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A Novel Dual Filtering Mechanism for Laser Safety Eyewear with Polycarbonate Lens Coated by Zirconium Dioxide and Silicon Dioxide

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Abstract:
In laser safety eyewear, due to the lack of complete blocking of ultraviolet and infrared rays, we proposed a structure based on one-dimensional multilayer composed of several layers of silicon dioxide and zirconium dioxide materials alternately behind polycarbonate lens. It is find out that the acceptance angle range to the photonic crystal is 0 to 39°. This incident angle range corresponds to the band gap of the photonic crystal. In the transverse electric polarization, with increasing incident angle, the width of the gap rises, while in the transverse magnetic polarization decreases. Our results show that in the transverse electric mode, the optical density gradually increases with increasing angle while it decreases in the transverse magnetic one. The higher optical density, the higher eye protection at specified wavelength. If the incident wavelength is placed in the band gap region, the field intensity gradually decays. Therefore, the proposed structure for laser

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safety eyewear can provide the maximum reflection on the surface of the lens. Our supposed structure for safety eyewear can be used in infrared lasers such as Nd: YAG, diode and Ti: sapphire.

1. INTRODUCTION

Working with lasers at different wavelengths and powers may be associated with risks and injuries for the operator, so, compliance with safety principles is vital [1]. Laser safety eyewear is used to protect eye tissues from damage caused by the beams emitted by a laser device [2]. Like the path of visible light, laser beams entering the eye pass through the cornea, aqueous humor, lens, and vitreous humor to focus on the retina. Depending on the intensity of the laser beam, each of these parts of the eye may react. Laser safety eyewear is utilized to protect the eye tissue from damage caused by the waves emitted from the laser device [2]. When light enters the eye, it passes through three parts: the cornea, the lens, and the retina. Depending on the intensity of the laser waves, each of these parts can react to light. This reaction can be due to heat absorption or as a result of a photochemical reaction. Generally, in the case of laser waves, this reaction will be of the heating type, which leads to severe tissue damage [3]. The waves emitted from laser devices with high energy will cause irreversible damage. For example, in UV or other conventional lasers such as Nd: YAG 1064, diode laser 808 or alexandrite 750 nm, which are in the range of visible and infrared light, the retina will be directly affected by severe damage. Depending on the intensity of the waves, these damages can lead to blindness and permanent vision loss. In other words, the stronger the laser energy, the more severe the damage to the retina [4,5]. Therefore, wearing laser safety eyewear is necessary and one of the obligations of working in this field [6].

For medium power levels, safety eyewear with plastic lens are selected, which are made of colored polycarbonate as an absorbing layer [7]. For high power lasers, glass is chosen. Glass has better resistance to laser light and scratches, but it is fragile against mechanical shocks. In addition to the mentioned materials, there are other combined products include glass and polymer layers [8].

Polycarbonate is placed in the category of transparent and flexible thermoplastics. Polycarbonate sheets can be used in different colors and designs. These sheets are resistant to ultraviolet rays to a great extent, and their color and transparency do not change against sunlight and are well able to prevent the penetration of harmful effects of ultraviolet rays. Low moisture absorption, high electrical and thermal resistance, and good impact and oxidation resistance are other properties of this thermoplastic. They are also biologically neutral and have good resistance to chemicals. The light transmission in polycarbonate can be between 35 and 82%, depending on its color [9].

Not many articles have been reported on laser safety eyewear. In published articles, some topics such as laser eyewear protection for soft tissue [10], eye-safety analysis for airborne laser systems flight test and training operations [12], laser safety programs in clinical practice [11], laser eye protection and color recognition and discrimination in aviation [13], femtosecond laser eyewear protection [14], ultrafast laser eyewear protection: measurements and precautions [15], laser safety features of eye shields [16], suitability of polycarbonate safety eyewear for UV laser eye protection [17], holmium laser goggles [18] have been investigated.

