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Thermally induced nonlinear optical response and optical power limiting of acid blue 40 dye

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ABSTRACT

We report the investigations of thermally induced third-order nonlinear optical and optical limiting characterizations for various concentrations of acid blue 40 dye in N,N-Dimethyl Formamide, studied by employing z-scan technique under cw He–Ne laser irradiation at 633 nm wavelength. The samples exhibited nonlinear absorption and nonlinear refraction under the experimental conditions. For lower concentration, the samples display both saturable absorption (SA) and reverse saturable absorption (RSA); whereas with increase in concentration, RSA behaviour prevails. The estimated values of the effective coefficients of nonlinear absorption β_{eff}, nonlinear refraction n_2 and third-order nonlinear susceptibility $\chi^{(3)}$ were found to be of the order of 10^{-2} cm/W, 10^{-4} esu and 10^{-6} esu respectively. Multiple diffraction rings were observed when the samples were exposed to laser beam due to refractive index change and thermal lensing. The effect of concentration and the laser intensity on the self-diffraction ring patterns was studied experimentally. The acid blue 40 dye also exhibited strong optical limiting properties under cw excitation and reverse saturable absorption is found to be the dominant nonlinear optical process leading to the observed nonlinear behaviour.

1. Introduction

Nonlinear optical materials are being greatly explored with great interest owing to their potential applications in all-optical switching, 3-D optical memory devices, optical modulation, telecommunications, human eyes and optical sensors protection, etc., and significant applications in biological and medical sciences [1,2,3,4,5,6]. Wide variety of materials are known to be optically nonlinear under cw laser illumination [7,8,9,10,11,12,13,14,15,16]. Optical materials with large nonlinearity, broad band spectral response and fast response time are the potential requirements for a good optical limiter. Optical limiting results from irradiance intensity dependent nonlinear optical properties of materials. Incident intense light alters the refractive and absorptive properties of the sample and hence it is important to determine the magnitude of the nonlinearity of a material so as to select a material as a possible optical limiter.

Among the various organic compounds, dyes are commercially available and they are inexpensive. Azo, Anthraquinone and Indigo are the major chromophores found in commercial dyes. Acid blue 40 belongs to the anthraquinone class and represents second most important class of commercial dyes after azo dyes. Anthraquinone dyes have been under extensive research, since they have interesting optical properties and also for excellent properties that are not attainable by azo dyes including brilliancy of colours, fastness and excellent dyeing properties such as levelling and dye bath stability [17,18]. Linear absorption, SA, RSA are the basic absorption processes in dyes. Materials with SA behaviour are widely used in mode locking, laser pulse compression, optical bi-stability, laser amplification. Whereas materials with RSA are used in optical limiting devices, two-photon fluorescence microscopy and imaging, 3D optical storage, up-conversion lasing, micro fabrication, etc. [19]. The study on third-order nonlinearity of acid blue 40 has not been reported. Further the transition behaviour of SA/RSA/SA is not addressed under cw laser at 633 nm wavelength till date. It is necessary to study the optical nonlinearity of present dye sample for its wide spread applications as mentioned above.

In this article, we report the results of thermally induced third-order nonlinear optical properties of acid blue 40 in solution investigated using z-scan technique under cw He–Ne laser. Further, we present the strong optical power limiting of the samples under

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cw regime, based on reverse saturable absorption process. Also, the effect of thermally induced negative lens is demonstrated through diffraction ring patterns.

2. Experimental

2.1. Materials and methods

Acid blue 40 dye (molecular weight 473.43 g mol^{-1}) was purchased from Sigma Aldrich and used as received. The molecular formula of dye sample is $C_{22}H_{16}N_3NaO_6S$. For determining the absorptive and refractive nonlinearities, the dye sample solutions with 26.4, 30.2, 35.2, 42.2 and 52.8 μM concentrations were prepared by dissolving them in research grade N,N-Dimethyl Formamide (DMF) separately and named as a, b, c, d and e. For optical limiting studies, we prepared additional samples along with above specified samples with 70.4 and 105.6 μM concentrations and named as f and g. The molecular structure of dye sample is shown in Fig. 1. The optical characterization of the sample under investigation was studied by recording the electronic spectra in the wavelength range 300–800 nm using UV-1601PC Shimadzu spectrophotometer as shown in Fig. 2.

