Non-Linear Optical Properties, Using Z-scan

7th semester Open Physics lab
INTEGRATED MSC
in
PHYSICS
by

Ravi Prakash Singh(1811122) **and** Shriman Keshri(1811150)

Supervisor: **Prof. Dr Ritwick Das**
(Associate Professor,(SPS) NISER)

Cosupervisor: **Dr. Gunda Santosh Babu**
(Scientific Officer-E,(SPS) NISER)

NISER,Bhubaneswar

Goal

- To study the basics of Non-Linear Optical Properties by using Z-scan Techniques.
- Taking measurements of transmitted power for open and closed aperture by translating the material in the z-direction.
- By fitting these data with the appropriate formulas, we will find the medium's nonlinear absorption coefficient and nonlinear refractive index.

Introduction

Nonlinear Optics is a branch of optics that deals with light behavior in nonlinear media(Polarization P relates non-linearly with electric field).
While considering nonlinear optical materials, two properties of interest are the material's nonlinear refractive index and its nonlinear absorption coefficients. Both change the intensity of light non-linearly when light passes through a medium.
The Z-Scan is based on the principle of spatial beam distortion used to measure the third-order optical nonlinearity and allows computing the contributions of nonlinear absorption and nonlinear refraction.

Nonlinear Optical Media

Z-Scan experiment is for showing the third order nonlinear optical material characteristics.
So now we need to know what is this nonlinear optical media is.
In a linear dielectric medium, there is a linear relation between Electric field and induced electric polarization.

$$\mathbf{P}(\mathbf{E}) = \epsilon_0 \left(\chi^{(1)}\mathbf{E}\right)$$

where ϵ_0 is the electric permittivity of vacuum and χ is the dielectric susceptibility of the medium.
In a nonlinear dielectric medium, P and E are related non-linearly.

$$\mathbf{P}(\mathbf{E}) = \epsilon_0 \left(\chi^{(1)}\mathbf{E} + \chi^{(2)}\mathbf{E}\mathbf{E} + \chi^{(3)}\mathbf{E}\mathbf{E}\mathbf{E} + \ldots\ldots\right)$$

where $\chi^{(n)}$ are the higher order susceptibilities which governs the nonlinear processes. When the intensity of the light will be sufficiently high, only then these higher order polarization terms will be significant.

1st order susceptibility $\chi^{(1)}$

When there is only $\chi^{(1)}$ dependence of polarisation on electric field then it is said to a linear optical material.
We can find -

- Linear Refractive index.

$$n \propto \mathit{Real}(\chi^{(1)})$$

- Absorption coefficient

$$\alpha \propto \mathit{Imaginary}(\chi^{(1)})$$

2nd order susceptibility $\chi^{(2)}$

When there is some $\chi^{(2)}$ dependence of polarisation on electric field then our material is showing nonlinear optical characteristics and they can be like-

- Electro Optic Effects
- Second Harmonic Generation

In the case of 2nd order, the material need to have some special properties and not all the materials are capable of having 2nd order characteristics. The material needs to have some specific intrinsic symmetry and energy level.

3rd order susceptibility. $\chi^{(3)}$

All the materials are potential to show the 3rd order non linear optical characteristics. Here $\chi^{(3)}$ dependence of polarisation on electric field . We can find -

- Nonlinear Refractive index.

$$n \propto Real(\chi^{(3)})$$

- Nonlinear Absorption coefficient

$$\alpha \propto Imaginary(\chi^{(3)})$$

Nonlinear wave equation

A wave equation for propagation of light in a nonlinear medium can be derived from maxwell equations

$$\nabla^2 \mathbf{E} - \frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \mathbf{P}}{\partial t^2}$$

since

$$\mathbf{P}(\mathbf{E}) = \epsilon_0 \left(\chi^{(1)}\mathbf{E} + \chi^{(2)}\mathbf{EE} + \chi^{(3)}\mathbf{EEE} + \ldots\ldots\right)$$

