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Optical Power Limiting for Eye Protection from Tunable Lasers

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1. INTRODUCTION

Due to the extensive use of lasers in aiming devices, range finders, and in remote sensing, the protection of eyes and sensors from laser beams becomes critically important. It has been a challenging task to provide protection from wave-length tunable lasers without the serious sacrifice of vision capability. In this work, we describe two different approaches which can significantly attenuate the laser beam through the whole visible region. One approach is to use specific geometric configuration with thin film aluminum mirrors^{1,2}. The other is to use the properties of reverse saturable absorption of fullerene^{3,4}. The combination of these two approaches can possibly become an effective device for eye protection from high power tunable lasers. The principle and mechanism to achieve eye protection will also be discussed.

The goal for eye and sensor protection is to attenuate the amount of incident light below the damage threshold. The ANSI standards indicate that for visible wavelengths and nanosecond pulse durations, the maximum permissible exposure on the surface of the corneas is about 0.2 μJ . The damage threshold by a nanosecond laser on a rhesus monkey was measured to be of the order of a few microjoules⁵.

In this work, we report our study of the attenuation of laser beams by thin aluminum film mirrors, prior studies of which have been covered extensively^{6,7}. We have, however, developed a novel approach that has produced promising results, using a system that has components that inhibit laser propagation by damage mechanisms. Our principal components consist of thin film mirrors. When a laser pulse is focused on such a mirror, the metal surface of the mirror is vaporized by part of the pulse, leaving a hole in the mirror. The rest of the pulse will then travel through the mirror rather than be reflected from it into the viewing system. Our approach incorporates a double-pass system (Fig. 1) designed to reach our goal of 1 μJ of energy throughout the system. This double-pass approach enables achieving very high attenuation by thin Al film compared to a previously reported sacrificing mirror approach.

The thin aluminum film mirror approach has a disadvantage in that the sacrificial components may need to be replaced from time to time. The other common approach for eye and sensor protection is to use nonlinear materials which have a high third order of susceptibility $\chi^{(3)}$. With $\chi_{im}^{(3)}$, high two-photon absorption cross sections can be obtained. Thus, as room light passes through the intense laser beam will be significantly attenuated by two-photon absorption process. However, there are no transparent materials available which have a high enough $\chi_{im}^{(3)}$ for eye protection by two-photon absorption, although extensive search has been pursued during the past decade^{6,7}. Some materials such as phthalocyanine have the properties of reverse saturable absorption (RSA) which can possibly be used for eye protection. Tutt and Kost⁸ found that fullerene in toluene solution has very low clamped energy for laser transmission compared to other nonlinear materials. We found that fullerene can absorb more than 100 photons during a picosecond laser pulse. This provides a good possibility of achieving eye protection from laser beams.

2. EXPERIMENTS AND RESULTS

The laser used was a Quanta Ray DCR Nd:YAG multimode Q-switched pulsed laser with a beam divergence of 0.5 mrad. The laser pulse length was 7 ns and frequency was doubled to produce 532 nm light. The Q-switch was activated once every 5 s while the laser cavity was oscillating at 10 Hz with the use of an external coincidence unit that enabled the Q-switch to activate synchronously with the activation of the laser oscillator using a digital counter and delay. Incident laser power was measured with a Coherent 210 power meter while the laser was operating at 10 Hz. Reflected power from the aluminum mirrors was measured with a Gentec ED-100A Joulemeter connected to a Tektronix 2235 100-MHz oscilloscope. Several types of mirrors were used. Thin film mirrors were

purchased from National Photocolor Company. These mirrors were made from black nitrocellulose with a thickness of $2\text{ }\mu\text{m}$ with $400\text{ }\text{\AA}$ of aluminum coating.

The single reflection from an aluminum mirror was insufficient to reduce the incident laser pulse to a safe level. Therefore, a double-pass system was designed to achieve a greater attenuation of the incident light. This optical system was designed as illustrated in Fig. 1. The configuration allows the front part of the laser pulse reflected from the surface of the second mirror to return to the damaged spot. If the damage mechanisms occur swiftly enough, then the light will pass through the damaged area and not be reflected back to the deflector or the eye. The incident laser pulse travels through a beamsplitter and then is focused with a 2.5-cm lens onto the first mirror. The light reflected from the first mirror passes through another 2.5-cm lens and is perpendicularly incident on a normal front surface mirror. Light is then reflected back to refocus at the original focal spot. The light is then returned to the beamsplitter and then to the detector. During this work, we tried to prevent any reflected light from the lenses used by tilting them at a small angle, and traced the reflected light to ensure there was no contribution from the reflection of the lenses.

Ideally, the light that was reflected back from the second Al mirror would pass through the spot already damaged on the surface of the first Al mirror and not return to the beamsplitter and detector. The results depicted in Fig. 2 show a peak energy transmittance of $31\text{ }\mu\text{J}$ for the mirror with dyed mylar backing. Both reflected energy and damaged area were measured.

