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Laser induced optical bistability in MgPc dye

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ABSTRACT

In the present work, optical bistability using a Fabry-Perot cavity containing MgPc dye dissolved in toluene of different concentrations have been experimentally investigated by using a single mode Q-switched nanosecond Nd:YAG laser operating at ~532nm. The nonlinear refractive index n_2 is numerically estimated from the bistabe loop and found to be in close approximations with the previously reported values. The nature of the bistable loop depicts the reverse saturable absorption (RSA) process in the medium under study. Absorptive type bistability is found to be predominant over dispersive bistability.

Keywords: Optical bistability, Fabry-Perot cavity, Optical switching, Differential gain

INTRODUCTION

Experimental observation of optical bistable phenomenon was first observed by Gibbs et al.[1] in 1976, in which a F-P etalon containing Na vapor inside the cavity was used and the observed bistable behavior was explained with the light induced refractive index change of the medium. Optical bistability deals with the co-existence of two stable output states corresponding to single input state with the hysteresis loop originating from the unique intensity dependence of nonlinear parameters.[2] Under the action of an intense coherent optical beam, the device may exhibit a nonlinear response to the incident beam in the sense that the transmitted intensity is a nonlinear function of incident intensity. Based on such a nonlinear response, this type of material can be used as an optical differential amplifier, optical switch, optical limiter, optical clipper, optical discriminator, or an optical memory element depending on the chosen nonlinear medium and operating conditions.[3,4] The desirable properties of a bistable device are large nonlinearity, faster response time, and good thermal and chemical stability. The optical bistability can be of active mode in a laser system or passive arising in an interferometer with saturable absorber.[5-7] Theoretically, it is considered as a first order phase transition in a system of non-equilibrium situations [8]. Magnesium phthalocyanine (MgPc) is a good nonlinear material as it is having fast response and high value of $\chi^{(3)}$.[9]

In the present course of study, we have investigated the optical switching, optical limiting and differential gain properties of MgPc dye in solution form with varying concentration.

THEORETICAL PRELIMINARIES

From the theory of the Fabry-Perot interferometer, in a F-P cavity of mirrors reflectivity R, we know that for a plane incident wave, the transmitted intensity I_t, is determined by [10]

$$I_t = \frac{1}{1+F\sin^2(\frac{\phi}{2})} I_0 \quad (1)$$

Where I_0 is the incident intensity, ϕ as the roundtrip nonlinear phase shift given as

$$\phi = \frac{2\pi}{F} \quad (2)$$

Finesse of the F-P cavity given as

$$F = \frac{\pi\sqrt{Re^{-\alpha L}/_2}}{1-Re^{-\alpha L}} \quad (3)$$

Where α is the linear attenuation coefficient of the medium.

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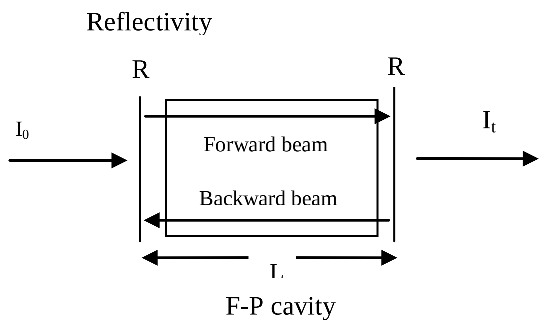


Figure 1. Schematic illustration of a F-P cavity containing a nonlinear medium

The overall intensity of the intra-cavity field, I_i which involves the forward and backward components,

$$I_i^{+} = \frac{1}{(1-R)} \cdot \frac{1}{1+F\sin^2(\frac{\phi}{2})} I_0 \tag{4}$$

$$I_i^{-} = \frac{R}{(1-R)} \cdot \frac{1}{1+F\sin^2(\frac{\phi}{2})} I_0 \tag{5}$$

will be [11]

$$I_i = I_i^{+} + I_i^{-} = \frac{(1+R)}{(1-R)} \cdot \frac{1}{1+F\sin^2(\frac{\phi}{2})} I_0 \tag{6}$$

Nonlinearity alone is insufficient to assure bistability. It is the feedback that permits the nonlinear transmission to be multi-valued. The two required components essential for the optical bistable response of the bistable device are high nonlinearity and feedback which can be achieved either by some electronic mean or by Fabry-Perot resonator.

