Infrared Physics & Technology 85 (2017) 62–65

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Regular article

# Realization of compatible stealth material for infrared, laser and radar based on one-dimensional doping-structure photonic crystals

Ji-Kui Zhang [a], Jia-Ming Shi [a,*], Da-Peng Zhao [a], Qi-Chao Wang [a], Cheng-Ming Wang [b]

[a] State Key Laboratory of Pulsed Power Laser Technology, Hefei 230037, China
[b] National Laboratory for Physical Sciences at the Microscale, Hefei 230026, China

## HIGHLIGHTS

- Fabricated a doping structural one-dimensional photonic crystal (1-D PC) with Ge, ZnSe and Si was to achieve compatible stealth of 8–14 μm waveband and 10.6 μm; and then combine it with radar absorbing material (RAM) to make a compound, which is a multi-waveband stealth material that can realize compatible stealth of 8–14 μm infrared atmospheric window, 10.6 μm laser and radar wave; the reflection spectra of this compound was tested, and the result shows a high average reflectance (89.5%) in 8–14 μm waveband, and a reflective valley (39.8%) in the wavelength of 10.6 μm, and in radar band, especially between 7.8 and 18 GHz, the radar power is strongly absorbed by this material and the reflected energy attenuate over 10 dB within the range from 11.1 GHz to 18.3 GHz, even 24.5 dB to the most in the frequency of 14.6 GHz.

## ARTICLE INFO

*Article history:*
Received 22 December 2016
Revised 17 May 2017
Accepted 24 May 2017
Available online 27 May 2017

*Keywords:*
Compatible stealth
Photonic crystals
Doping structural

## ABSTRACT

To inhibit the radiant infrared energy between 8 and 14 μm, which is the infrared atmospheric window, and decrease the echo power of detecting laser and radar, to achieve compatible stealth, a doping structural one-dimensional photonic crystal (1-D PC) with Ge, ZnSe and Si was fabricated; and then combine it with radar absorbing material (RAM) to make a compound. After that, the reflection spectra of this compound was tested, and the result shows a high average reflectance (89.5%) in 8–14 μm waveband, and a reflective valley (39.8%) in the wavelength of 10.6 μm, which is the wavelength of $CO_2$ laser; and the reflectance in radar band shows that at high frequency, especially between 7.8 and 18 GHz, the radar power is strongly absorbed by this material and the reflected energy attenuate over 10 dB within the range from 11.1 GHz to 18.3 GHz, even 24.5 dB to the most in the frequency of 14.6 GHz.

## 1. Introduction

In modern detecting technology field, detecting waveband has been broadened from visible light to infrared and radar waveband, which presenting a challenge to stealth technology. Further, there have been emerged a multi-waveband detecting tendency in recent year, which demands a compatible stealth technology. In this case, further researches have been done [1] to find ways to realize infrared, laser and radar compatible stealth, most of them are based on compatible stealth materials. As to infrared stealth materials, they need low emissivity to inhibit infrared radiant power, for infrared detectors are operating on passive mode; however, laser and radar stealth materials need a low reflectance, meaning a high absorptivity considering the Principle of Conservation of Energy, to reduce the echo power. According to Kirchhoff's law [2], we know that emissivity and absorptivity are numerically equal; the above spectral requirement is ambivalent for the most frequently used laser wavelength is within infrared wavebands. However, photonic crystal [3–5], as a new artificial periodic structure function material, can realize broadband thermal infrared stealth based on its high-reflection photonic band gap (PBG) [6–10], a range of frequency which electromagnetic wave bearing the same frequency cannot go through. And when a defect [11–13] was added into the periodic structure of PC, there will appear a reflectivity valley, where the reflectance is lower compared to another band, in other word, a "hole-digging" reflection spectrum will emerge, therefore, compatible stealth of infrared and laser can be achieved. Based on PC theory, Wang [14] has designed and fabricated infrared-radar stealth-compatible materials; Zhang [15] has realized ultra-low emissivity in mid and far infrared wave band using a heterogeneous structure PC deposited from Ge and ZnS; Based on doping theory, Miao [16] has realized compatible

---

* Corresponding author.
*E-mail address:* s_jiaming@126.com (J.-M. Shi).

http://dx.doi.org/10.1016/j.infrared.2017.05.018
1350-4495/© 2017 Elsevier B.V. All rights reserved.

stealth for mid, far infrared waveband and laser in the wavelength of 10.6 μm using only one PC.

