

Self-diffraction in bacteriorhodopsin films for low power optical limiting

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Abstract: We demonstrated a novel technique for low power optical limiting using self-diffraction in bacteriorhodopsin (bR) films. A cw Ar-Kr laser is used as the pump (input beam, 568 nm) and the output is the first order self-diffracted beam with an observed efficiency of about 0.01%. Input beam intensity is varied over three orders of magnitude in the range of milliwatt to watts per cm² with output clamped at eye safe level of about 0.13 mW/cm². Threshold intensity for limiting is governed by the saturation intensity of M-state of bR and hence can be varied by choosing films with different lifetimes.

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1. Introduction

Optical limiters are nonlinear devices which exhibit linear transmittance at low intensities and strongly attenuate the beam at high intensities. Since the development of high power lasers, it has become essential for the development of such devices to protect human eye and optical sensors from intense laser beams. Early optical limiters for cw lasers were based on thermal lensing phenomenon where the heating induced the index variation causing thermal blooming resulting in a beam that was no longer focused at the same focal plane. Since then different techniques [1-5] such as nonlinear absorption, photo refraction, nonlinear scattering, thermal beam spreading, excited state absorption, two-photon absorption etc., have been proposed in the literature. Most of these techniques are for high intensity pulsed lasers and are found to have a limiting threshold around 0.1 J/cm^2 .

There is also a need of optical limiters for low power cw lasers because even laser pointers with power in the 1-5 mW range can damage the human eye if directly exposed for time of less than 0.25 seconds [6]. The maximum permissible exposure of such a laser is calculated as $\sim 2.5 \text{ mW/cm}^2$, corresponding to 0.63 mJ/cm^2 for a safe exposure of 0.25 seconds. Self-diffraction and optical limiting properties are studied in organically modified sol-gel material containing palladium-octaisopentyloxy-phthalocyanine under cw laser illumination [7]. Significant optical multiple diffraction rings of the sample were observed when the cw Ar^+ laser was focused normally into the sample by a positive lens and the beam patterns out of the sample were projected onto the screen. The number of rings and size of the outermost ring were both dependent on the input intensity. Limiting behavior was recorded when the output power is detected after the aperture. Recently a passive low power cw optical limiter based on photothermal defocusing in a polymer that was placed between two optical fiber ends is demonstrated [8]. Such a device has potential applications to compensate the intensity fluctuations in the telecommunication channels (1530 – 1560 nm). A low power cw optical limiter based on photoanisotropy in azobenzene films was also demonstrated recently [9]. Here the transmittance of an input beam that passes through the film between two crossed polarizers is enhanced at low intensities and clamped at high intensities. The limiting threshold is adjustable by changing the intensity of the exciting beam inducing the photoanisotropy. Though this technique has an advantage of changing the threshold levels and at the same time working at low intensities, it is an active limiter and requires a second beam to induce the photoanisotropy. Similar optical limiting in bacteriorhodopsin (bR) [10] using its birefringence has also been demonstrated. In this article we report a lensless passive optical limiter based on a novel concept of using the first order self-diffraction of the bR film for optical limiting with the output clamped at eye safe levels of 0.13 mW/cm^2 .

bR is a naturally occurring transmembrane protein found in living systems that converts light energy into metabolic energy by pumping protons across the cell membrane. It is related to visual pigment rhodopsin contained in the cone cells of human retina. bR has received considerable attention due to its potential application in real time holography, optical pattern recognition and nonlinear optical effects [11, 12]. Vanhanen et al carried out a two-wave mixing experiment [13] to study self-diffraction efficiency of 13-demethyl bR film on rise times and its effects on the gratings in the film. bR displays a characteristic broadband absorption profile in the visible spectral region and when the molecule absorbs light it undergoes several structural transformations in a well-defined photocycle shown the Fig. 1. Here we have considered only two states for the bR cycle, B and M, as the lifetimes of the other states are in picosecond to microsecond scale, which are negligible in comparison to the M state lifetime. Upon excitation with photons (wavelengths $\sim 500\text{-}600 \text{ nm}$), the molecule

goes through a series of short-lived intermediate states to the relatively long-lived M state which has an absorption maximum at 410 nm wavelength. The M state can revert to the initial state via thermal relaxation process (typically in the order of milliseconds) or by a photochemical process (typically in the order of nanoseconds) upon excitation with blue light. The lifetime of the M state depends on the reprotonation process and can be varied from milliseconds to tens of seconds.