The optical kerr coefficient n_2, is given as[12]

$$\frac{4\pi}{\lambda} n_2 I_i L \cos\theta = \phi \tag{7}$$

Here, L is the length of the cavity, θ is the angle of incidence and I_i is mean optical intensity in the F-P cavity given as

$$I_i = \frac{(1-R)\eta I_0 e^{-\alpha L/2}}{(1-\sqrt{Re^{-\alpha L/2}})^2} \tag{8}$$

With η as the coupling coefficient and α as the linear absorption coefficient of the intra-cavity medium as there is always some losses due to absorption of the interacting field.

I_t is an explicit function of I_0. For a given value of I_0, I_t may have multi-valued solutions, which is the mathematical origin of optical hysteresis loop. The two parallel expressions for the transmissivity of the nonlinear Fabry-Perot etalon are [13]:

$$T = \frac{I_t}{I_0} = \frac{1}{1+F\sin^2\frac{\emptyset}{2}} \tag{9}$$

$$T = \frac{(1-R)}{(1+R)} \frac{I_i}{I_0} \tag{10}$$

A bistable loop appears if the Airy function, T is intersected at least three times by straight line function given by eq. (10).

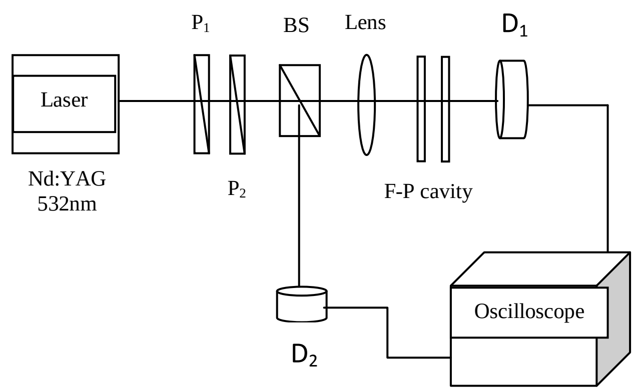


Figure 2. Experimental setup for optical bistability: P_1, P_2 - Polarizer's, D_1, D_2 – Photo-detectors, BS- beam splitter

EXPERIMENTAL

Magnesium pthalocyanine (MgPc) (99.9%) has been procured from Sigma Aldrich in powder form. Homogeneous solutions of different concentration were prepared using toluene as a solvent (in the range 0.1-0.3mM) after stirring for two hours. Toluene was selected as a preferable solvent as it have negligible absorption at ~532nm and less evaporation compared with alcohol group of solvents. Samples have been taken in quartz cuvette of path length 1mm. Absorption spectra of MgPc dye solution is shown in fig.3. The absorption spectrum was carried out by using UV-visible spectrophotometer (model no. 18-1885-01-0151) with spectral band width of 2nm. It is very clear from the spectrum that the sample is showing very less absorption at ~532 nm wavelength that is a desirable characteristic of the material for the bistability experiment.

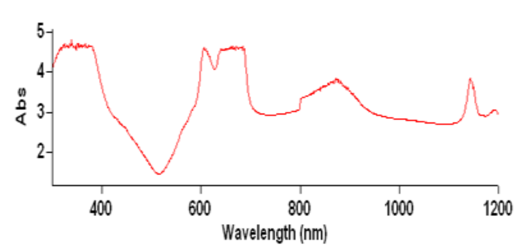
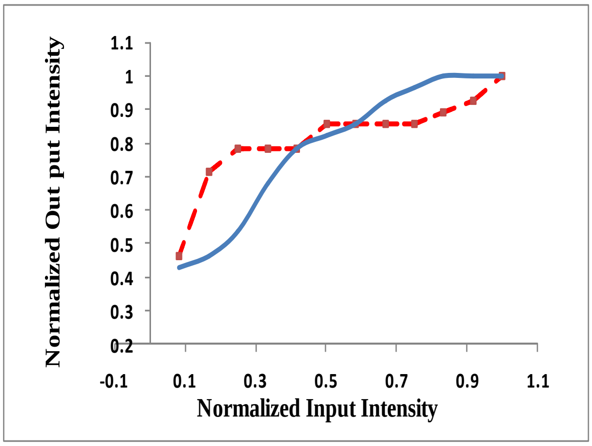


Figure 3. Linear Absorption spectra of MgPc dye

A single mode Q-switched Nd:YAG laser operating at ~532 nm wavelength of 5ns pulse width with a repetition rate of 10 Hz is used for the investigation of bistability in MgPc dye. The energy per pulse of the laser is 200mJ.