In this paper, we firstly deposit a doping structural 1-D PC with low emissivity in 8–14 μm infrared waveband and low reflectance in laser wavelength of 10.6 μm; then, combine it with RAM, and finally it turn out that compatible stealth of 8–14 μm, 10.6 μm laser and high frequency radar wave band can be realized.

## 2. Theory

To calculation the reflection and transmission of the electromagnetic wave in PC, we employ the transfer matrix method (TMM) [17], which is well suited to the calculation concerning multi-layer materials. TMM is based on Abeles method, in which forward and backward electric field E+ and E− are employed to obtain the reflectance and transmission. Abeles showed that, for stratified films with m layers, the relation between the amplitudes of the electric fields of the incident wave, reflected wave and transmitted wave through m layers can be expressed as

$$\begin{pmatrix} E_0^+ \\ E_0^- \end{pmatrix} = \frac{C_1 C_2 C_3 \ldots C_{m+1}}{t_1 t_2 t_3 \ldots t_{m+1}} \begin{pmatrix} E_{m+1}^+ \\ E_{m+1}^- \end{pmatrix} \tag{1}$$

Here, $t_j$ ($j$=1, 2,…,m + 1) is the Fresnel transmission coefficient through the $(j-1)$th layer and $C_j$ is the propagation matrix given by

$$C_j = \begin{pmatrix} \exp(i\phi_{j-1}) & r_j \exp(-i\phi_{j-1}) \\ r_j \exp(i\phi_{j-1}) & \exp(-i\phi_{j-1}) \end{pmatrix} \tag{2}$$

where $r_j$ is the Fresnel reflection coefficient. Specifically, $t_j$ and $r_j$ can be expressed as below using the complex refractive index $\hat{n}_j = n_j + ik_j$ and the complex refractive angle $\theta_j$. For parallel (P) polarization, one has

$$t_{jp} = \frac{2\hat{n}_{j-1}\cos\theta_{j-1}}{\hat{n}_{j-1}\cos\theta_j + \hat{n}_j\cos\theta_{j-1}} \tag{3}$$

$$r_{jp} = \frac{\hat{n}_{j-1}\cos\theta_j - \hat{n}_j\cos\theta_{j-1}}{\hat{n}_{j-1}\cos\theta_j + \hat{n}_j\cos\theta_{j-1}} \tag{4}$$

Similarly, for perpendicular (S) polarization, we have

$$t_{js} = \frac{2\hat{n}_{j-1}\cos\theta_{j-1}}{\hat{n}_{j-1}\cos\theta_{j-1} + \hat{n}_j\cos\theta_j} \tag{5}$$

$$r_{js} = \frac{\hat{n}_{j-1}\cos\theta_{j-1} - \hat{n}_j\cos\theta_j}{\hat{n}_{j-1}\cos\theta_{j-1} + \hat{n}_j\cos\theta_j} \tag{6}$$

Moreover, the complex refractive indices and the complex incident angles follow Snell's law $\hat{n}_{j-1}\sin\theta_{j-1} = \hat{n}_j\sin\theta_j$. The parameters $\phi_{j-1}$ in Eq. (2) represent the changes in the phase of the wave between the (j − 1)th and the jth boundaries, which are expressed as

$$\phi_0 = 0 \tag{7}$$

$$\phi_{j-1} = \frac{2\pi}{\lambda}\hat{n}_{j-1}d_{j-1}\cos\theta_{j-1} \tag{8}$$

