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Non-linear optical properties and all optical switching of Congo red in solution

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ABSTRACT

We present the results from investigations of the nonlinear properties of Congo red solutions using Z-scan technique with a continuous wave argon ion laser at 514 nm. The magnitude and sign of the third-order nonlinear refractive index n_2 of aqueous solution of Congo red were determined. The nonlinear refractive index was found to vary with concentration. Third-order nonlinearity is dominated by nonlinear refractive index, which leads to strong self-defocusing and self diffraction in the samples studied. A pump and probe technique was used to investigate the origin of nonlinearity. Furthermore the nonlinear refractive index effect was utilized to demonstrate all optical switching. The optical limiting behavior based on nonlinear refractive index was investigated.

In recent decades, there has been considerable interest in searching for materials exhibiting nonlinear optical effects. These effects are of great technological importance for use in future applications within electronic and photonic devices [1,2]. An example of interest that has attracted a lot of attention is the light induced refractive index changes which exploit third order susceptibility $\chi^{(3)}$ properties of the materials.

The light induced refractive index changes are commonly described by the relationship $n = n_o + n_2 I$, where n_o is the linear refractive index, I is the intensity of the light and n_2 is a nonlinear refractive index coefficient. This coefficient is an effective parameter that contains many interesting nonlinear optical effects, such as laser induced grating, soliton pulse propagation in waveguides [3,4], optical switching [5–7] a self-focusing, self-defocusing, self-phase modulation, self diffraction, optical bistability and optical limiting [8–13]. Many materials such as photo refractive materials [14], Buckminster-fullerenes [15,16], fluoride glasses [17] and polymers [18] have been investigated for these applications. In general optimal nonlinear optical materials for optical devices must have a high nonlinearity, low absorption, fast response time, a large dynamic range and a broadband spectral response. Searches for such materials are in progress.

In this work, we report the experimental measurements of third order nonlinear refractive index n_2, of a Congo solution with a continuous wave (cw) argon ion laser at 514 nm using the Z-scan technique [19]. The measurements of nonlinear refractive index n_2 were repeated for different Congo red concentrations, and the nonlinear refractive index shows linear dependent on the Congo red concentration. The pump and probe technique was used to demonstrate optical switching and also used to determine the response time of the nonlinear effect; such response time which gives us the information about the origin of the nonlinearity. Self diffraction of the laser beam which arises due to refractive index variation is also investigated experimentally.

The general structure of the Congo red is shown in Fig. 1a. Congo red is a sulfonated azo dye. When first synthesized it was used for dying fabric but this was discontinued when it was found to be toxic, and sensitive to light and pH. It is used extensively as a biological stain and in particular as a histological dye for amyloid proteins. Investigations have shown it to be useful in the detection of a number of diseases which include Alzheimer's, prion, Parkinson's and Huntington's. It has been shown to have therapeutic effects in amyloidosis. The sodium salt is water soluble and can give a red colloidal solution [20]. The linear absorption spectrum of the Congo red in distilled water with 4 mg/l concentration is shown in Fig. 1b. The spectrum shows absorption peaks at 497 nm and 347 nm.

The Z-scan technique was used to measure the nonlinear refractive index. This technique relies on the fact that the intensity varies along the axis of the convex lens and is maximum at the focus. Hence, by shifting the sample through the focus, the nonlinear refraction can be measured by observing the spot size variation at the plane of finite aperture/detector combination. The experiment

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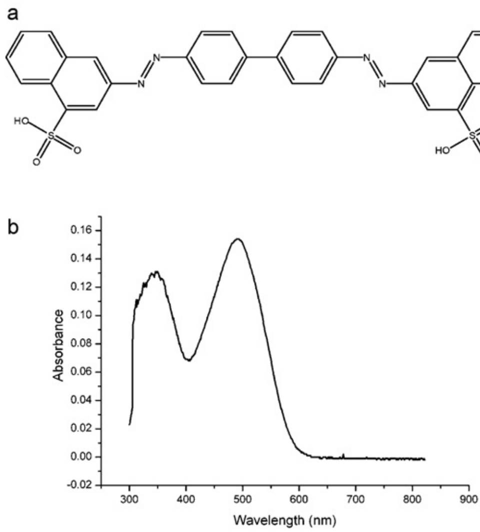

Fig. 1. (a) Chemical structure of the Congo red and (b) linear absorption of the Congo red in solution.

was performed with an air-cooled Ar ion laser beam operating at 514 nm with a power range of 4–20 mW. The beam was focused to a beam waist of 30 μm with a lens of 5 cm focal length, giving a typical power density range of 1×10^{10}–2×10^{10} W/m^2. The transmission for the sample was measured with an aperture in the far-field of the lens, as the sample moved through the focal point.

