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Design and characterization of one-dimensional photonic crystals based on ZnS/Gefor infrared-visible compatible stealth applications

Dong Qi [a], Xian Wang [a,*], Yongzhi Cheng [a,b], Rongzhou Gong [a], Bowen Li [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, Hubei 430081, China

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ABSTRACT

One-dimensional photonic crystals (1DPCs) based on ZnS/Ge for compatible stealth of infrared and visible were firstly proposed theoretically and investigated experimentally. Owing to the equal inclination interference, the designed 1DPCs structure can be fabricated with a certain color corresponding to the different responded wavelength. In addition, the average emissivity of the proposed structure can reach as low as 0.054 at infrared atmosphere window of 3–5 μm. The as-prepared structure indicates that it is feasible for 1DPC to achieve infrared-visible compatible stealth.

1. Introduction

In recent years, stealth technology has received widespread attention due to its widespread applications [1–3] in aircraft, ships, tanks and individual soldiers, which can make them less visible by various detections. In the past, the main attention for the stealth technology application research has been paid to the radar or infrared wave range. However, with the rapid development of modern detection technology, the multiple detection approaches operated in microwave, infrared and even to visible have been proposed and applied in practices. Thus, the compatible stealth technology for infrared-visible wave is being urgent need. Extensive work on visible light stealth has been reported so far. For example, invisibility cloak [4,5] to create an illusion by guiding the light and make it appear on the other side; and camouflage coating [6] to camouflage the objectives in the fixed background. In addition, infrared stealth technology has attracted great attention to protect targets from advanced infrared detection. As major materials and structures, core-shell composites [7], nano-composite films [8] and multilayer structures [9,10] are aimed at reducing the infrared emissivity intensity in the atmospheric windows of 3–5 μm and 8–14 μm. However, single-type stealth technology is impossible to meet the demands of modern and future military. Surprisingly, there were few reports about infrared-visible compatible stealth for multilayer structure. Therefore, to develop a novel infrared-visible compatible stealth, multilayer structure is quite important.

Photonic crystals (PCs) as a kind of metamaterial [11,12] firstly proposed by Yablonovitch [13] and John [14] in 1987, which have been attracting a great amount of researches due to their wide applications such as omnidirectional reflector [15], thermal emitter [16] and filter [17]. Similar to the electrons in semiconductor materials, the photonics will be manipulated and cannot propagate due to the interference of Bragg scattering [18] if their frequencies fall within the frequency band gaps. Hence the PCs are also called as photonic band gap (PBG) structure [19]. However, the application of one-dimensional photonic crystals on infrared-visible compatible stealth has been neglected so far in the previous studies.

In this paper, 1DPCs were employed to achieve compatible stealth of infrared-visible wave of 3–5 μm. A novel structure is composed of alternating Ge (average refractive index 4.0) [20] and ZnS (average refractive index 2.43 at 0.3–0.9 μm and 2.2 at 2.8–5.4 μm) [21] layers with a total of 4 periods and the center wavelength is 3.8 μm. The designed structure $H_s(Ge/ZnS)^3Ge$ is specifically shown in Fig. 1, where H_s represents variable thickness surface layer of ZnS. Excellent compatible stealth performance has

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

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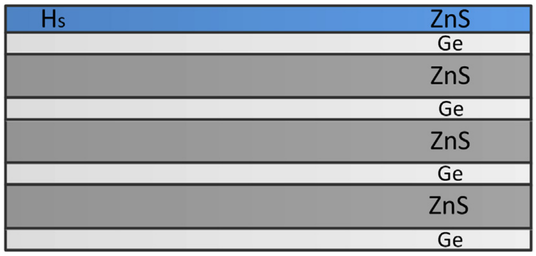

Fig. 1. Schematic of the designed structure $H_s(Ge/ZnS)^3Ge$ prepared on quartz glass substrate.

been achieved with various colors to camouflage the objectives and ultra-low infrared emissivity. Therefore, this study offers a significant pathway for span-new 1DPCs application of infrared-visible compatible stealth.

2. Theoretical analysis and design

Different colors of 1DPC structure are achieved based on thin film equal inclination interference [22]. The simplified surface structure of 1DPCs is shown in Fig. 2:

The optical path difference (OPD) between two columns of reflected waves is expressed as:

$$\delta = n_2\left(\overline{AB} + \overline{BC}\right) - n_1\overline{AD} = 2h\left(\frac{n_2}{\cos\beta} - n_1\tan\beta\sin\alpha\right) = \frac{2h}{\cos\beta}\left(n_2 - n_2\sin^2\beta\right) = 2n_2h\cos\beta = 2h\sqrt{n_2^2 - n_1^2\sin^2\alpha} \quad (1)$$