Despite the existence of materials to that filter ultraviolet rays, infrared rays (≈750 to1400 nm) can not be blocked. Also, the safety eyewears that can block both ultraviolet and infrared regions have not been well developed. Therefore, we need complete protection against laser rays. Laser safety eyewear filter dangerous rays in two ways: the first way is that the rays are absorbed through the thickness of the lenses. In this method, the lenses may heat up during long-term use. In the second case, the lenses prevent the light from entering like a mirror and reflect the rays [2].

Due to the lack of complete blocking of ultraviolet and infrared rays and also to block laser rays at any incident angle, we proposed a structure based on one-dimensional (1D) photonic crystal. According to this structure, we considered several layers of Silicon dioxide and Zirconium dioxide materials alternately behind polycarbonate lenses. Our supposed arrangement for safety eyewear can be used in infrared lasers such as Nd: YAG, diode and Ti: sapphire.

2. THEORY

To describe the function of laser safety eyewear, it is necessary to remember concepts such as optical density (OD), maximum permissible exposure (MPE) and visible light transmittance (VLT). The MPE is highly dependent on the wavelength, duration of exposure and the type of living tissue. The OD indicates the ability of the glasses to absorb the destructive energy of the laser [19]. To choose the suitable protective glasses against laser rays, the OD should be considered according to the type and power of the laser used, and the amount of required protection. The OD is usually in the range of 0 to 7 or higher. The larger the OD, the more protection against the eye damages. The calculation of the OD is as follows:

$$OD=\log(1/T), \qquad T=I_I/I_0 \qquad [1]$$

Where T is the transmission coefficient, Ii is the intensity of incident wave on the glasses and It is the intensity of transmitted wave. The lower the percentage of transmission, the higher the OD value [19].

Polycarbonate is the most common material to manufacture of laser safety eyewear. Tanaka Y. et al. reported that polycarbonate lenses do not provide complete filtering against visible and infrared rays [20]. Here, to solve this problem, the band gap mechanism is proposed. So, a periodic multilayer consisting of silicon dioxide (SiO2) and zirconium dioxide (ZrO_2) materials is selected behind the polycarbonate lenses. This structure acts as a second filter. The first filter is the polycarbonate lens.

It is necessary to mention that ZrO_2 is heat resistant; it may reduce the heating of the goggles and protect the wearer's skin from heating in contact with the goggles. Laser beams passing through the goggles and reaching the eye will still cause tissue reactions where the laser beams contact with the eye tissues and thermal reactions may occur. The only way to prevent thermal reactions in the eye caused by laser beams is to prevent the laser beams from entering the eye. The ZrO2 is one of the well-studied transition-metal oxides in optical fields. Because of the excellent optical properties of the ZrO_2 films, such as high refractive index, big optical band gap (5.1–7.8 eV), low optical loss, and high transparency in the visible and near-infrared region, they are widely used in the optical fields, including high-reflectivity mirrors, broadband interference filters, and active electro-optical devices [21]. Also, the SiO_2 is one of the most applied low-index and inexpensive materials in optical coatings. It is incredibly useful in optics and optical coatings. Not only is it incredibly long-lasting even under high-temperature conditions, but it also has excellent transparency better contrast, resistant to thermal shock and refractive index properties. This makes it the perfect choice for many high-end optical applications, including lenses and windows.

Photonic crystals consist of an alternating insulating or conductive-insulating structure. As semiconductors affect the movement of electrons due to alternating electric potential, photonic crystal crystals have the same situation regarding the movement of photons. This similarity results from the similarity between the Schrödinger equation in solid-state physics and the Helmholtz equation in electromagnetic field propagation. Photons can pass through the photonic crystals or be reflected. The range of wavelengths not allowed to pass is called the photonic band gap (PBG). The 1D PBG materials have been widely used as optical thin films [22, 23].