Fig. 2 shows the normalized transmittance through closed aperture for Congo red solution for 4 mg/l concentration and incident intensity of 2×10^{10} W/m^2. The peak valley configuration is a signature of negative refractive nonlinearity i.e. self defocusing.

Self -focusing and self-defocusing were also observed with the naked eye. Fig. 3a shows the variation of the spot size at the far field as a function of the sample position relative to the focal plane for the 4 mg/l concentration sample. The first photograph was taken well before ($-z$) where the nonlinear effect is not present because of low intensity in this region. Similar spot size shape was observed long after (+z) (not shown). Fig. 3b was taken at the prefocal transmittance maximum and Fig. 3c was taken at the postfocal transmittance minimum. The above implies that self focusing and self defocusing can be easily observed with a cw laser. This can be used as a quick check for nonlinear behavior of materials before proceeding with the experiment.

The measurable quantity ΔT_{p-v} can be defined as the difference between the normalized and valley transmittances, $T_p - T_v$.

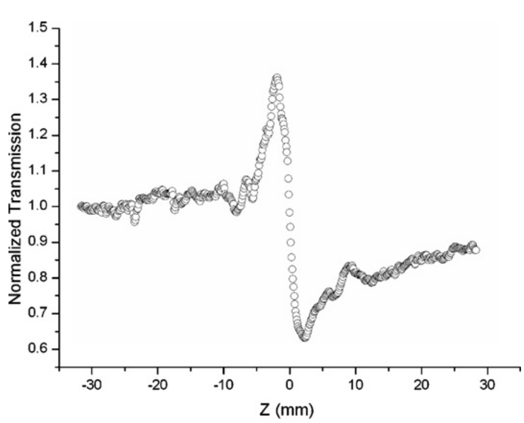

Fig. 2. Normalized transmittance (closed aperture) for 4 mg/l Congo red concentration at 14 mW.

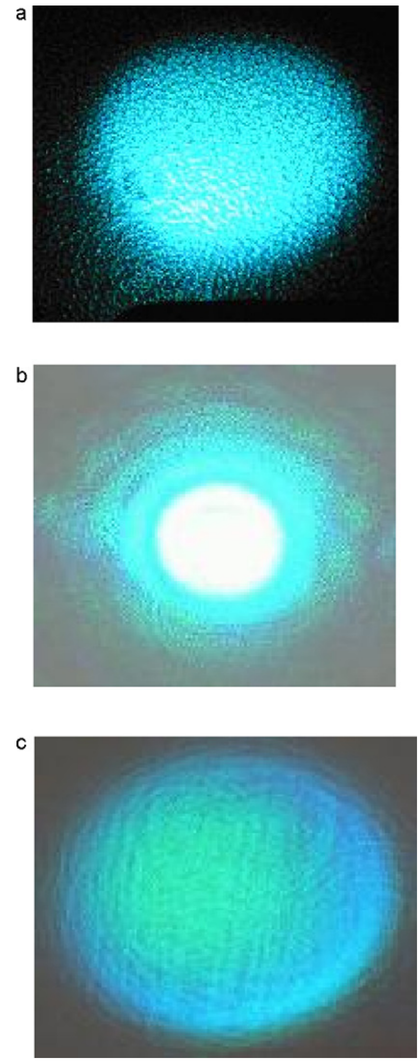

Fig. 3. Photographs show the variation of the spot size as a function of the sample position relative to the lens focal point. (a) Before focus where no nonlinear effects are present. (b) Prefocus transmittance maximum. (c) Postfocus transmittance minimum.

The variation of this quantity as a function of $|\Delta\varphi_o|$ is given by [21]:

$$\Delta T_{p-v} = 0.406(1 - S)^{0.25}|\Delta\varphi_o| \quad (1)$$

where $\Delta\varphi_o$ is the on-axis phase shift at the focus and S is the linear aperture transmission given by $S = 1 - \exp(-2r_a^2/(1/W_a^2))$ where r_a is the aperture radius and W_a is the beam radius at the aperture in the linear case. The on axis phase shift is related to the third order nonlinear refractive index (n_2) by [21]:

$$n_2 = \frac{\Delta\varphi\alpha\lambda}{2\pi I_o(1 - e^{-\alpha l})} \quad (2)$$

where α is the linear absorption coefficient, l is the thickness of the sample. I_o is the peak intensity at the focus, and λ is the wavelength of the laser beam.

The experimentally determined value of n_2 for 4 mg/l is found to be 1.17×10^{-14} m^2/W. This value is in agreement with the value of nonlinear refractive index measured for ionic liquids with Z-scan method at 514 nm [22] and 1000 times larger than the nonlinear refractive index measured in thiopene based conjugated polymers [23] and two orders smaller than the reported value of fast green FCF dye [24].