Due to half-wave loss, OPD δ is defined newly as:

$$\delta_1 = 2n_2h\cos\beta \pm \frac{\lambda}{2} = 2h\sqrt{n_2^2 - n_1^2\sin^2\alpha} \pm \frac{\lambda}{2} \quad (2)$$

Therefore, the equation of constructive interference can be expressed as:

$$2n_2h\cos\beta \quad or \quad 2h\sqrt{n_2^2 - n_1^2\sin^2\alpha} = (2j+1)\frac{\lambda}{2} \quad (3)$$

The color of thin film is related to the wavelength λ of constructive interference, which means we can obtain thin films with certain color by changing the physical thickness h of surface layer. In addition, oblique incidence (0–60°) has been considered on the surface. The wavelength λ of constructive interference can be calculated from the equation (3) as follows ($j = 0, 1, 2, \ldots$):

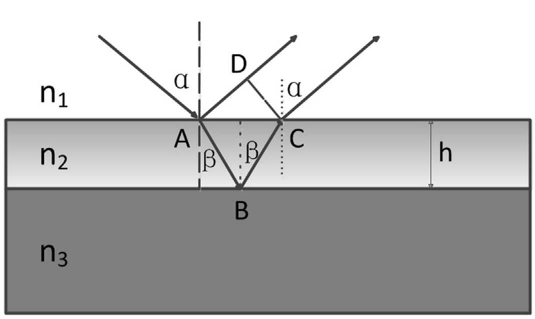

Fig. 2. Light-path diagram of equal inclination interference for surface layer with the physical thickness h and refractive index n_2.

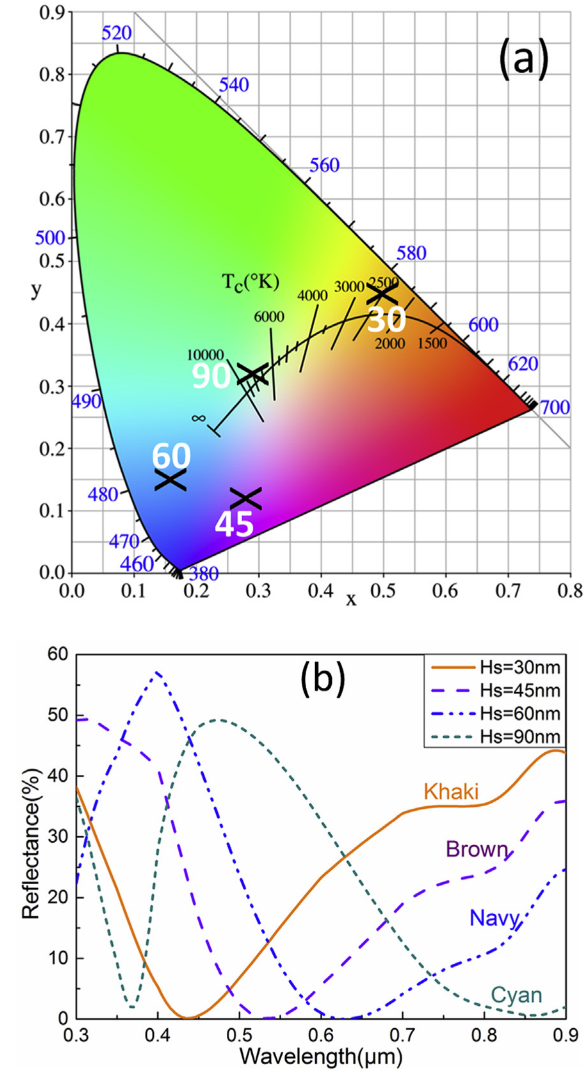

Fig. 3. Four designs with different surface layer thicknesses of 30 nm, 45 nm, 60 nm and 90 nm: (a) CIE 1931 Chromaticity Diagram with black crosses marked color coordinates. (b) Reflection spectra at 0.3–0.9 μm with certain reflection peaks and color of surface.

$$\lambda = \begin{cases} \dfrac{4h\sqrt{n^2 - \sin^2\alpha}}{2j+1} & Oblique\ \ Incidence \\ \dfrac{4hn}{2j+1} & Normal\ \ Incidence \end{cases} \quad (4)$$

The dispersion formula of ZnS [21] can be expressed as:

$$n^2 = 8.393 + \frac{0.14383}{\lambda^2 - 0.2421^2} + \frac{4430.99}{\lambda^2 - 36.71^2} \quad (5)$$

Average refractive index at 0.4–0.8 μm is calculated as 2.43. The relative deviation D between oblique and normal incidence can be derived:

$$D = \frac{4h}{2j+1}\frac{\left(n - \sqrt{n^2 - \sin^2\alpha}\right)}{n} \le \frac{4h}{2j+1} \times 6.58\% \quad (6)$$

So the effect of oblique incidence can be neglected due to the maximum deviation 6.58%.