a



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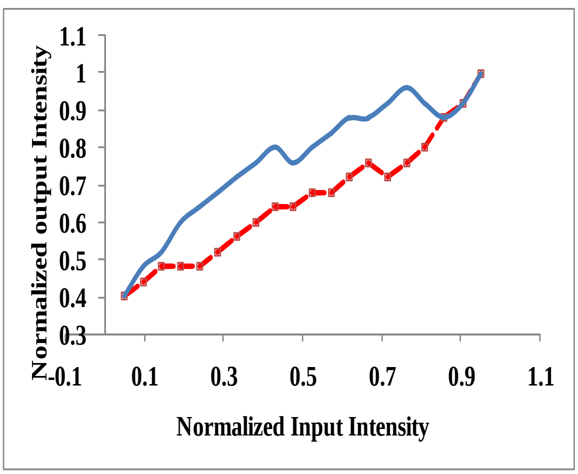

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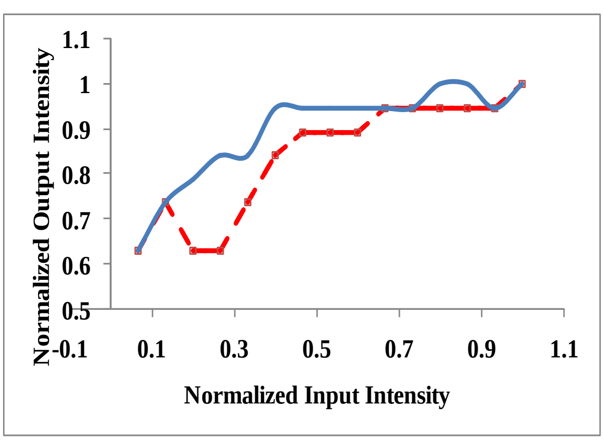

Figure 4. Optical bistability response of MgPc dye in solution at 532 nm wavelength of Nd:YAG laser with solid lines (——) for increasing input intensity and arrows lines for decreasing input intensity with concentration **(a)** 0.1mM **(b)** 0.15 mM **(c)** 0.2mM

The input light intensity is varied using modulator containing two polarisers, P_1 and P_2. The input intensity is non- zero in cross polarization position. The input optical intensity is having some finite value because of some leakage unpolarized component of light energy through P_1. A lens of focal length 150 mm is used to focus the laser beam on the dye medium with a focused spot size of 98µm. Two silicon photo detectors D_1 and D_2 (Thorlab, DET-110) are positioned to detect the input and output light power as per the experimental setup.

Results and Discussion

The optical bistable/multistable curves of MgPc dye solution of different concentration are shown in fig. 4. The maximum input intensity of Nd:YAG laser used was 30.6 x 10^2 MW/cm^2. Fig. 4(a) shows the bistable loop for the 0.1mM concentration of MgPc in toluene with linear absorption coefficient 0.05cm^{-1}. Assuming the coupling coefficient η=1, the nonlinear refractive index n_2 is calculated to be ~1.955x 10^{-15}cm^2/W with threshold input intensity of 12.4 x 10^2 MW/cm^2. In optical bistable profile, three modes namely optical switch mode, differential gain mode (slope > 1) and optical power limiting mode are obtained. The bistable mode indicates the existence of two steady state outputs corresponding to a single input state hence indicates the possibility of either **ON** or **OFF** state which can be utilized as an optical switch. The differential gain region implies a large change in output corresponding to a small change in input intensity. Fig. 4a clearly indicates the existence of differential gain mode. In optical limiting regime, output signal does not alter with change in input intensity. For 0.2mM concentration, optical limiting characteristics of MgPc are demonstrated. Therefore, the material can be utilized as an optical limiter as well. In fig. 4(b) and 4(c), the output intensity is decreasing with decreasing input intensity which is a reverse trend in bistable loops. This occurs due to intensity dependent absorption process. With the increased concentration, more no. of photons will be entrapped resulting reverse saturable absorption.

In MgPc, the origin of optical bistability is due to nonlinear refraction as well as nonlinear absorption. With increase in concentration, absorptive bistability dominates over dispersive bistability. This may happen because of the increases area of absorption cross-section (σ_a) in the sample for the input energy. In the five level energy diagram of the dyes, intersystem crossing may play significant role in decreased output as transition from T_1 state to ground state S_0 is forbidden. The molecule may undergo ESA (excited state absorption) and can go to higher states by absorbing input pulses. Moreover, large change in absorption characteristic is essential to give rise to absorptive bistability, while only small change in kerr coefficient is needed to give rise optical switching because of the interferometric nature of F-P etalon.

Conclusion

Optically Bistable behavior of MgPc dye dissolved in toluene have been investigated with the change in input intensity of high power laser. The nonlinear refractive index of MgPc in toluene has been estimated to be ~1.955x 10^{-15} cm^2/W. The result shows that in MgPc, the RSA process occurs and absorptive bistability dominates. The effect of concentration of dye molecules is also discussed.

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