Here, the numerical method used in this article is the transfer matrix method (TMM) [24]. For the transverse electric polarization (TE) mode by entering the boundary conditions at the interface between the layers, the transfer matrix between the layers is obtained according to the following equation [24]:

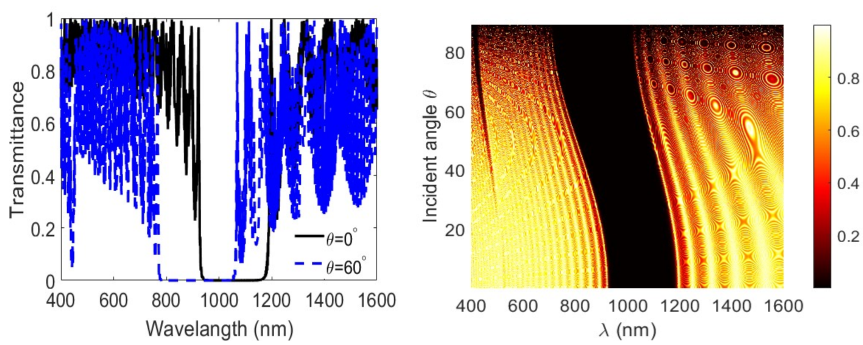
$$M_j(\Delta z,\omega)=\begin{pmatrix}\cos(k_z^j\Delta z) & j/q_j\sin(k_z^j\Delta z)\\ jq_j\sin(k_z^j\Delta z & \cos(k_z^j\Delta z)\end{pmatrix} \quad [2]$$

Where $k_z^j = (\omega/c)\sqrt{\varepsilon_j}\sqrt{\mu_j}\sqrt{1-\sin^2/\varepsilon_j\mu_j}$ is the component of the wave vector along the z axis, c indicates the speed of light, $q_j = \sqrt{\varepsilon_j}/\sqrt{\mu_j}\sqrt{1-\sin^2/\varepsilon_j\mu_j}$ for TE mode. The transmission coefficient is

$$t(\omega,\theta) = \frac{2\cos\theta}{(m_{11}+m_{22})\cos\theta + i(m_{12}\cos^2\theta - m_{21})} \quad [3]$$

3. RESULTS AND DISCUSSION

As mentioned before, for the complete filter of ultraviolet and infrared waves in the laser safety eyewear, we proposed a structure as {polycarbonate lens/ $[AB]^N$}, namely we used a photonic crystal behind the polycarbonate lens. The first layer in the photonic crystal structure is ZrO_2 with a refractive index of n_A=2.1 and the second layer is SiO_2 with a refractive index of n_B=1.46, and their thickness is assumed to be d_A=120 and d_B=180 nm, respectively. Also, the thickness of the polycarbonate lens is 2 mm, and its refractive index is 1.59. The periodicity of the layered structure is N=15. Here, all materials are supposed to be linear, homogeneous, and nonabsorbent. The thickness of the layers follows the relationship of a quarter wavelength to have a large band gap, namely $n_Bd_B=n_Bd_B=\lambda_0/4$, where λ_0 is the reference wavelength corresponding to the wavelength of the center of the band gap. The gap is maximum for a quarter wave condition. Under this condition, reflected wave from each layer are precisely in phase at the midgap wavelength.



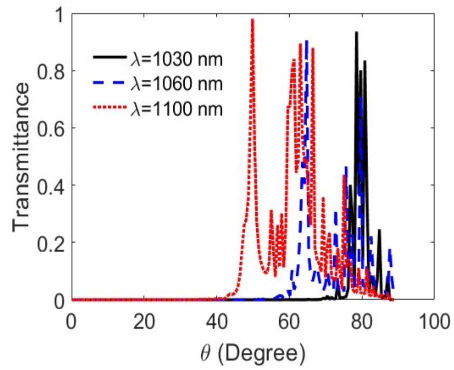
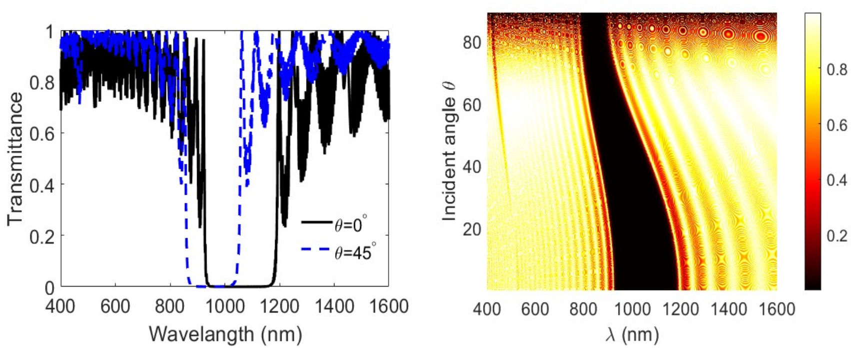