Experimental results of reverse saturable absorption for C_{60} in toluene are shown in Fig. 3. A Nd:YAG laser frequency doubled to 532 nm was telescoped down to 2.0 mm beam diameter. The laser beam intensity distribution was measured as neo-Gaussian. The incoming and transmitted laser energy per pulse were measured by a calibrated photodiode or a power meter. C_{60} was purchased from Texas Fullerene Corporation without further purification. During the experiment, C_{60} was dissolved in research grade toluene purchased from Aldrich Chemical without further purification. Data were taken in single shot protocol. All data were obtained after determining background laser beam attenuation through a pure toluene sample.

Each of the data points represents a single shot measurement. Power limiting processes were measured for different combinations of C_{60} concentrations and cell thicknesses (path lengths). The transmitted laser fluences become limited (clamped) at 320 , 165 , and 45 mJ/cm^2 for the cell with an optical path of 10 mm with concentration at 1×10^{-4} , 1.65×10^{-4} , and $3.3 \times 10^{-4}\text{ M}$, respectively. The transmitted laser fluence was limited at 168 mJ/cm^2 in a 5 mm cell containing $3.3 \times 10^{-4}\text{ M}$ solution, which is about the same as the one with a concentration of $1.65 \times 10^{-4}\text{ M}$ and 10 mm cell path. This indicates that the amount of C_{60} in the laser beam is the primary factor in determining the transmitted laser fluence.

From Fig. 3 it is noticed that the number of laser photons absorbed in a single pulse is much greater than the number of C_{60} molecules in the laser beam. Since the concentrations of C_{60} and the laser fluences are known, the number of photons absorbed per molecule can be measured. Results are shown in Fig. 4. At the highest fluence, more than 100 photons are absorbed in a single molecule. Similar results were obtained for a picosecond laser pulse (see Fig. 5). The number of photons absorbed during a 25 ps laser pulse also reaches 100 photons per molecule. Since both the thin film mirrors with double-path geometry and C_{60} solution show strong attenuation of the laser beam, the combination of both approaches can prevent the need to replace mirrors and may enhance the attenuation. In Fig. 6, a double-path geometry was used with a C_{60} cell. The cell replaced the first Al mirror in Fig. 1, clearly indicating that double-path geometry gives better laser beam attenuation.

3. DISCUSSION

A multilevel dual component model is proposed to account for the remarkable absorptive capability observed. In this model, a C_{60} molecule in the ground state S_0 absorbs one laser photon to form excited state S_1 , which may convert to a triplet state that can subsequently resonantly absorb another laser photon to T_n state. The T_n state of C_{60} can quickly transfer energy to the solvent (namely toluene) to produce excited toluene molecules. Since toluene has strong absorption at 266 nm for transition from $^1A_1 \rightarrow ^1B_2$, the energy transfer process from C_{60} to toluene can make toluene in 1B_2 which can have strong absorption for additional photons. This model satisfies the demand that more than 100 photons per C_{60} be accommodated at high flux level without dissociating (or otherwise destroying) the absorbing species. We assume photons can be absorbed in the following way:

where * represents molecules in a state higher than the first excited state and † represents $C_6H_5CH_3$ in an excited vibrational state.

As indicated in Eqs. (1)-(5), the ground state fullerene $C_{60}(S_0)$ is designated by a , $C_{60}(T_1)$ by a' , $C_{60}(T_n)$ by a'' , the solvent (toluene) in its ground state by b , excited toluene by b' , and a second excited state of the solvent by b'' . We also define $I(x, t_r)$ as the laser intensity after penetrating a distance x into the sample, where $t_r = t - x/v$ is the retarded time which stays fixed as one moves with the photons through the sample, and the concentrations of $C_{60}(S_0)$, $C_{60}(T_1)$, and $C_{60}(T_n)$, $C_6H_5CH_3(^1B_1)$, and $C_6H_5CH_3$ are defined as $N_a(x, t_r)$, $N_{a'}(x, t_r)$, $N_{a''}(x, t_r)$, and $N_b(x, t_r)$, respectively. Finally σ_a , $\sigma_{a'}$, and σ_b are the absorption cross sections of the corresponding molecules. Assume also that the stimulated emission cross section for a' is equal to the absorption cross section for a similarly for a' and a'' . With these definitions, the model represented by Eqs. (1)-(6) gives for the intensity:

$$\begin{aligned}
 \left(\frac{\partial I(x, t_r)}{\partial x} \right)_{t_r} &= -\sigma_a [N_a(x, t_r) - N_{a'}(x, t_r)] I(x, t_r) \\
 &\quad -\sigma_{a'} [N_{a'}(x, t_r) - N_{a''}(x, t_r)] I(x, t_r) \\
 &\quad -\sigma_b N_b(x, t_r) I(x, t_r).
 \end{aligned} \quad (6)$$

We can also write a set of coupled differential equations for the concentrations $N_i(x, t_r)$. In the equations for the concentrations we assume an ultrafast energy transfer from excited C_{60} molecules to solvent molecules and a very fast quenching rate of excited solvent molecules, then $N_{a''}$ and $N_{b''}$ can be adiabatically eliminated and the reduced set of equations for N_a , $N_{a'}$, and N_b can be solved.

