
Low-threshold optical power limiting of cw laser illumination based on nonlinear refraction in zinc tetraphenyl porphyrin

Kaladevi Sendhil, C. Vijayan*, M.P. Kothiyal

Department of Physics, Indian Institute of Technology, Madras, Chennai 600036, India

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Abstract

The increasing use of low power cw lasers in various applications calls for the design of optical limiters with low thresholds. To this end, the optical nonlinearity exhibited by zinc tetraphenyl porphyrin at low laser powers is utilized to design an optical limiter for low threshold operation. The basic parameter responsible for limiting action, the nonlinear refractive index of the medium, is measured using the Z-scan technique and found to have a value of $-1.4 \times 10^{-7} \text{cm}^2/\text{W}$ at the helium–neon laser wavelength of 632.8 nm. The origin of nonlinearity is explained on the basis of the thermal lens model. It is shown that effective optical limiting at desired threshold values can be achieved by the optimal choice of aperture size and experimental geometry.

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1. Introduction

With the extensive use of continuous wave (cw) lasers at power levels ranging from $\mu$W to kW in various applications, the need for protecting the human eye and the sensors used in handling the cw output has become increasingly important. Under cw illumination, the form of optical nonlinearity exhibited by materials is predominantly refractive rather than absorptive [1,2] and suitable schemes based on nonlinear refraction have to be exploited for obtaining the limiting action. Certain materials such as liquid crystals, porphyrins, organics such as azobenzene, etc. are known to be optically nonlinear under cw laser illumination [3–5]. The refractive index of these materials depends on the input intensity, resulting in either focusing or defocusing effects on the incident laser beams. The defocusing effect under cw laser irradiation, usually associated with nonlinearity of thermo-optic origin, can be used for the design of an optical limiting device. An aperture can be used to limit the cross section of a beam defocused by the nonlinear medium, thereby controlling the output intensity. This type of optical limiting based on the nonlinear refraction has been demonstrated successfully with a few materials such as phthalocyanines and InO$_3$ [6–8].

Porphyrin compounds known to optically limit high power pulsed [9] laser beams using the nonlinear absorption (NA) properties have been reported to exhibit a nonlinear refractive index $n_2$ (in the range of $-10^{-8} \text{cm}^2/\text{W}$) when excited with low power continuous wave laser sources as well [4,10,11]. The negative value of the nonlinear refractive index indicates the defocusing nature of the material. Porphyrins are $\pi$-conjugated materials with delocalized electrons and have their absorption bands mainly in the visible region (Soret band—400–440 nm, Q band—500–650 nm) which make them attractive candidate materials for optical limiting applications for a wide variety of cw laser sources whose wavelengths lie in the visible region.

In this paper, we report on the optical nonlinearity in zinc tetraphenyl porphyrin [ZnTPP] in toluene solvent at...
low cw laser power levels and demonstrate the optical limiting of a cw laser beam employing the nonlinear refractive index ($n_2$) of ZnTPP under cw laser illumination is determined by the well-known closed Z-scan set up formulated by Sheik-Bahae et al. [12] and analysed on the basis of the ‘thermal lens model’ proposed by Cuppa et al. for thermal nonlinearity [13]. The dependence of the threshold value on the aperture size makes it convenient to optimize the threshold intensity of in optical limiting, permitting it to be tailored according to the sensitivity and damage threshold of the photodetector or sensor under study.

2. Experimental techniques

Zinc tetraphenyl porphyrin was synthesized and purified according to procedures reported in literature [14,15]. It was dissolved in highly purified spectroscopic grade toluene and the concentration of the solution was maintained at $\sim 10^{-4}$ M. The solution was filled in a 1 mm quartz cuvette whose absorbance in the visible range is negligibly small.

The UV–Vis absorption spectrum of ZnTPP in toluene solvent was obtained using a Hitachi U-3400 spectrophotometer. The nonlinear refractive index ($n_2$) of the ZnTPP was determined by the closed Z-scan method developed by Sheik-Bahae et al. [12] where a linearly polarized Gaussian beam from a He–Ne laser of wavelength 632.8 nm and power 20 mW is focused by a convex lens of focal length 100 mm and passed through the sample. As the sample is scanned through the beam, the far field profile shows intensity variation across the beam profile, which is recorded through an aperture. Open aperture Z-scan was performed on the material in order to probe nonlinear absorption mechanisms, which yielded a negative result. Also, the experiment was repeated with pure solvent (toluene) to measure its contribution and no significant feature was observed in either the open or the closed Z-scan traces.

The experimental set-up for the demonstration of optical limiting of the laser beam by ZnTPP under cw laser illumination is shown in Fig. 1. This is very similar to the standard Z-scan geometry and the same parameters were used as for the Z-scan experimental set-up. Additionally a polarizer–analyser combination (PA) was used to vary the input power. The cuvette containing the nonlinear medium is placed just after the focal point. An aperture $A$ of variable diameter is used to control the cross-section of the beam coming out of the sample cuvette. This beam is then made to fall on the optical sensor, a photodetector in this case. The input laser intensity is varied systematically and the corresponding output intensity values were measured by the photodetector. Images of the beam profile, incident on the sample as well as modified by the nonlinear medium were recorded using a CCD camera placed in the output plane of the sample.