Fig. 1: The transmission spectrum of TE mode with the polycarbonate lens.

The transmission spectrum is plotted versus wavelength for TE (Fig. 1) and TM (Fig. 2) polarizations. The supposed wavelength region is 400 up to 1600 nm. In this range, we see a band gap from 750 to 1200 nm. For both TE and TM polarizations, as the incident angle increases, band gap edges shift towards lower wavelengths. As can be seen in Figs. 1, 2, in the TE polarization, by increasing incident angle, the width of the gap enhances, while in the TM polarization decreases.



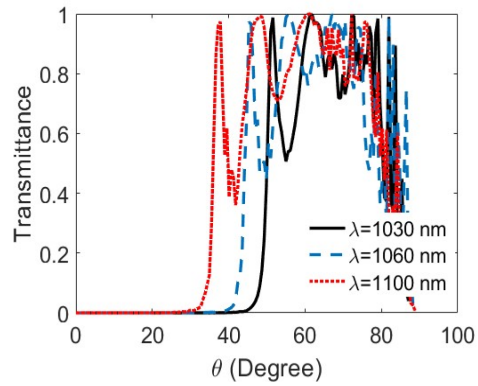


Fig. 2: The transmission spectrum of TM wave.

The changes in the bandwidths with the increase of the incident angle are due to the change in the effective optical path length inside the crystal and the constructive or destructive interference of the reflected rays from different layers. The different band structure in TE and TM waves originates from the TMM relations.

The incident angle range (acceptance angle range) to the photonic crystal is 0 to 39°. In other words, the maximum incident angle to the photonic crystal is 39°. This angle can be calculated using Snell's relation as

$$n_{air}\sin\theta_0 = n_{polycarbonate}\sin\theta_r \rightarrow \theta_r = \sin^{-1}\left(\frac{n_{air}\sin\theta_0}{n_{polycarbonate}}\right), \qquad [4]$$

Where n_{air} =1, the maximum incident angle to the polycarbonate lens $\theta_0 = 90^{\circ}$ and $n_{polycarbonate}$=1.59. So the angle of θ_r is equal to $\sin^{-1}\left(\frac{n_{air}\sin\theta_0}{n_{polycarbonate}}\right) = 39^{\circ}$.

As shown in Fig. 1(bottom panel), this incident angle range corresponds to the band gap of the photonic crystal. Therefore, in the first stage, some part of the incident wave to the glasses is filtered by the polycarbonate lens. This blocking is not done entirely, according to Ref. [20]. As a second mechanism for filtering, the photonic crystal, attached to the back of the polycarbonate lens, can block the waves (see bottom panel in Figs. 1, 2).