We can have

$$\mathbf{P} = \epsilon_0 \chi^{(1)}\mathbf{E} + \mathbf{P}_{NL}$$

here $\mathbf{P}_{NL}$ is

$$\mathbf{P}_{NL} = \chi^{(2)}\mathbf{EE} + \chi^{(3)}\mathbf{EEE} + \ldots\ldots$$

Now, by using the equations, $n^2 = 1 + \chi$ and velocity of light in a medium of refractive index n is given by $\mathrm{v} = \frac{c}{n}$, we can write wave equation in a nonlinear medium

$$\nabla^2 \mathbf{E} - \frac{1}{v^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \mathbf{P}_{NL}}{\partial t^2}$$

This is our basic equation in the theory of nonlinear optics.

Third-order Nonlinear Optics

If we take the case of non-linear 3rd order material then Polarisation will be

$$\mathbf{P}(\mathbf{E}) = \epsilon_0 \chi^{(1)} \mathbf{E} + 0 + \epsilon_0 \chi^{(3)} \mathbf{EEE}$$

if the **E** is electric field of light going in the media then,

$$\mathbf{E} = \frac{1}{2}\left(E_0 e^{ikz - i\omega t} + E_0^* e^{-ikz + i\omega t}\right)$$

Put this and get

$$\mathbf{P}(\mathbf{E}) = \epsilon_0 \left(\chi^{(1)} + \frac{3}{4}\chi^{(3)} \left|E_0\right|^2\right) \mathbf{E}$$

Hence $\chi_{\text{eff}} = \chi^{(1)} + \frac{3}{4}\chi^{(3)} \left|E_0\right|^2$. We have relation between refractive index n and susceptibility χ_{eff}

$$n^2 = 1 + \chi_{\text{eff}} = 1 + \chi^{(1)} + \frac{3}{4}\chi^{(3)} \left|E_0\right|^2$$

$$n^2 = n_0^2 + \frac{3}{4}\chi^{(3)} \left|E_0\right|^2 = n_0^2 \left(1 + \frac{3\chi^{(3)} \left|E_0\right|^2}{4 n_0^2}\right)$$

$n_0^2 = 1 + \chi_0$ (where n_0 is the linear component of refractive index). Now take square root both side and use binomial expansion, we get

$$n = n_0 \left(1 + \frac{3}{8n_0^2}\chi^{(3)} |E_0|^2\right) = n_0 + \frac{3}{8n_0}\chi^{(3)} |E_0|^2$$

By using relation $I = \frac{1}{2}\epsilon_0 n_0 c |E_0|^2$

$$n = n_0 + \frac{3}{4}\chi^{(3)} \left(\frac{I}{\epsilon_0 n_0^2 c}\right)$$

$$n = n_0 + n_2 I$$

here $n_2 = \frac{3\chi^{(3)}}{4\epsilon_0 n_0^2 c}$ is a nonlinear component of the refractive index

Experiment setup

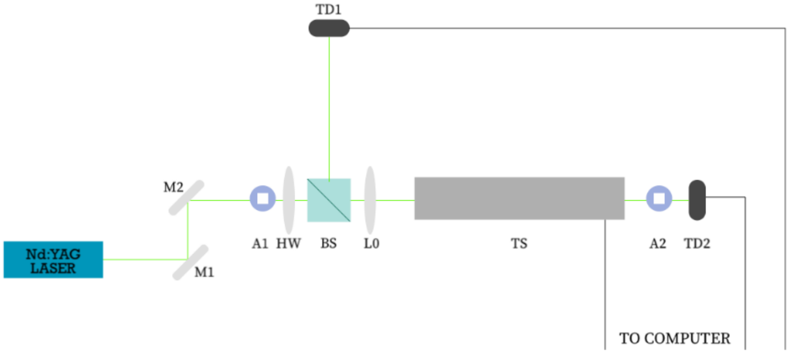
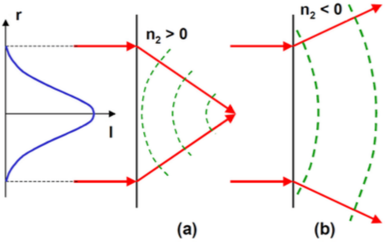


Figure: Schematic of the Experimental Setup.

