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# Design and fabrication of energy efficient film based on one-dimensional photonic band gap structures

Xian Wang [a, *], Dong Qi [a], Fang Wang [a], Yongzhi Cheng [a, b], Yan Nie [a], Rongzhou Gong [a]

[a] School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, 430074, China
[b] School of Information Science and Engineering, Wuhan University of Science and Technology, Wuhan, 430081, China

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## ABSTRACT

A photonic band gap structure of $(SiO_2/TiO_2)^5$ with Ag system for energy efficient film was proposed theoretically and experimentally. The calculated transmittance spectra show high transmittance in the visible range, but ultra-low transmittance in the wavelength ranges of ultraviolet and infrared. Besides, the effects of the incident angle and two opposite directions on the optical characteristics were studied. The results demonstrate that the structure can simultaneously satisfy the demands of lighting and heat insulating as energy efficient window film. The cross-section morphology indicates that the sample has good periodicity in accordance with the design, whereas the experimentally measured transmittance spectra are well matched with the theoretical calculation.

## 1. Introduction

Globally, buildings are responsible for 30–40% of energy consumption so far. Heating and lighting are the primary consumption in most of the buildings [1]. The wavelength range of the solar and thermal radiation, in particular, mainly concentrates at 0.28–2.15 μm and 3–25 μm, respectively [2,3]. It was reported that energy efficient window is an efficient way to reduce unwanted solar heat transferring through windows. Over the past few decades, a number of low emissivity (low-e) films for energy efficient window, including dielectric (D)-metal (M) system, such as D/M, D/M/D, and D/M/D/M/D, have been investigated [4–7]. However, it remains a challenge to further improve the compatibility of low-eat 0.28–0.4 μm (Ultraviolet), 0.8–2.15 μm (Near-Infrared) and 3–25 μm (Mid and Far Infrared) on the premise of high transparency in visible range.

Recently, photonic crystals (PCs) [8,9], as a kind of artificial periodic dielectric structural materials [10,11], have been attracting a great amount of research interest due to the characteristics in manipulating the electromagnetic (EM) waves. A large number of applications, such as mirror application [12], omnidirectional reflector [13], optical absorption [14] and thermal emitter [15,16] have been proposed and studied. Similar to the electrons in semiconductor materials, the incident waves whose frequencies falling within the frequency band gaps usually cannot propagate in the PCs [17,18]. It is conjectured that photonic crystal structures, which own a flexible photonic band gap (PBG) by controlling the structural parameters, can realize selective transmission in different wavebands for energy efficient film. However, up to now, the application for energy efficient film of one-dimensional photonic crystals (1DPC) has been neglected in the previous studies.

In this work, a novel composite structure consisting of 1DPC and Ag system was proposed to achieve low-e and enhanced spectral selectivity for energy-efficient window. The 1DPC is composed of alternating $TiO_2$ and $SiO_2$ layers with a total of 5 periods, while the Ag system comprises a thin Ag layer sandwiched with $TiO_2$ layers. For visible range, $TiO_2$ and $SiO_2$ are the well-known high and low index dielectric oxide materials for 1DPC because of their non-absorbing and non-dispersive characteristics [19]. On the other hand, the Ag is a high extinction coefficient material and show low transmission in ultraviolet and infrared [5]. We found that the designed structure of $(TiO_2/SiO_2)^5/TiO_2/Ag/TiO_2$ exhibits excellent selective transmittance performances at visible and infrared frequencies, i.e., high visible light transparency and low-e characteristics. This study offers a significant pathway to 1DPC applications for energy efficient window film.

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* Corresponding author.
*E-mail address:* wangx@hust.edu.cn (X. Wang).

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## 2. Structural design and experimental procedure

### 2.1. Structural design

As we know, energy efficient window should possess high transmittance in the visible range but as low as possible transmittance in the infrared. For the sake of realizing desirable spectral selectivity at visible and infrared frequencies, the composite structure consisting of 1DPC and Ag system, i.e. $(TiO_2/SiO_2)^5/TiO_2/Ag/TiO_2$, was designed by using transform matrix method (TMM) below and optical coating design software Essential Macleod [14,20].

We assume that the wavelength of incident electromagnetic wave is $\lambda$, based on the Maxwell equations and transform matrix theory, the transform matrix for $m$th layer can be expressed as:

$$M_m = \begin{bmatrix} \cos\delta_m & i\dfrac{\sin\delta_m}{\eta_m} \\ i\eta_m \sin\delta_m & \cos\delta_m \end{bmatrix} \tag{1}$$

