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Eye-protection glasses against YAG laser injury based on the band gap reflection of one-dimensional photonic crystal

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Abstract

Eye-protection glasses against YAG laser injury based on band gap reflection of one-dimensional photonic crystal (PC) is designed and manufactured in this paper. The laser beam (wavelength 1.06 μm) is reflected by the one-dimensional PC (with the transmission 10^{-7}) and absorbed by the phosphatic glass substrate (with the transmission 1% for 1.06 μm), so the transmission of the device for wavelengths of1.06 μm can reach 10^{-9}. The glasses have enough capabilities to protect the eyes from injury of ns-YAG lasers whose energy density is 1 J/cm^2 for all incident angles, and also to avoid a second injury to others from the reflected laser beams. The transmission of the glasses is beyond 70% for the visible lights. The testing data of the eye-protection glasses agree well with the theoretical predictions.

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Keywords: Eye-protection glasses; Photonic crystal; Band gap; Films

1. Introduction

Laser eye protection has become a key aspect of laser technology since lasers were achieved in 1960. Lots of work has been performed on this [1–5]. There are many kinds of laser eye-protection glasses in the market. Some of them can defend eyes against two or many wavelength laser beams and transmission of one kind of laser beam is 99.9%. Some of them can even protect eyes against tuning lasers. However, there are more rigorous demands for the newly invented large-power laser beam weapons.

A good laser eye-protection glass must have a very small laser beam transmission from the weapons but adequate transmission for visible light. It is the purpose of this article to design and manufacture a YAG laser eye protection based on the band gap reflection of one-dimensional photonic crystal (PC). PCs have been the subject of research for about two decades [6,7], which have a photonic band gap (PBG) owing to the periodic dielectric modulation. The electromagnetic wave whose frequency is within PBG cannot propagate in this structure. PCs are classified mainly into three categories, that is, one-dimensional, two-dimensional, and three-dimensional crystals according to the dimensionality of the materials period stack [8]. We combined the function of one-dimensional PC and the absorption of glass substrate to design the YAG eye laser protection glasses. The results of this study may be useful for researchers to achieve more effective laser protection glasses that are based on PCs.

2. Design and manufacture of the device

Configuration of the eye-protected glasses against YAG laser injury is shown in Fig. 1. Two kinds of

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materials with different refractive indices were alternately vaporized and deposited on the phosphatic glass substrate. The multilayer films form a one-dimensional PC. The material is periodic in the z-direction, and homogeneous in the xy-plane. The refractive index profile of the PC is a stepwise function

$$\begin{aligned} n(z) &= n_1,\ 0<z<b, \\ &= n_2,\ b<z<\Lambda,\ \text{with } n(z)=n(z+m\Lambda), \end{aligned} \tag{1}$$

where $\Lambda = a+b$ is the lattice period of the one-dimensional PC, m the arbitrary integer, n_1, n_2 are the refractive indices of the materials, and a and b denote the thickness of films made by the two kinds of materials, respectively.

Many studies have been published on the calculation of the one-dimensional PC. The electromagnetic wave in this structure is the Bloch wave and satisfies the following dispersive relation [9,10]:

$$K(\beta,\omega) = (1/\Lambda)\cos^{-1}[(A+D)/2], \tag{2}$$

where

$$A = \exp(-\mathrm{i}k_{1x}a) \times \left[\cos k_{2x}b - \frac{i}{2}\left(\frac{k_{2x}}{k_{1x}} + \frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}b\right], \tag{3}$$

$$D = \exp(-\mathrm{i}k_{1x}a) \times \left[\cos k_{2x}b + \frac{i}{2}\left(\frac{k_{2x}}{k_{1x}} + \frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}b\right]. \tag{4}$$

$K(\beta,\omega)$ is the Bloch wave number, k_{1x} and k_{2x} denotes the x component of the wave vectors k_1 and $k_2$in the first- and second-constituent dielectric layer. For $|(A+D)/2|<1$, $K(\beta,\omega)$ is the real number, and the laser beam can transmit through the PC. However, for $|(A+D)/2|>1$, $K(\beta,\omega)$ is an imaginary number, the laser beam cannot transmit through the one-dimensional PC and is totally reflected, which corresponds to the band gap of the one-dimensional PC. The critical case of $|(A+D)/2|=1$ corresponds to the edges of the band gap of the PC.

