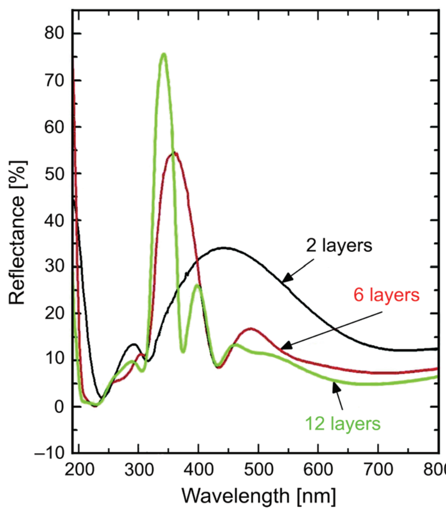


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Fig. 2. Transmittance of Ag/SiO_2 with different number of layers.

Fig. 3. Reflectance of Ag/SiO_2 with different number of layers.

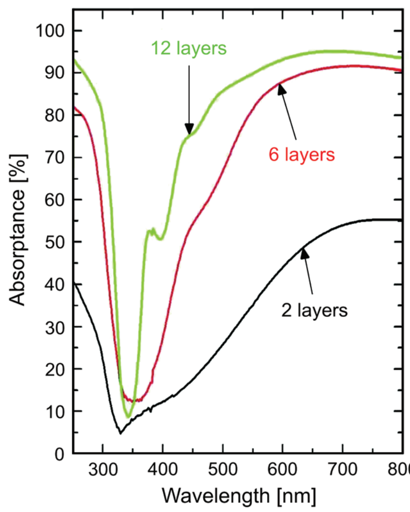


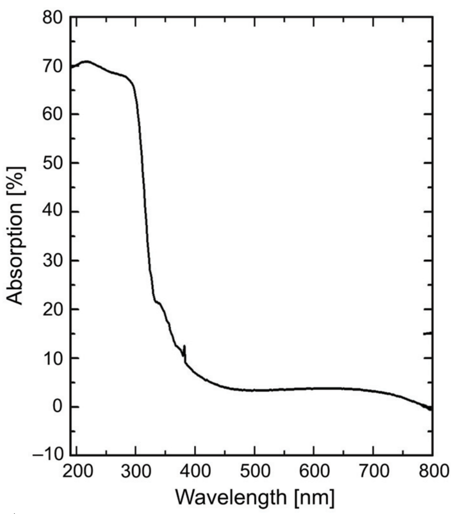
Fig. 4. Absorption spectra of Ag/SiO_2 with different number of layers.

enhancing effect occurs on the Ag/SiO_2 system. But the transmittance reduces from about 30% at 6 layers to 20% at 12 layers.

The reflectance spectra of the Ag/SiO_2 system with different number of layers are shown in Fig. 3. As we expect, the reflectance at visible and infrared region is extremely low, which distinguishes the case of the bulk Ag. The reflectance of 2 layer sample is 20% on average in the visible light range while the reflectance of the 6 and 12 layer structure is about 10% and 7%. This demonstrates that the reflectance reduces with respect to the periodic numbers not only in visible light but also in larger wavelength such as infrared range. This derivation of phenomenon will be discussed later.

Figure 4 shows the absorption spectra of Ag/SiO_2 structures. It is seen that in visible light and infrared wave regions, the more layers there are, the higher the absorption. For structures with any number of layers, the absorption increases from blue region to the red and infrared regions, and gradually reaches a stable value when the wavelength is sufficiently long. This stable value of the 2 layer sample is about 40% and the 6 and 12 layer samples are 80% and 90%, respectively.

To discuss the spectra intensively, we also measure the absorption spectra of Ag film and TiO_2/SiO_2 multi-layer structures, shown in Figs. 5 and 6, respectively. As seen from Figs. 4–6, the absorption spectra of the three structures are nearly identical when the wavelength is below 400 nm and display a “kink” at about 350 nm. When the wavelength is larger than 400 nm, the absorption of Ag film and TiO_2/SiO_2 structure shows a low value which is smooth and steady. Conversely, the spectrum of Ag/SiO_2 multi-layer structures increases gradually and reaches a considerably high value as described previously, which represents the absorption enhancement effect.



