Optical limiter with an organic solution sandwiched between a polymer slab and a polymer grating

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An optical limiter was designed and fabricated. The device consists of an organic solution sandwiched between a polymer slab and a transparent relief polymer grating with a triangular groove. At low power the device has a high transmittance because the refractive index of the solution is matched with those of the slab and the grating materials and because the grating does not diffract. However, high power makes the organic solution thermally vaporize and makes the indices of the solution, slab, and grating materials become mismatched, which causes the grating to appear. The incident light is strongly absorbed, scattered, and self-defocused by the organic solution, and the grating suppresses the zero-order diffraction. Thus the transmitted light energy becomes lower than the damage threshold of human eyes or optical sensors. The device is an effective protection for human eyes or optical sensors against broadband pulsed-laser damage.
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1. Introduction

Nowadays, laser sources are not confined to use in the laboratory but are widely used in many applications, including many areas of industry and medicine as well as the military. Despite the great contributions they make to our society, they also pose a potential hazard for human eyes and optical sensors,[1–3] such as the possibility of damage from pulsed lasers or temporary blinding by continuous-wave lasers. So it is very important to develop optical limiters that can strongly attenuate intense optical beams while exhibiting high transmittance for low-intensity ambient light levels to protect human eyes or optical sensors from intense laser pulses. Ideal limiters would have high linear transmittance for low-input-energy laser pulses and low transmittance for input energies above a user-specified value so that the output would become clamped. In addition, an ideal limiter would have a rapid response (picoseconds for some applications), a broadband response (e.g., the visible spectrum), and a large dynamic range. But achieving this level of protection has been made more difficult by the increasing variety of laser wavelengths. With nearly every wavelength that is emitted by these sources, there is a need to develop optical limiters and tunable filters that can suppress harmful radiation.

In recent years the greatest interest in optical limiters has been focused on optical sensors or on the protection of optical detectors.[4–6] Many schemes have been suggested for optical limiters, including the use of nonlinear absorption,[7] nonlinear refraction,[8] and nonlinear scattering[9] or mismatched indices.[10] Until now neither linear nor nonlinear optical limiters can singly meet the requirements for protecting optical sensors against the nanosecond tunable laser over the whole visible range. In this paper we combine the linear and nonlinear effects to design an optical limiter. This device can be used to avoid damage to optical sensors or optical detectors from a broadband laser.

2. Theoretical Principles of the Device

In this section we mainly discuss the function of the transparent relief polymer grating in the device. Since diffraction gratings were developed about 200 years ago, they have been widely and continuously studied because of the important role that their dispersion capability plays in spectroscopic instruments.[11] Here we just briefly summarize the theory.

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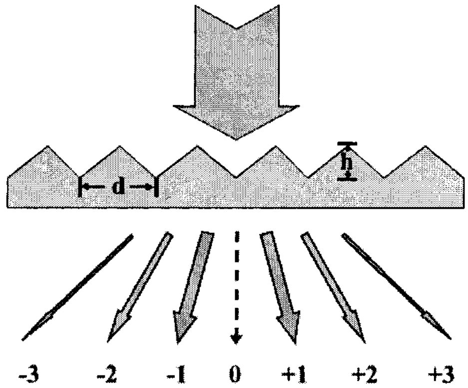

Fig. 1. The polymer grating with a triangular groove structure: d, the period of the grating; h, the peak groove height of the grating. The arrow above the grating illustrates the incident beam, and the arrows below the grating illustrate the diffracted beams.

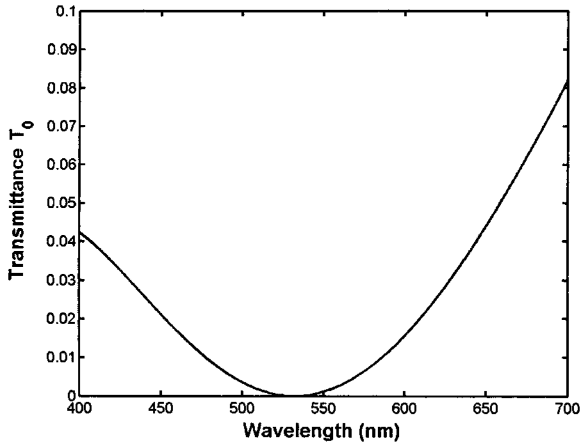

Fig. 2. Triangular groove grating transmittance of the 0-order diffraction beam in the visible spectrum.