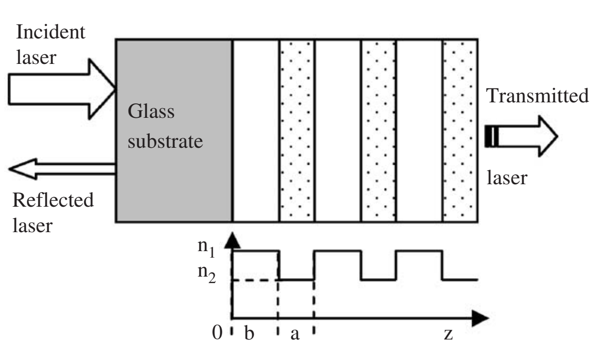

Fig. 1. Configuration of the laser eye-protection glasses based on one-dimensional PC. In the bottom of this figure is refractive index distribution of the PC. The multilayer structure is periodic in the z direction ($\Lambda = a+b$) and homogeneous in the $x-y$ plane. a and b are the thickness of the materials SiO_2 and ZrO_2, respectively.

Firstly, we will investigate the function of the one-dimensional PC. We choose ZrO_2 and SiO_2 to make the one-dimensional PC. The larger refractive index is $n_H = n_{ZrO_2} = 2.10$, and the smaller one is $n_L = n_{SiO_2} = 1.46$. The optical thickness of each film is $\lambda_0/4$, where λ_0 is the center wavelength of the band gap. The PC composes of 27 periods and the total thickness of the PC is only 8.18 μm. Neglecting the absorption and the dispersion of the materials, we calculated the transmission of the PC for the wavelength 1.06 μm versus the incident angle, as shown in Fig. 2. Obviously, when the incident angle on the PC is larger than 65°, the transmission of the laser at the wavelength 1.06 μm increases. This is because in this case, the wavelength 1.06 μm is shifted out of the band gap of the PC. On the other hand, the laser transmission of the PC at 1.06 μm is about 10^{-7} when the incident angle is less than 65°. Fig. 3 illustrates the transmission of the PC versus the wavelength at $\theta = 0$ (the solid line) and $\theta = 65°$ (the dashed line), respectively. The band gap was shifted toward shorter wavelength when the incident angle increased. From Fig. 3, we can see that the band gap was shifted toward shorter wavelength when the incident angle increased.

As mentioned above, the one-dimensional PC can only defend laser beams that are incident at an angle below 65°. To break the limitation, we should consider the function of the substrate. In our design, the substrate was made of phosphatic glass which has a large absorption for the YAG laser beam (1.06 μm), but a large transmission for visible light. The refractive index of phosphatic glass is $n_g = 1.498$ and the thickness of the substrate is 3 mm. The transmission of phosphatic glass

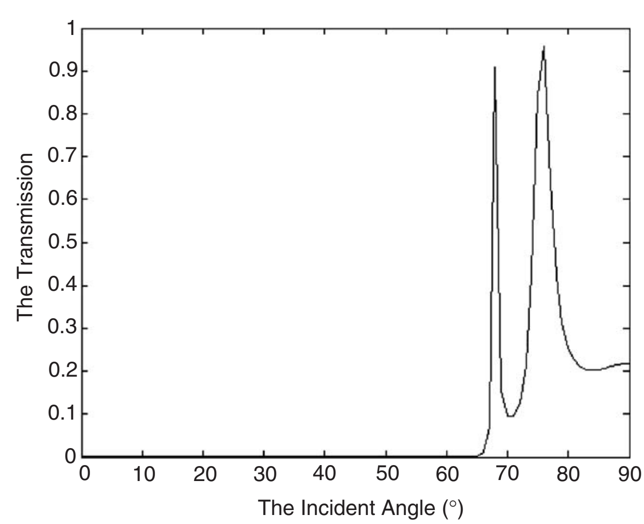

Fig. 2. The transmission of the wavelength 1.06 μm of the one-dimensional PC versus the incident angle. When the incident angle reaches 65°, the transmission of the laser increases immediately.

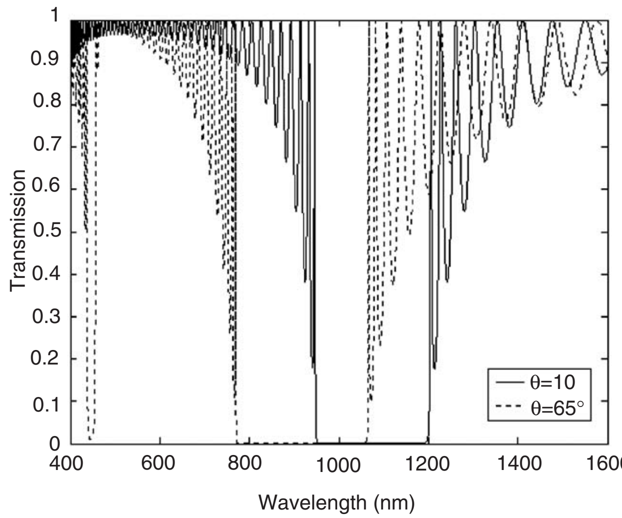

Fig. 3. Transmission of the PC versus the wavelength under the incident angle at $\theta = 0^\circ$ and 65°. The solid and the dashed line denote the cases of the incident angle being at 0° and 65°, respectively.