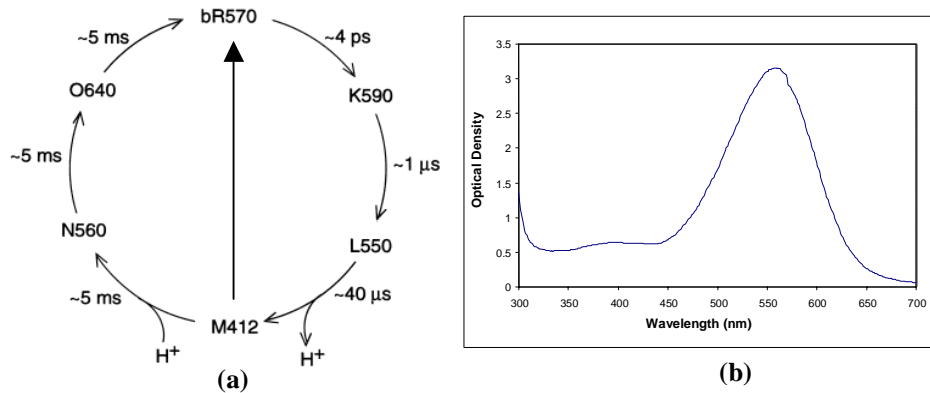


Fig. 1. (a) Schematic of bR photocycle. The numbers after the letter symbols for the intermediate states indicate the absorption maxima in nm. (b) Absorption spectra of bR film

2. Results and discussion

The sample that we used was purchased from Munich Innovative Biomaterials GmbH, prepared by doping bR in a polymer film of poly-vinyl alcohol. Optical density of the film is about 3 at 570 nm. Self-diffraction is obtained by splitting the incoming laser beam, 568 nm from Ar-Kr laser (Coherent Innova 70C Spectrum), beam diameter ~2.5 mm, into two equal powers and recombining them over a small angle (~10°) in the sample as shown in Fig. 2. The first order self-diffracted beam is the output in our experiments and is reflected onto a power meter 1 (Newport power/energy meter model # 1825C) through a set of apertures to reduce the background light from the surroundings and by two mirrors (M₂ and M₃). The input power is measured using a power meter 2 (Melles Griot broadband power/energy meter model # 13PEM001) and is varied by using variable neutral density filters. Output from these power meters is connected to a PC through an ADC card for data collection and further processing. Each data point is collected by averaging over a period of 90 seconds. The whole experimental setup is mounted on a vibration isolation table.

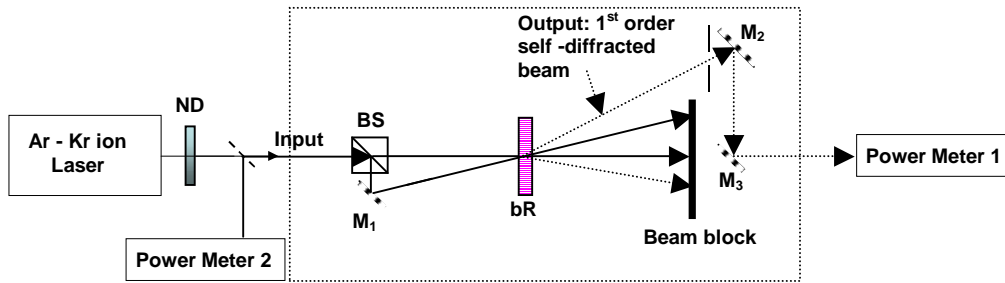


Fig. 2. Schematic of the experimental setup used to observe the optical limiting behavior in the self-diffraction signal where BS: beam splitter, M_1 , M_2 , M_3 – mirrors, bR – Bacteriorhodopsin film, ND – Neutral density filter.