With these solutions, one can integrate the equation for I over t_r to get an equation for the fluence at a point x up to time t_r :

$$\sigma_a N_{a0} x = 2 \int_2^{\infty} \frac{du}{\alpha (1 - e^{-2u}) + \beta (e^{\frac{1}{2}u} - 1)}, \quad (7)$$

where $Q(x, t_x) = (\hbar\omega)^{-1} \int_{-\infty}^{t_x} \sigma_a I(x, s) ds$ is the ground state absorption cross section times the fluence at x up to time t_x . Also, $\alpha = (2 + Y_2/2 - Y_1)(2 + Y_2)^{-1}$ and $\beta = (2Y_1)x[Y_2(Y_2 + 2)]^{-1}$ and the unitless factors Y_1 and Y_2 are ratios of excited state absorption cross sections to ground state absorption, $Y_1 = \sigma_a/\sigma_a$ and $Y_2 = \sigma_b/\sigma_a$, and N_{a0} is the initial concentration of C_{a0} .

Figure 7 shows Q vs Q_0 (transmitted versus incident scaled fluence) for $Y_1 = 2.7$, and $Y_2 = 0.2$ with $N_{a0}\sigma_a x$ at 0.66 and 1.3, respectively. Predicted and measured power limiting forms are in good qualitative agreement. We find the feature of energy transfer to the solvent on a time scale short enough to circumvent decomposition of the absorbing molecules to be unexpected and remarkable when the absorption of more than 100 photons per molecule in a picosecond laser pulse is involved. More work will definitely be needed to resolve the details.

4. CONCLUSION

Reverse saturable absorption of C_{a0} and sacrificial mirrors with double-path geometry have been examined for eye protection from laser beams of picosecond and nanosecond lasers. Both approaches can achieve significant attenuation to protect eyes from serious or permanent damage although the clamped energy is still higher than the permissible values of ANSI standards. The combination of these two approaches can eliminate the need to replace sacrificial mirrors. The phenomena of absorbing 100 photons in a single picosecond pulse definitely deserves further study for its mechanism.

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FIGURES

Fig. 1 Laser light is sent through a beam splitter to the first mirror, then to the second mirror, then returned to the first mirror and reflected back to the beamsplitter from which it is sent to the detector.

Fig. 2 Reflected energy (●) and damaged areas (*) versus incident energy. No further measurements were made for energy incidence higher than 50 mJ because no reflected energy was detected. A type 2 mirror was used.

Fig. 3 Optical power limiting in toluene with cell optical path of 10 and 5 mm. Transmitted fluences for 10 cm optical path were clamped at 45, 165, and 320 mJ/cm² for 1x10⁻⁴, 1.65x10⁻⁴M, respectively. The clamped fluence for 5 cm cell with C₆₀ concentration at 3.35x10⁻⁴ is very close to the one at 1.65x10⁻⁴M with double the optical path. The +, Δ, and ◊ represent data from the concentration of 1x10⁻⁴, 1.65x10⁻⁴, and 3.3x10⁻⁴ M/l with cell path of 10 mm, respectively. O represents the results from the concentration of 3.3x10⁻⁴ M/l with 5 mm cell path.

Fig. 4 Number of photons absorbed by each C_{60} molecule for cells with various lengths. The +, Δ , and O represent data from 3, 7, and 10 mm cell path, respectively.

Fig. 5 Experimental and theoretical optical power limiting of C_{60} toluene solutions irradiated by 25-ps laser pulses. Experimental results of the 10-mm path-length cell with these solutions were $T = 0.9$ (O), $T = 0.8$ (+), and $T = 0.5$ (Δ). Where T represents the transmission of the cell.

Fig. 6 Experimental results for double-path geometry compared to single pass transmission measurement. The concentration of C_{60} was $1 \times 10^{-4} M$. The laser beam size was 2 mm. The attenuation factor of 1000 was achieved with input laser fluence higher than $2 J/cm^2$. The + and Δ represent results from double path and single path, respectively.

Fig. 7 Plot of Q vs Q_0 for $Y_1=2.7$ and $Y_2=0.2$ for different values of $N_{a0}\sigma_a x$. Q_0 is proportional to incident photon fluence and Q is proportional to transmitted fluence. The discrete points are calculated numerically for $N_{a0}\sigma_a x = 0.66$ and 1.33, respectively. Triangles and squares indicate experimental results.