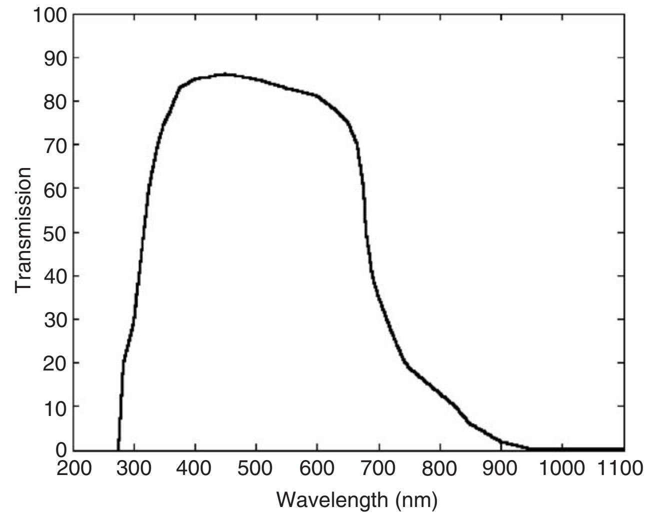

Fig. 4. Transmission curve of the phosphatic glass substrate versus the wavelength. The thickness of substrate is about 3 mm.

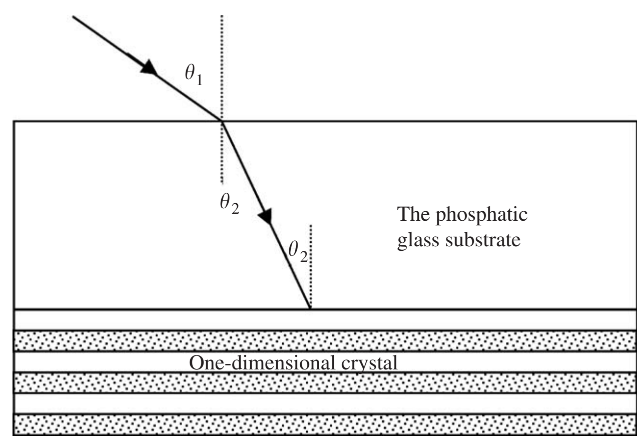

Fig. 5. Laser beam transmission in the device. θ_1 is the incident angle on the substrate. θ_2 is the refractive angle also the incident angle on the one-dimensional PC.

substrate tested experimentally is shown in Fig. 4. Clearly, the transmission of the wavelength 1.06 μm is about 1%.

When the laser beam is incident upon the surface of the substrate side at the incident angle θ_1, as shown in Fig. 5, according to the Snell' law, we have

$$n_0 \sin\theta_1 = n_g \sin\theta_2, \tag{5}$$

where n_0 and n_g are the refractive indices of air and phosphatic glass, respectively. θ_2 is the refractive angle and is also the incident angle on the one-dimensional PC. The maximal refractive angle θ_{2max} (which denotes the maximum value which the angle θ_2 can reach) is derived as

$$\begin{aligned}\theta_{2\max} &= \sin^{-1}(n_0/n_g \sin\theta_{1\max}),\\ &= \sin^{-1}(1.0/1.498 \sin(\pi/2)),\\ &= 41.88^\circ.\end{aligned} \tag{6}$$

It is much less than the critical angle 65°. So we conclude that the eye-protection glasses can defend the laser beam that covers all incident angles.

Suppose that the transmission of the phosphatic substrate glass is 1%, we also calculate the output power corresponding to the following input power of YAG laser 0.2, 0.4, 0.6, 0.8, 1.0 W, (indicated by stars in Fig. 6). The line connecting the stars is linear and the slope of it is the transmissivity. The transmission can reach 10^{-9}. That is to say that our device can defend the injury of YAG laser whose energy density is up to 500 J/cm^2 to the eyes (as the destruction threshold energy density of eyes is 0.5 μJ/cm^2) [11]. In practice, this device can be used to defend the laser of which the incident energy density is less than 1.0 J/cm^2 because of the destruction threshold energy density of the phosphatic glass.

