

Investigation of Olive Oil as a New Photonic Liquid Crystal for Optical Communication Systems

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Abstract: This project introduces a prospective material for photonic laser applications. The material is olive oil which is classified as organic compound, having a good nonlinear optical properties candidate to be used in photonic applications. Many organic compounds that olive oil is contained, phospholipids, cholesterol, glycolipids, fatty acids compound which are able to behave as lyotropic liquid crystal. So, these compounds are characterized by wide photonic applications. A high purity sample of olive oil has been subjected to spectrophotometer to determine the absorption spectra. Then, the nonlinear optical properties represented by nonlinear refractive index and nonlinear absorption coefficient are determined using a highly sensitive method known as z-scan technique. z-Scan experiment was performed using a CW Nd:YAG and SHG Nd:YVO4 lasers in two parts. The first part has been done using a closed aperture placed in front of the detector to measure the nonlinear refractive index at two wavelengths (1064nm and 532nm) and versus incident powers at 1064nm. The second part was done using an open aperture to measure the nonlinear absorption coefficient at two wavelengths (1064nm and 532nm) for different incident powers at 1064nm.

Key-Words: liquid crystal, z-scan, third order susceptibility, nonlinear absorption coefficient, nonlinear refractive index

1. Introduction

Organic materials are applied in nonresonant photonic applications because these materials can show very high nonlinear coefficients, high damage threshold and good transparency at short wavelengths.

In 2007 Omer Namer [1] investigated experimentally and theoretically that the olive oil can be categorized as an organic dye, which can be used as an active laser material. One of these investigations showed that the olive oil behaves as a nonlinear material where it has a "blue shift" in some excited wavelengths. Therefore, the nonlinear optical properties of olive oil which are of prominent importance for photonics applications have been found in this research. Lyotropic liquid crystals are one of liquid crystals obtained by varying the temperature or concentration [2], which is obtained when an appropriate concentration of material is dissolved in some solvent. The most common systems those formed by amphiphilic molecules (molecules possess a hydrophilic part that interacts

strongly with water and a hydrophobic part that is water insoluble).

The olive oil represents the one class of lyotropic liquid crystal in nematic phase [3]. Liquid crystals are optically highly nonlinear materials in that their physical properties (temperature, molecular orientation, density, electronic structure, etc.). These are obtained by an applied optical field. The polarized light beam from laser source can induce an alignment or ordering in isotropic phase. These result in a change in refractive index. In isotropic phase the change in refractive index is due to the density change following arise in temperature. In the nematic phase the change in the refractive index depend directly on the temperature. The reorientation of molecules in liquid crystals depends on the phase of liquid crystals. For the isotropic phase the liquid crystal molecules are randomly oriented owing to thermal motion. So an intense laser field will force the anisotropic molecules to align themselves in the direction of optical field through the dipolar interaction.

2. Third order susceptibility

The organic material can have non-resonant third-order nonlinear optical susceptibility tensor $\chi^{(3)}$, which is complex quantity relating the complex amplitudes of the electrical field and polarization. For example, Fig.1 shows the third-order nonlinear optical susceptibility of Au:SiO2 nanocomposite medium [3,4]. For non resonance excitation, real part of the third-order nonlinear susceptibility related to the nonlinear refractive index n_2 and the imaginary part of the nonlinear optical susceptibility related to the nonlinear absorption coefficient β as following equations [5]:

$$\chi^{(3)} = \sqrt{(\text{Re}\chi^{(3)})^2 + (\text{Im}\chi^{(3)})^2} \quad (1)$$

$$\text{Re}\chi^{(3)} = 2n_o \epsilon_o c n_2 \quad (2)$$

$$\text{Im}\chi^{(3)} = n_o^2 \epsilon_o c \lambda \beta / 2\pi \quad (3)$$

where: n_o is a linear refractive index, and can be given by Cauchy formula [5].

$$n(\lambda) = I + J/\lambda^2 + K/\lambda^4 \quad (4)$$

where, $I=1.451$ and $J= 1.154 \times 10^4$, $K = -1.132 \times 10^9$, ϵ_o : vacuum permittivity, c : light speed in vacuum.

The absorption of the material is also intensity dependant given by:

$$\alpha = \alpha_o + \beta I \quad (5)$$

where α_o is linear absorption coefficient.