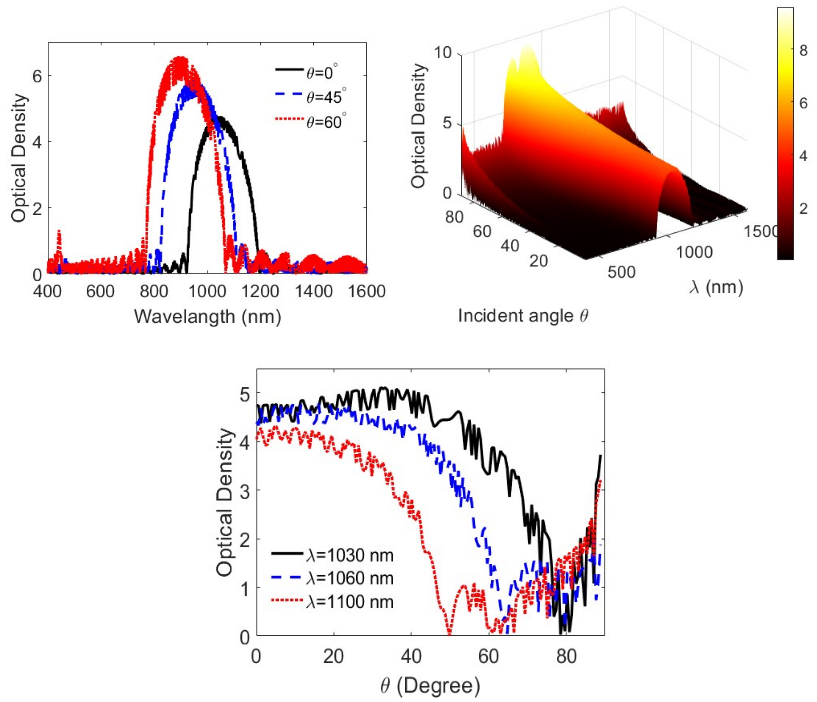
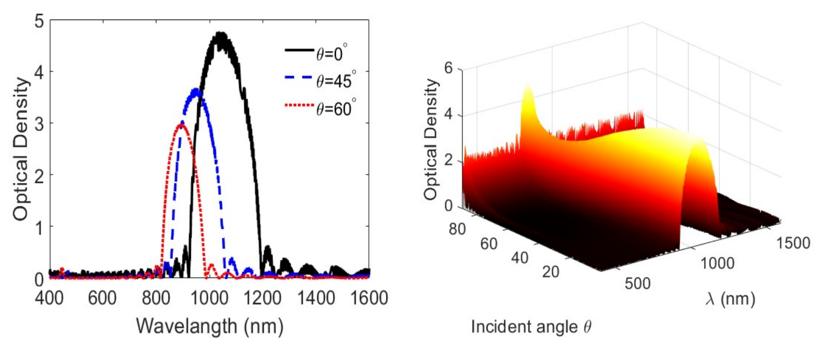


Fig. 3: The Optical density of mode with the polycarbonate lens.



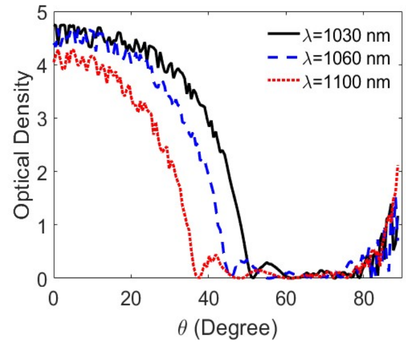


Fig. 4: The Optical density of TM mode with the polycarbonate lens.

As we know, optical density (OD) is critical parameter that affects the choice of anti-laser glasses. By using relation 1, the optical density diagram is obtained (see Figs. 3 and 4). It is shown that in the TE mode, the optical density OD gradually increases with increasing angle (see Fig. 3), at the same time; it decreases in the TM polarization (see Fig. 4). In the TE wave, for example, at angles of 0, 45 and 60 degrees, the OD is 6.5, 5.5 and 4.5 respectively. For TM polarization, at the same angles, the OD is 5.5, 3.5, and 2.5, respectively. The higher the OD, the higher the degree of protection. In the TE polarization in the wavelength range of 800-900 nm the highest OD is observed about normal incident angle. But in the TM wave, the same result occurs in the wavelength 1000-1100 nm.