Self-focusing and defocusing

Self-focusing and defocusing is a non-linear optical processes induced by the change in refractive index of materials exposed to intense electromagnetic radiation. A medium whose refractive index increases with the electric field intensity acts as a focusing lens(fig a) for a Gaussian beam,while if it decreases with electric field intensity acts as defocusing lens(fig b).



Experimental observations

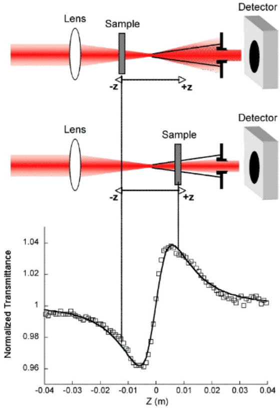


Figure: Non-Linear Refraction

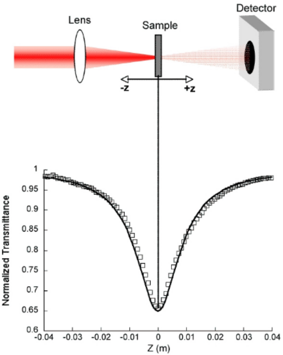


Figure: Non-Linear Absorption

Theoretical Calculation

We use Gaussian beam with

$$E(r,z,t) = E_0(t)\frac{w_0}{w(z)}\exp\left[-\frac{r^2}{w^2(z)} - \frac{ikr^2}{2R(z)}\right]\exp[-i\phi(z,t)]$$

where $\mathrm{w(z)}$ is the radius of the beam at z, E_0 is the electric field at the beam waist $(\mathrm{z}=0, \mathrm{r}=0)$ and the last term contains all the radially uniform phase variations.

The beam exiting the sample has complex electric field which has phase distortion, we use Gaussian decomposition method in which the exiting Gaussian beam is decomposed through Taylor series expansion of non-linear phase term. At aperture we get electric field $\mathrm{E}_a(\mathrm{r},\mathrm{t})$ as a function of $\Delta\phi_0$. Spatially integrating $|E_a(r,t)|^2$ upto aperture radius r_a we get transmitted power $\mathrm{P}_T(\Delta\phi_0(t))$. Normalized transmittance $\mathrm{T(z)}$ is given by

$$T(z) = \frac{\int_{-\infty}^{\infty} P_T(\Delta\phi_0(t))\,dt}{S\int_{-\infty}^{\infty} P_i(t)dt}$$

$\mathrm{P}_i(\mathrm{t})$ is instantaneous input power within the sample.

Most important parameter is ΔT_{p-v}, difference between the highest value and lowest value of the transmittance. Based on numerical fitting we get a relation between T_{p-v} and $\Delta\phi$

$$\Delta T_{p-v} \simeq 0.406(1-S)^{0.25}\,|\Delta\phi_0|$$

We have formula to find the transmittance, without the use of S value.
For closed aperture,

$$T(z,\Delta\phi) = 1 + \frac{4\Delta\Phi_0 x}{(x^2+1)(x^2+9)} - \frac{2\left(x^2+3\right)\Delta\psi_0}{(x^2+1)(x^2+3)}$$

For very small opening, Open aperture,

$$T(z,S=1) = 1 - \frac{\beta L_0 L_{eff}}{2^{3/2}\left(1+x^2\right)}$$

$$x = \frac{z_0}{z}, \quad \Delta\Phi_0 = kn_2 I_0 L_{eff}, \Delta\psi_0 = \beta I_0 L_{eff}/2$$

What we are going to do.

- We want to do the experiment in lab and fit data with the appropriate formulas, we will find the medium's nonlinear absorption coefficient and nonlinear refractive index.
- We are thinking to build a simple optical logic if its possible to build some simple optical transistor using this properties.*