Where the parameters of matrix can be described as $\delta_m = \frac{2\Pi}{\lambda} n_m d_m \cos\theta_m$ and $\eta_m = \begin{cases} n_m/\cos\theta_m & TM \\ n_m & TE \end{cases}$; n is the refractive index, d is the physical thickness; $\varepsilon$ and $\mu$ are the permittivity and permeability, respectively; the subscript m denotes the number of layer. Refraction angle $\theta_m$ is calculated by Snell theorem:

$$n_m \sin\theta_m = n_{m-1}\sin\theta_{m-1} = \cdots n_0 \sin\theta_0 \tag{2}$$

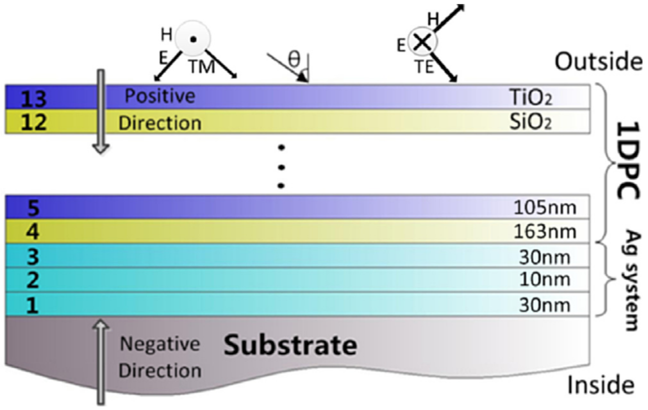

**Fig. 1.** Schematic of the composite structure with 1DPC and Ag system.

Equivalent transform matrix can be derived from equations (1) and (2):

$$M = \prod_{m=1}^{m} M_m = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \tag{3}$$

The transmittance coefficient ($t$) of the designed system is derived from the relation:

$$t = \frac{2P_1}{(m_{11} + m_{12}P_m)P_1 + (m_{21} + m_{22}P_m)} \tag{4}$$

where$P_1 = \sqrt{\frac{\varepsilon_1}{\mu_1}}\cos\theta$ and $P_m = \sqrt{\frac{\varepsilon_m}{\mu_m}}\cos\theta$ are used to denote the coefficients of external environment on incident and emergent interfaces. Transmittance $T$ can be calculated by the equation$T = \frac{P_m}{P_1}|t|^2$.

The photonic band gap can be calculated with the following parameters: the refraction index dispersion formula of $TiO_2$ and $SiO_2$ are $n_h^2 = 5.913 + \frac{0.2441}{\lambda^2 - 0.0803}$ and $n_l^2 = 1 + \frac{0.6961663\lambda^2}{\lambda^2 - 0.0684043^2} + \frac{0.4079426\lambda^2}{\lambda^2 - 0.1162414^2} + \frac{0.8974794\lambda^2}{\lambda^2 - 9.896161^2}$, where λ is the wavelength of EM wave, $n_h$ and $n_l$ represent the refraction index of $TiO_2$ and $SiO_2$, respectively. First of all, a center wavelength ($\lambda_0 = 0.95$ μm) with the median of PBG (0.8–1.21 μm) is equal to the optical thicknesses ($n \cdot d$). For a single 1DPC structure, the layer thickness ($d$) of the high and low refractive index ($n$) dielectric materials can be determined by the equation $n \cdot d = \lambda_0/4$, respectively [21,22]. Then the layer thickness and number of periods are optimized so as to maximize the reflection peak intensity. After a series of optimization of the structural parameters, we can obtain the desired 1DPC and Ag system, as specifically presented in Fig. 1.

### 2.2. Fabrication and characterization

The composite film of $(TiO_2/SiO_2)^5/TiO_2/Ag/TiO_2$ in Fig. 1 was deposited on K9 glass substrate (diameter 30 mm, thickness 3 mm) using e-beam evaporation deposition technology from 99.99% pure $TiO_2$, $SiO_2$ and Ag targets. The deposition rates of $TiO_2$, $SiO_2$ and Ag sub-layers were approximately 0.3 nm/s, 0.8 nm/s and 0.1 nm/s, respectively. All the depositions are carried out without any external substrate heating and the chamber pressure was $2.1 \times 10^{-3}$ pa. The thicknesses of the individual layers were monitored using multichannel quartz crystal monitors (InficonIC6).

The cross-section morphology of the film was observed by field

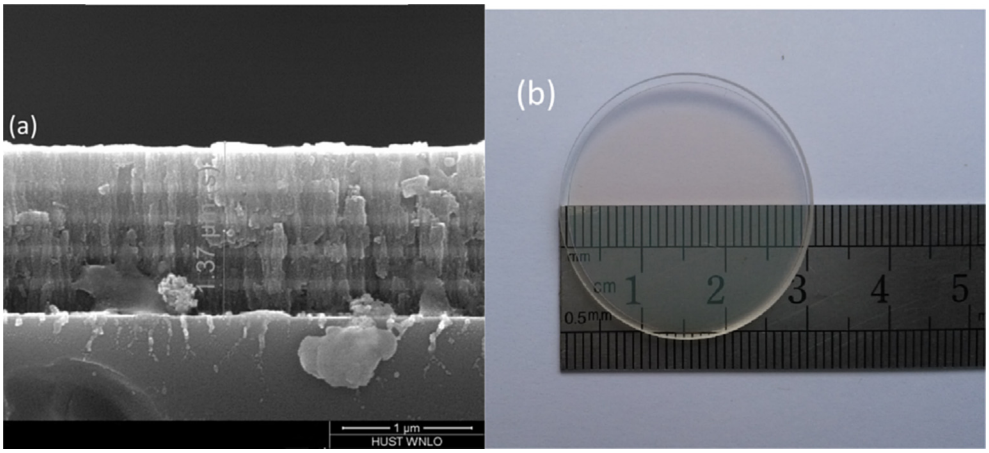

**Fig. 2.** (a) Cross-sectional SEM image and (b) photograph of the composite structure.