Here, λ is the wavelength of the incident light in vacuum and $d_{j-1}$ is the thickness of the (j − 1)th layer. By letting $E_{m+1}^- = 1$, one gets the overall reflection coefficient r and the transmission coefficient t, which are respectively

$$r = \frac{E_0^-}{E_0^+} = \frac{c}{a} \tag{9}$$

$$t = \frac{E_{m+1}^+}{E_0^+} = \frac{t_1 t_2, \ldots, t_{m+1}}{a} \tag{10}$$

The quantities a and c are the elements of the matrix

$$C_1 C_2 C_3, \ldots, C_{m+1} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \tag{11}$$

Using Eqs. (9) and (10), we can easily get the energy reflectance

$$R = |r|^2 \tag{12}$$

For perpendicular and parallel polarizations, the energy transmittances are

$$T_S = \mathrm{Re}\left(\frac{\hat{n}_{m+1}\cos\theta_{m+1}}{\hat{n}_0\cos\theta_0}\right)|t_S|^2 \tag{13}$$

$$T_P = \mathrm{Re}\left(\frac{\cos\theta_{m+1}/\hat{n}_{m+1}}{\cos\theta_0/\hat{n}_0}\right)\left|\frac{\hat{n}_{m+1}}{\hat{n}_0}t_S\right|^2 = \mathrm{Re}\left(\frac{\hat{n}_{m+1}\cos\theta_{m+1}}{\hat{n}_0\cos\theta_0}\right)|t_P|^2 \tag{14}$$

There Re indicates the real part.

## 3. Design and preparation

A doping structural 1-D PC with the structure of SUB|(ZnSe, Ge)3|(ZnSe, Si) (ZnSe, Ge)2|AIR, as Fig. 1 shows, is designed. SUB denotes the substrate, a material that has no spectral influence on propagation properties of infrared energy; and AIR represents the air. In 8–14 μm infrared waveband, the average refractive indices of Ge and ZnSe are about 4 and 2.44, respectively; when the average refractive indices of Si, as a doping material, is about 2.2 [18,19]. This bedded structure can periodically modulate the propagation of electromagnetic wave within it, and bring out some PBGs in some wavebands; one can adjust the position of those PBGs to which he interested in by some reasonable methods, such as the kind of coating materials, the thickness of each layer and so on. In this manuscript, we get a PGB by TMM, and move it to 8–14 μm infrared waveband to make a high reflectance. To realize the compatibility of 8–14 μm infrared waveband and 10.6 μm laser, after that, a defect was introduced into the periodic structure according to doping theory of PC, and then a reflective valley in the wavelength of 10.6 μm emerged; the curve in anticipation is shown in Fig. 2.

The 1-D PC is deposited on a polished silicon wafer scrubbed by anhydrous alcohol, then it is fixed to the substrate plate in the coating chamber before being further cleaned by argon discharge plasma for 20 min under a pressure of 10 Pa; the degree of vacuum in coating chamber is set to as low as $8 \times 10^{-4}$ Pa, under this circumstance, the electron gun will work well and the depositing rate, monitored by quartz monitor crystal, would be more accurate. Vaporized coating materials bombard by electron gun will splash onto the silicon wafer alternately.

The RAM in this paper we selected is a compound of magnetic iron fiber absorbent and urethane plastic. Magnetic iron fiber is

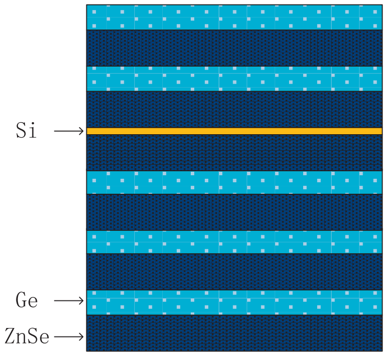

**Fig. 1.** Schematically bedded structure of the PC.