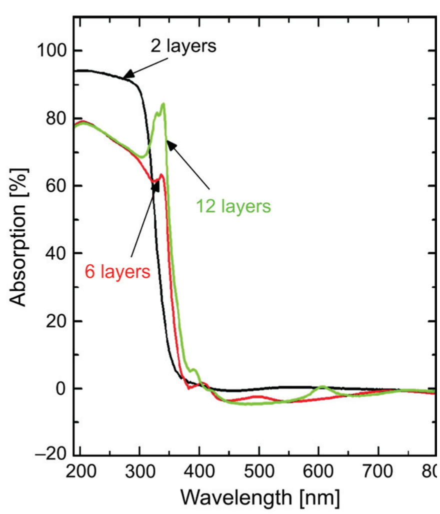


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Fig. 5. Absorption spectrum of Ag.

Fig. 6. Absorption spectra of TiO_2/SiO_2 multi-layer structures with different number of layers.

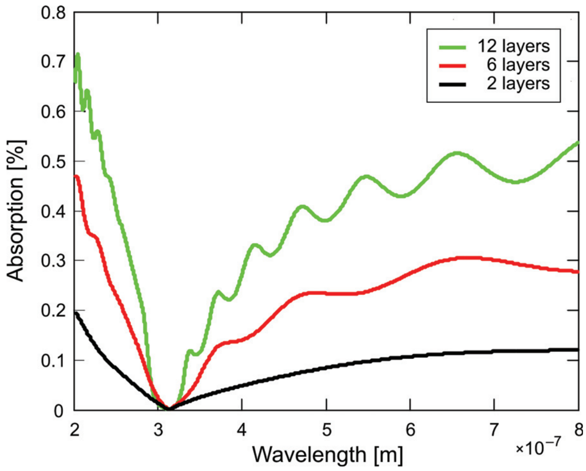

Fig. 7. Calculated absorption spectra of Ag/SiO_2 with different number of layers.

The absorption spectra measured in our experiment (Fig. 4) coincide with the theoretical results from the transfer matrix method in Fig. 7. Both spectra show a kind of high−low−high tendency from 200 nm to 1000 nm wavelength region. The impurity of the sample induces the energy loss so that the theoretical absorptions are lower than the experimental results. Here, the peculiar photonic band structure is a critical factor which causes the absorption enhancement effect. The propagation modes which lied in the PBGs are moved away to the photonic bands. Consequently, more propagating states are localized in the photonic bands due to the conservation of states. When the thickness of the metallic layer is lower than the relevant skin depth of the corresponding metal, some electromagnetic wave will traverse the metallic layer and propagate in the 1D photonic crystal structure. In the periodic photonic crystal structures, the PBGs and the photonic bands are formed due to the multiple Bragg scatterings and thus the considerable transmission for frequencies within photonic bands is produced. As a result, more energy will propagate in the metallic-dielectric structure and we can see a large absorption enhancement. The absorption can be easily obtained from $A = 1 - T - R$. With the enhancement of the absorption in visible light and infrared wave regions, the transmittance and reflectance depression can happen accordingly. That is why the transmittance and reflectance spectra are exhibited above.

5. Conclusions

We have designed and prepared a kind of metallic-dielectric photonic crystal constructed by the silver and silicon films. It is found that the absorption of 1D metallic-dielectric PCs can be enhanced considerably over the corresponding metal. The measured transmittance and reflectance is decreased which is affected by the increase of absorption. These effects enhance with increasing number of layers in such multi-layer structures. The characteristics of the absorption spectra coincide with the theoretical calculations. We will prepare other kinds of metallic-dielectric photonic crystal structures to study further the absorption enhancement. This work will be a useful reference when designing and producing some apparatus such as, eyes--protecting to laser and heat-absorbing window.

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