The structure under consideration is shown in Fig. 1. It is a periodic corrugation with a triangular groove boundary, where d and h denote the period and the peak groove height of the grating, respectively. To simplify our discussion, we assume that the incident light is a plane wave and that it normally illuminates the grating. It is well known that the transmitted light is formed from many diffractive beams that correspond to different diffraction angles in the grating, as schematically shown in Fig. 1. According to the grating equation, we obtain

$$\sin \theta_m = m\lambda_0/nd, \tag{1}$$

where m is an arbitrary integer denoting the diffraction order, θ_m is the diffraction angle of the m-order diffraction beam, n is the refractive index of the grating materials, and λ_0 is the wavelength of the incident light in vacuum.

According to Eq. (1), when the period of the grating is approximately equal to the incident wavelength, i.e., $d \approx \lambda_0$, the ± 1-order diffraction angle satisfies the following equation:

$$\theta_{\pm 1} \approx \arcsin(\pm 1/n), \tag{2}$$

where $\theta = \arcsin(1/n)$ is just the critical angle of the total internal reflection on the interface of the air and the rear plane of the polymer grating. Then the grating can transmit only the 0-order and the ± 1-order diffraction beams; at the same time, other beams of higher order are reflected owing to the total internal reflection when $d \approx \lambda_0$. Thus the grating acts as an aperture to transmit only the 0-order diffraction beam to the optical detectors or optical sensors. To reduce the flux of the 0-order diffraction beam, we should carefully control the peak groove height of the grating h, as shown in Fig. 1.

Using Fourier analysis and assuming $h = k\lambda_0/\Delta n$, we can calculate the intensity transmittance of the 0-order diffraction beam as a function of the wavelength λ for the grating with a triangular groove structure as[12]

$$T_0 = \frac{\sin^2(k\pi\lambda_0/\lambda)}{(k\pi\lambda_0/\lambda)^2}, \tag{3}$$

where k is an arbitrary natural number and Δn is the refractive-index difference between the air and the grating materials. Figure 2 shows the relationship with $k = 1$ and $d \approx \lambda_0 = 532$ nm in the visible spectrum. Clearly the transmission is less than 10% in the whole visible spectrum. The triangular groove structure grating has a minimum transmittance for light of 532 nm wavelength.

3. Design and Manufacture the Device

We combine the linear and nonlinear effects to design the optical limiter. It consists of an organic solution sandwiched between a polymer slab and a transparent relief polymer grating with a triangular groove structure. The slab and the grating are made of modified polycarbonate (mPC), which has a high transmittance for visible light ~93% and a high antietching capability for many kinds of acid, alkali, and organic solution (toluene solution, chloroform solution, etc). The refractive index of the mPC is 1.5. We made the organic solution by putting lead phthalocyanine [$PbPc(CP)_2$] and carbon-60 (C_{60}), which are two kinds of reverse saturable absorption materials widely studied,[13–16] in toluene ($C_6H_5CH_3$). The organic solution is index matched with the polymer slab and grating at low input fluence; that is to say, the device is transparent, as shown in Fig. 3(a). High input fluence can change the index of the solution; vaporize it to form a bubble; and activate the grating to diffract, reflect, and reduce most of the output light in order to protect optical detectors or optical sensors, as shown in Fig. 3(b).

The fabrication process for the optical limiter is as follows:

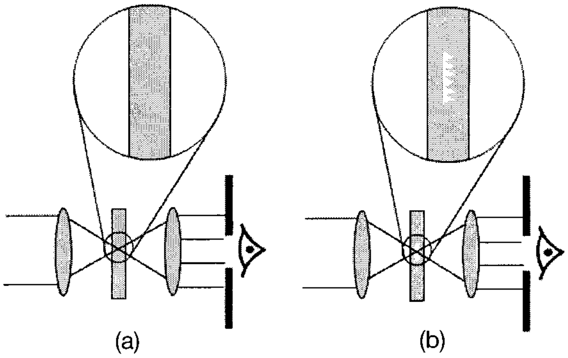

Fig. 3. Illustration of the optical device at two different input fluences: (a) with low input fluence the indices are matched and so the grating disappears; (b) with high input fluence a bubble is created because of the thermal effect, the indices are mismatched, and so the grating is activated.

1. The metal aluminum is vaporized on the inner surface of the toughened glass template.
2. According to the period and the peak groove height of the grating designed in Section 2, we make a triangular structure grating on the metal aluminum film by using a triangular structure graver.
3. The mPC monomer and initiator are simultaneously cast into a mold in which one side is a glass slab and the other side is the metal aluminum grating. Then the sample is put into a heater.
4. After the sample was annealed to eliminate materials stress, the triangular groove structure mPC grating is made.
5. The solution of lead phthalocyanine and carbon-60 in toluene is poured into the mold in which one side is an mPC slab and the other side is the mPC grating. The cell of the device is not completely filled because the bubble responds to low pressure by growing. The thickness of the solution is ~80 μm in the cell. The optical-limiting device is finally formed by encapsulation.