In Figs. 3 and 4 (bottom panel), the OD is plotted in terms of the incident angle and for three different wavelengths located in the infrared region. For selected wavelengths as 1030 (solid line), 1060 (dashed line), and 1100 nm (dotted line), the maximum OD can be seen in the incident angles from 0 to 10 degrees. For example, at λ=1060 nm (wavelength of Nd: YAG laser), the lowest OD is obtained about incident angles greater than 60° degrees. For each selected wavelength, the OD behavior versus incident angle is shown in Figs. 3 and 4 (bottom panel).

In Fig. 5, we have sketched the field intensity distribution as a function of depth at normal incidence for both TE and TM waves in the supposed structure. The wavelengths of the edge of the bandgap (λ=820 nm) and inside the bandgap (λ=950 nm) were chosen to plot the electric field intensity distribution. At each interface between layers, the tangential component of electric and magnetic fields must be continuous. If the wavelength is located in the band gap region, then the field intensity decays (see the left panels in Fig.5). Therefore, the proposed structure can provide the maximum reflection on the surface of the lenses. But, if the incident wavelength is placed in the passband, it can pass through the structure (see the right panels in Fig.5). Also, the field intensity in the TE polarization is more than that of the TM one.

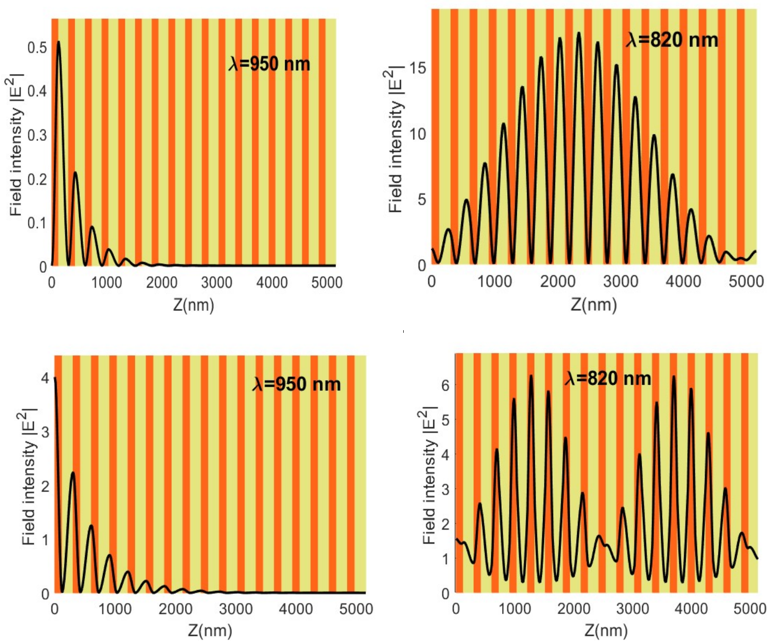


Fig. 5: The field intensity of TE (two upper panels) and TM (two bottom panels) versus depth in the supposed structure corresponding to the inside and band edge wavelengths.

4. CONCLUSIONS

In this paper, for a complete filtration of ultraviolet and infrared waves in laser safety eyewears, we proposed a structure composed of polycarbonate lens and a 1D periodic multilayer made of SiO_2 and ZrO_2 materials was used behind the lens. This structure acts as a second filter. The first filter is the polycarbonate lens as an absorption filter. The numerical method used in this article is the transfer matrix method. The supposed wavelength region is 400 up to 1600 nm. For both TE and TM polarizations, as the incident angle increases, band gap edges shift towards lower wavelengths. Also, in the TE polarization, with increasing incident angle, the width of the gap increases, while in the TM polarization decreases. It is found out that the incident angle range (acceptance angle range) to the photonic crystal is 0 to 39°. This incident angle range corresponds to the band gap of the photonic crystal. Our results show that in the TE mode, the optical density OD gradually increases with increasing angle while it decreases in the TM one. The higher the OD, the higher the degree of protection. If the incident wavelength is placed in the bandgap region, the field intensity gradually decays. Therefore, the proposed structure for laser safety eyewears can provide the maximum reflection on the surface of the lens. Our supposed structure can be used in infrared lasers such as Nd: YAG, diode and Ti: Sapphire.

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