3. Results and discussion

Fig. 2 shows the optical absorption spectrum of zinc tetra phenyl porphyrin in toluene solvent where the characteristic Soret band at 422 nm and Q-band at 548 nm are clearly discernible. The optical absorption coefficient of ZnTPP at the laser wavelength used for nonlinear optical experiments was found to be 0.1/cm from the optical spectrum. The laser wavelength, 632.8 nm, happens to be in the tail of the Q band of the absorption spectrum of ZnTPP. Fig. 3 shows the Z-scan trace obtained for ZnTPP solution with the cw He–Ne laser as the source. The occurrence of the pre-focal peak followed by the post-focal valley indicates that the sign of $n_2$ is negative. Though the absence of open Z-scan trace excluded any contribution from nonlinear absorption mechanisms such as reverse saturable absorption or two-photon absorption at this power level and wavelength, it is found that the curve is not symmetric. This asymmetric nature of the trace along with the fact that the source laser is cw suggests that the origin of the nonlinear refractive index is thermo-optic. The large value, 2.44, of the phase shift
\[ \theta = \Delta T/2 \] obtained from the Z-scan trace, where \( \Delta T \) is the difference between the transmittance of peak and valley, also points to the predominantly thermo-optic origin of the optical nonlinearity.

The value of \( n_2 \) was calculated using the thermal lens model (TLM) for Z-scan developed by Cuppa et al. [15] for thermal and nonlocal nonlinearity. The effective refractive index in a nonlinear medium is given by the expression

\[ n = n_0 + n_2 I, \tag{1} \]

where \( n_0 \) is the linear refractive index, \( n_2 \) the nonlinear refractive index and \( I \) the intensity of the incident beam at the focal point. The difference in the transmittance between peak and valley of the Z-scan trace is related to the nonlinear refractive index \( n_2 \) by

\[ n_2 = \Delta T \lambda / 4 \pi d I, \tag{2} \]

where \( d \) is the thickness of the nonlinear medium and \( \lambda \) is the wavelength of the laser used. The value of \( n_2 \) using TLM for the Z-scan result was found to be \(-1.4 \times 10^{-5} \text{ cm}^2/\text{W}\). The thermo-optic coefficient of the nonlinear medium was extracted from the \( n_2 \) value obtained from the Z-scan trace using the expression [7]

\[ n_{\text{thermal}} = (dn/dt)\lambda o_0^2 / 4k, \tag{3} \]

where \( \alpha \) is the absorption coefficient at the probe wavelength, \( o_0 \) the beam diameter at the focus, \( k \) the thermal conductivity and \( dn/dt \) the thermo-optic coefficient. The \( dn/dt \) value of the nonlinear medium was found to be \(-9.9 \times 10^{-3}/\text{K}\).

The spatial profiles of the incident beam and the beam modified by the nonlinear medium are recorded in order to study the intensity distribution. The profiles are shown in Fig. 4(a) and the corresponding intensity distribution obtained by scanning the images recorded by a CCD camera at the output plane is shown in Fig. 4(b). As can be seen from the images and the intensity distribution, the intensity distribution is nearly Gaussian for the incident beam whereas most of the energy is concentrated in the periphery of the defocused beam in the case of the beam modified by the nonlinear medium. This fact is made use of in the design of the optical limiter. The reason for unevenness in the intensity spread is that the medium is in liquid form and the beam becomes slightly distorted because of the uneven convection current occurring due to gravity.

The large nonlinearity is made use of in optical limiting applications with cw laser beams. Limiters with optimized parameters are designed by a proper combination of aperture size and experimental geometry to expunge the periphery of the defocused beam cross section where most of the energy is concentrated. Fig. 5 shows the optical limiting curves obtained with ZnTPP as the nonlinear material for two aperture sizes. The output intensity is found to vary linearly with input intensity only for small values of initial intensity for

**Fig. 3.** Z-scan trace of zinc tetra phenyl porphyrin under cw illumination.

**Fig. 4.** (a) Profiles of the input incident beam and the defocused beam; and (b) the corresponding intensity distribution.

**Fig. 5.** The plot of the optical limiting curves for different aperture sizes: (a) for 2 cm; and (b) for 1 cm.
both the aperture sizes. A threshold is reached at a low value of 1–3 mW of the input intensity with little change in the output intensity for larger values of the input intensities. Thus the output gets clamped and stabilizes at a low threshold. For curve (a) in Fig. 5 corresponding to the aperture diameter 2 cm, the threshold value is 2.26 mW and the output value gets clamped at the value between 0.26 and 0.29 mW. For curve (b) in Fig. 5 corresponding to the diameter of 1 cm, the threshold value is 1.42 mW. The output value gets clamped at 0.07 mW. Desired values of low threshold in the range of a few mW can be obtained by proper choice of the aperture size, for a given experimental geometry. The response time of the nonlinear medium to the cw laser illumination is observed to be 5 ms, which is typical of thermo-optic nonlinearity. This implies that the threshold of the limiter has to be set at a lower value than the actual damage threshold of the sensor to be protected so as to allow the intensity build up during the response time of the device.

4. Conclusion

The nonlinear optical response of thermo-optic origin exhibited by ZnTPP at low cw laser powers was studied and optical limiter action based on nonlinear refraction is demonstrated. The nonlinear refractive index was determined using the Z-scan technique and analysed on the basis of the thermal lens model. The origin of the nonlinearity appears to be predominantly thermo-optic. The variation in the output intensity was studied as a function of input intensity for two different aperture sizes and the influence of the aperture size on the threshold limit and output clamping power was analysed. The aperture size of 1 cm was found to correspond to a low threshold value of 1.42 mW and a stable clamped output at 0.07 mW. Whereas limiters based on nonlinear absorption phenomena have been designed for use with high power pulsed laser sources, aperture-limited designs based on thermo-optic nonlinearity such as the one studied here can be used as efficient limiters in the low power cw regime.

References