As shown in the Fig. 3, we obtained good optical limiting curve as the input intensities are varied over three orders of magnitude. In order to observe the limiting close to the real situation (as the laser threat from unknown source) the input beams are not spatially filtered and used directly onto the film. In the linear region, we observed diffraction in the first order for intensities as low as 10 mW/cm^2 . The diffraction efficiency at low intensities in the first order diffraction signal is estimated to be around 0.01% and much lower diffraction efficiencies can be obtained with films of longer M-state life times. Lower limit of 1 mW/cm^2 is primarily due to the limit of our measurement capabilities with the instruments. Even for input intensities of less than 1 mW/cm^2 we observed measurable first order diffracted output which indicates grating formation at these intensities. The diffraction efficiencies observed in the present experiment are much lower than what has been quoted by Munich Innovative Biomaterials GmbH (about 1%). This could be because of poor quality of the input beam.

The threshold for limiting the output depends on the saturation of M state which in turn depends on its lifetime. As such, bR films with different M state lifetimes can be chosen to obtain different threshold levels. Also for these studies a 50-50 beam splitter is used to generate the two arms as shown in the Fig. 2. When they recombined to form the diffraction grating in the bR film, the modulation depth is estimated to be one. When the arms are of unequal intensity, then the modulation depth will be less than one and hence the diffraction efficiency will be decreased. So the parameter – ratio of the intensities of the two arms – can be varied to obtain the desired output limiting levels.

There was scattering from our films particularly at higher intensities. This scattering intensity was estimated by closing one of the pump beams. The data presented in the Fig. 3 is obtained with scattering signal being subtracted as a background. Even when the input intensities are as high as 9 W/cm^2 we observed no damage to the film. The data is reproducible even after several cycles of recording at the same spot on the film.

Diffraction efficiency η has been derived for an absorptive grating by H. Kogelnik [14] as

$$\eta = \exp\left(\frac{-2d\alpha_0}{\cos\theta}\right) \left\{ \sin^2\left(\frac{\pi dn_1}{\lambda \cos\theta}\right) + \sinh^2\left(\frac{d\alpha_1}{2 \cos\theta}\right) \right\} \quad (1)$$

Here α_0 is the absorption coefficient of the material in dark, d is the thickness of the film, θ is the Bragg angle and λ is the wavelength of the reading beam. α_1 and n_1 are the amplitude of the modulation of absorption coefficient and refractive index induced by the writing beams respectively. As bR shows an inhomogeneously broadened absorption spectrum, we introduce

the nonlinear saturation behavior [15] into n_1 and α_1 through $\alpha_1 = \alpha_{B \rightarrow M} \left(\frac{I_s}{I_{in} + I_s} \right)^{1/2}$,

where I_{in} is the input intensity, $I_s (= h\nu/\sigma\tau)$ is the saturation intensity of the bR film (M-State), h is the Planck's constant, ν is the photon frequency, σ is the absorption cross-section of B-state, τ is the M-state lifetime and α_{10} and n_{10} are the effective amplitude absorption coefficient and effective refractive index coefficient at low intensities. The data is fitted with the simplified nonlinear diffraction efficiency η_{nl} equation,

$$\eta_{nl} = \exp\left(\frac{-2d\alpha_0}{\cos\theta}\right) \left\{ \frac{d^2 [\pi^2 n_{10}^2 + (\lambda\alpha_{10}/2)^2]}{4\lambda^2 \cos^2\theta} \right\} \left[\frac{I_s}{(I_{in} + I_s)} \right] \quad (2)$$