4. Experimental Testing

The experimental setup used to test the optical-limiting behavior of our device is shown schematically in Fig. 4. The light source is a pulsed *Q*-switch Nd:YAG laser system. Single pulses of 5 ns FWHM at 532 nm with a TM_{00} mode are used. First, the diameter of the laser beam is set at 4.3 mm by use of a beam expander. Then the beam is 50:50 split into two beams by a beam splitter. One of the beams serves as a reference beam and is detected after the lens 4; the other is focused by lens 1 and is sent into the optical limiter. The light transmitted through the optical limiter is detected after it passes through an aperture and two lenses (lens 2 and lens 3), as shown in Fig. 4. The focal length of the lenses is 26.7 cm. The Rayleigh range is 40 μm.

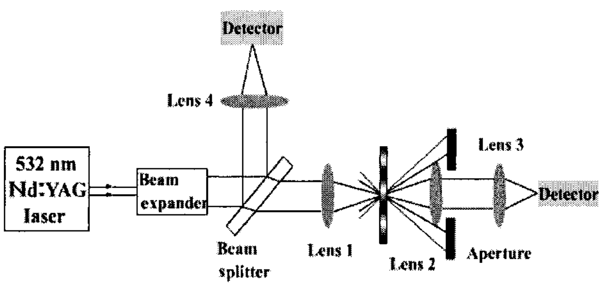

Fig. 4. Experimental setup for testing the limiting properties of the device. The light source is a 532 nm Nd:YAG pulsed laser. The pulse width is 5 ns.

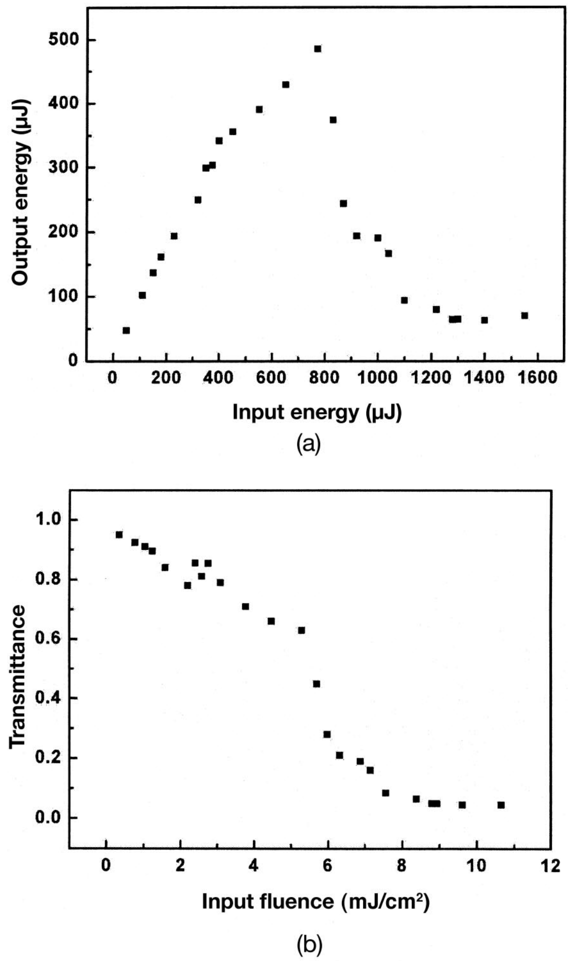

Fig. 5. Optical-limiting behavior of our device, measured at 532 nm: (a) output energy versus input energy and (b) transmittance versus input energy fluence.

The optical limiting behavior of our device is shown in Fig. 5, where (a) is the curve of the output energy versus the input energy and (b) is the curve of the transmittance versus the input fluence. It can be concluded that a bubble is created when the input energy increases to ~800 μJ (the corresponding input energy fluence is 5 mJ/cm^2). The polymer grating appears, and the transmission is suddenly decreased, as shown in the figure.

5. Discussion and Conclusion

In this paper we propose a novel optical-limiting device. It is made by combining organic solution, lead phthalocyanine, and carbon-60 in a toluene solution, which is then sandwiched between a mPC slab and a transparent mPC grating with a triangular groove structure. The refractive index of the solution is matched with the slab and grating materials at low input fluence. But the high input fluence creates a bubble in the organic solution owing to the thermal effect, so the grating appears because the solution's refractive index becomes mismatched with those of the slab and grating materials. In our experiment a bubble is created in the solution when the input energy increases to $\sim 800\ \mu J$ (the corresponding input energy fluence is $5\ mJ/cm^2$). The device combines linear effect and nonlinear effects to protect human eyes and optical sensors from damage due to high-energy lasers whose energy fluence is beyond the damage threshold of optical detectors or optical sensors. It is an effective optical-limiting device used to avoid damage to optical sensors or detectors from broadband laser systems.

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