3. Experimental testing

We show the eye-protection glasses against YAG laser injury based on the band gap reflection of one-dimensional PC in Fig. 7. It has a 54-layered dielectric film (27 periods). When the YAG laser beam whose wavelength is 1.06 μm is vertically incident on the substrate side of the eye-protection glasses, we used the spectrometer to test the transmission spectrum of the device whose results are shown in Fig. 8. The transmission for the visible electromagnetic spectrum exceeded 70%. For this reason, this YAG laser eye-protection glasses does not influence the observing effect through the device.

4. Conclusion and discussion

In this paper, we designed and manufactured eye-protection glasses against YAG laser beam (wavelength

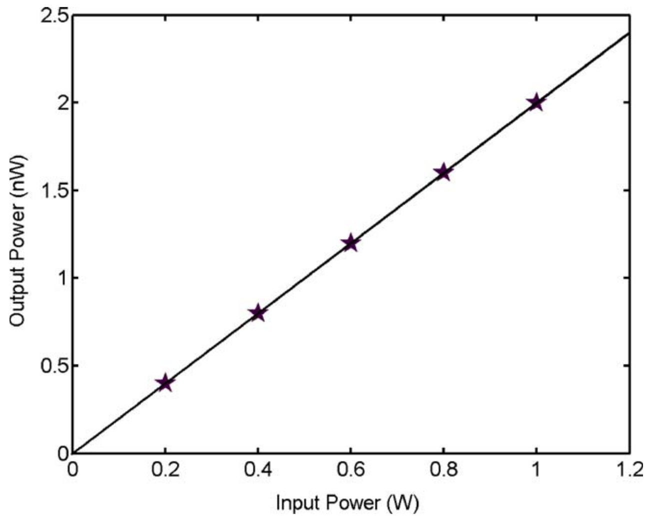

Fig. 6. Curve of the output power verses the input power for the eye-protection glasses with 27 period film layers on the phosphatic glass substrate. The five stars denote the output power corresponding to the following input power, 0.2, 0.4, 0.6, 0.8, 1.0 W.

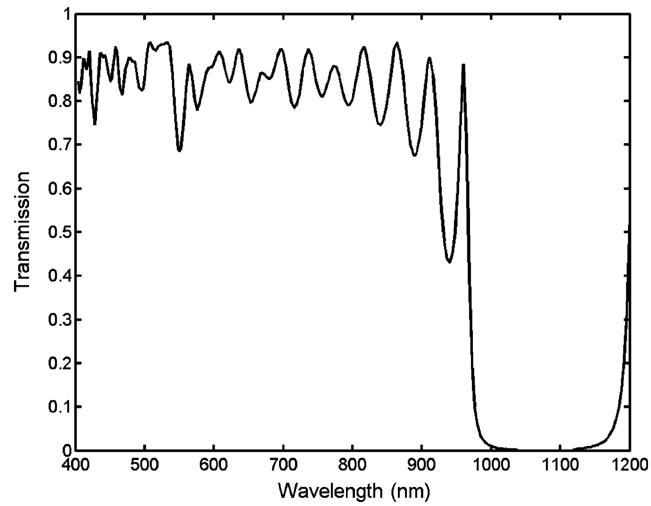

Fig. 8. Experimental transmission spectrum of the YAG laser eye-protection glasses based on the one-dimensional PC. The transmission of the YAG laser wavelength of 1.06 μm is about 10^{-9}, but the transmission of visible light is beyond 70%.

Fig. 7. Photo of the designed eye-protection glasses against YAG laser based on the one-dimensional photonic crystal.

1.06 μm) injury based on the band gap reflection of one-dimensional PC. Combining the function of the one-dimensional PC and that of the phosphatic glass substrate, the glasses can defend the YAG laser that covers all incident angles. The transmission of the YAG laser pulses (ns) through the device is only 10^{-9}. Considering the destruction threshold of phosphatic glass, we think that the device has enough capabilities for defending the eyes from injury of 1.06 μm wavelength YAG laser pulses (ns) whose energy density is 1 J/cm^2. The transmission of the visible lights is beyond 70%. Because the reflected laser beam has been twice absorbed by the phosphatic glass substrate, it avoids the second injury to the others by the reflected laser beam. The testing data of the eye-protection glasses agree well with the theoretical predictions. Our study could be useful for researchers to achieve more effective laser protection glasses which are based on PCs.

Acknowledgments

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