Using the Kramers-Kronig relation, the change in the refractive index is determined by the relation as [16]

$$n_{10}(\lambda) = n_M(\lambda) - n_B(\lambda) = \frac{\ln(10)}{2\pi^2 d} P.V. \int_0^\infty \frac{[A_M(\lambda') - A_B(\lambda')]}{1 - (\lambda'/\lambda)^2} d\lambda' \quad (3)$$

where d is the thickness of the film, A_M is the absorption of the M state, A_B is the absorption of the B state and P.V. represents the Cauchy principal value of the integral. Similarly the change in the absorption is determined using the relation [16]

$$\alpha_{10}(\lambda) = \alpha_M(\lambda) - \alpha_B(\lambda) = \frac{\ln(10)}{d} [A_M(\lambda) - A_B(\lambda)] \quad (4)$$

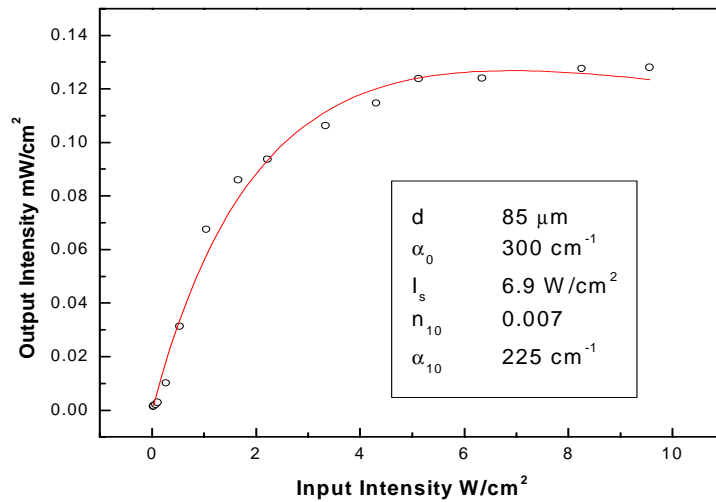


Fig. 3. Theoretical fit (solid line) using the equation 2 to the experimental data (open circles)

Figure 3 shows the best theoretical fit (solid line) of the experimental data (open circles), using Eq. (2) ($I_{out} = \eta_{nl} I_{in}$), from which α_0 , α_{10} , n_{10} , I_s and d are deduced. The values of n_{10} (0.007) and I_s ($6.9 \text{ W}/\text{cm}^2$) agree approximately with the values 0.0049 and $2.355 \text{ W}/\text{cm}^2$

reported in ref. 11. α_{10} and n_{10} are also obtained using Eqs. (3) and (4) as 242 cm^{-1} and 0.007 respectively. These values agree with α_{10} and n_{10} from the experimental fit (300 cm^{-1} and 0.007).

We have observed good optical limiting at 488 nm, 647 nm also with the output clamped at different intensities. The results of 568 nm are predominantly due to absorption grating whereas in the case of 488 nm and 647 nm wavelengths, the gratings may be due to absorption and refractive index modulation.

The configuration shown in Fig. 2 can easily be adapted into a device when the beam block and mirrors, M_2 and M_3 , are replaced with an appropriately oriented dichroic mirror of 100% reflectivity. In such geometry incoherent light appears directly at the output whereas the laser threat (coherent beam) will form a grating and hence be limited through the first order self-diffraction.

3. Conclusions

We studied self-diffraction of bR films with cw low power 568 nm laser beam. First order self-diffracted beam is the output which is clamped at eye safe intensities of 0.13 mW/cm^2 for input intensities observed up to 9 W/cm^2 . Clamping even at lower intensities can be achieved by choosing unequal intensities for the two interfering beams. The procedure provides a novel technique for optical power limiting for low power cw lasers. As the technique is based on interference of two beams, it may require vibration isolation.

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