2.2. Z-scan experimental technique

The third-order nonlinear susceptibility $\chi^{(3)}$ of acid blue 40 in DMF was evaluated by employing z-scan technique developed by Sheik-Bahae et al. [20,21]. Z-scan is a single-beam technique which offers simplicity as well as high sensitivity for measuring the nonlinear absorption (NLA) and nonlinear refraction (NLR) simultaneously. In the present experiment, a polarized Gaussian laser beam is focussed to a narrow waist. The sample is mounted on the micrometer translation stage. By translating the sample between +z and −z positions along the *z*-direction, the transmitted intensity through the sample was measured. The measurements were recorded with and without the presence of aperture at far field in front of the photo detector. As the sample moves through the beam focus ($z = 0$), self-focussing or self-defocussing modifies the wave front phase, there by modifying the detected beam intensity. Z-scan experiments were performed by using Thor labs HRP350-EC-1 CW He–Ne laser at 633 nm wavelength as an excitation source. The laser beam was focussed to a spot size of 36.78 μm and the Rayleigh length Z_R of 6.71 mm using a 5 cm focal length lens with input power 20.2 mW. The samples were placed in a cuvette of 1 mm thickness. Hence, the thin sample approximation is valid as the sample thickness is less than the Rayleigh length Z_R [20,21].

Optical power limiting measurements were carried out to investigate the power limiting behaviour of the dye. The schematic experimental setup is shown in Fig. 3. The sample solutions were placed at the focal plane of the lens. The input power of the laser beam was varied by using neutral density filter and the resultant output power through the samples was recorded using a photodetector fed to Thor labs PM320E dual channel optical power and energy meter.

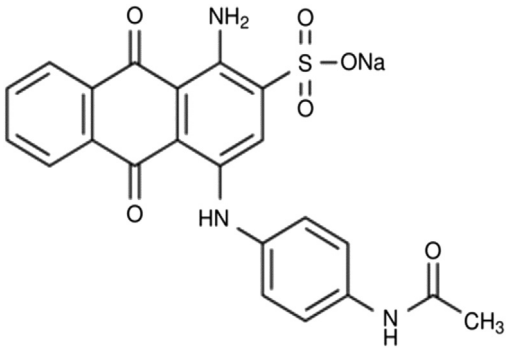

Fig. 1. Molecular structure of acid blue 40.

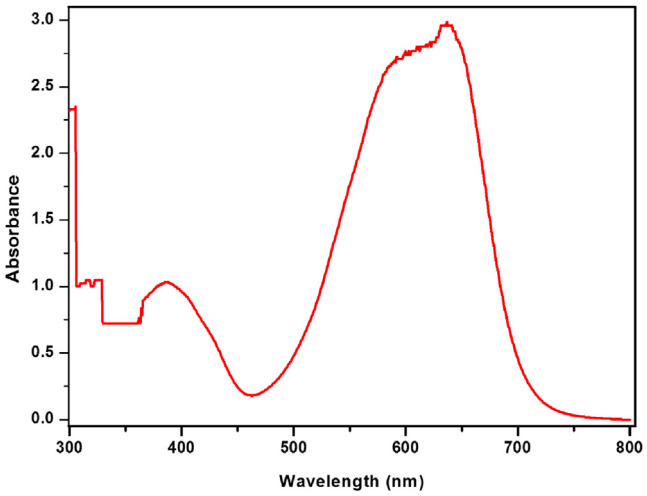

Fig. 2. Absorbance spectra of acid blue 40 in DMF.

3. Results and discussions

3.1. Nonlinear absorption and refraction

To examine nonlinear absorption and nonlinear refraction behaviours of the dye, open aperture and closed aperture z-scan experiments were carried out at an input intensity of 9.51×10^6 W/m^2. The open aperture z-scan traces obtained for dye samples are shown in Fig. 4. When the sample is away from the focus, the light intensity is low. For lower concentration (26.4 μM), at far field (Fig. 4(a)) the transmittance increases with the increase in focal intensity and depicts SA type of behaviour. However, when the sample approaches focus ($z = 0$), there is a shift in the behaviour and the transmittance decreases with increase in intensity indicating RSA. But again sudden switch over to SA from RSA is observed when the sample is at the focus. Therefore we can say that with increase in focal intensity, nonlinear absorption switches from SA/RSA/SA. In other words, for increase in focal intensity, RSA response becomes weaker where upon SA occurs. For next higher concentration (30.2 μM) at the far field, the transmittance through the sample increases resulting in SA type of behaviour. However, as the sample approaches focus ($z = 0$), the transmittance suddenly decreases forming a well-defined dip at the focus, indicating the occurrence of RSA behaviour as shown in Fig. 4(b). Above results depict the switch over of SA and RSA behaviour in the dye sample and this switch over behaviour of nonlinear absorption is in good agreement with reported results [19,22,23,24,25].

For all other higher concentrations, at far field we did not observe SA behaviour that is, there was a disappearance of initial

Fig. 3. The schematic optical limiting experimental setup.