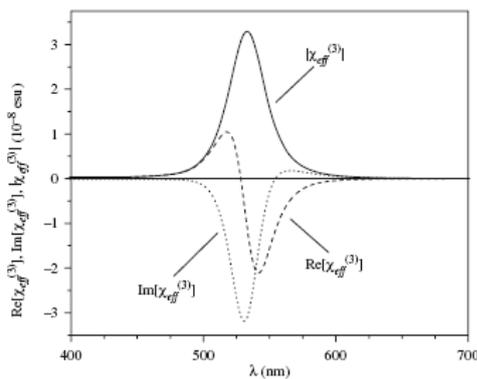


Fig. 1: Real part (dashed line), imaginary part (dotted line) and modulus (solid line) of the effective third-order nonlinear susceptibility [4].

A nonlinear process that can be associated with real (rather than virtual) energy levels and population changes in those levels is that of saturable absorption. This process occurred when the nonlinear absorption coefficient $\beta < 0$, which

can be appeared when a strong light absorption between two levels causes saturation (bleaching) of the corresponding electronic transition. The two levels involved surface plasmon resonance ground and excited state [6]. A nonlinear process that involves the transfer of energy to excited energy levels of the material, as in the case of a saturable absorber, is the process of two-photon absorption. This process occurred when the nonlinear absorption coefficient $\beta > 0$ [7]. The nonlinear parameters, which represented by the n_2 and β can be found by the z-scan model.

The Z-scan technique is a simple and direct method to characterize both the nonlinear refraction and nonlinear absorption. It's based on a single beam method. It refers to the process of inserting a sample in a focused Gaussian beam and translating it along beam axis through a focal region. The wave front distortion from self-focusing or self-defocusing will be caused the kerr nonlinearity. The beam power propagating through a small aperture at far field varies with a sample position. Measuring the out put versus position sample allows to determination of nonlinearity. There are two method of z-scan, the closed-aperture and open-aperture system [8].

2.1 Closed-Aperture Z-Scan:

A closed-aperture Z-Scan measures the change in power intensity of a beam, focused by lens L in Fig. 2. Photo-Detector PD collects the light that passes through an axially centered aperture A in the far field. The change in on-axis intensity is caused by self-focusing or self-defocusing by the sample S as it travels through the beam waist. A TEM₀₀ Gaussian beam has greatest intensity at the centre and will create a change in index of refraction forming a lens in a nonlinear sample[1].

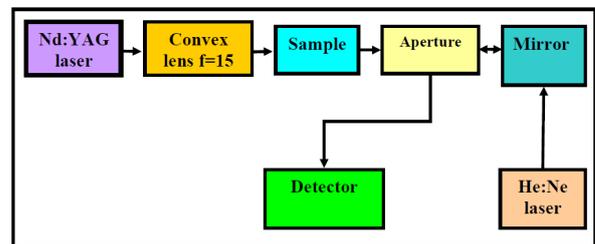


Fig. 2: closed-aperture Z-scan of experimental work.

To show how the Z-scan normalized transmission as a function of Z is related to the nonlinear refraction of the sample, if a medium with a negative nonlinear refraction index and a thickness smaller than the diffraction length of the focused beam. This can be considered as a thin lens of variable focal length. Beginning far from

the focus ($Z < 0$), the beam irradiance is low and nonlinear refraction is negligible. In this condition, the measured transmittance remains constant (i.e., Z -independent). As the sample approaches the beam focus (focal point of lens), irradiance increases, leading to self-lensing in the sample. A negative self-lens before the focal plane will tend to collimate the beam on the aperture in the far field, increasing the transmittance measured at the iris position. After the focal plane, the same self-defocusing increases the beam divergence, leading to a widening of the beam at the aperture and thus reducing the measured transmittance. Far from focus ($Z > 0$), again the nonlinear refraction is low resulting in a transmittance Z -independent. A pre-focal transmittance maximum (peak), followed by a post-focal transmittance minimum (valley) is a Z -scan signature of a negative nonlinearity. An inverse Z -scan curve (i.e., a valley followed by a peak) characterize a positive nonlinearity. The relative on-axis transmittance of the sample measured (at the small aperture of the far-field detector) is given By [6]:-

$$T(z, \Delta\Phi_0) = 1 - \frac{4\Delta\Phi_0 Z / Z_0}{[(Z^2 / Z_0^2) + 9][(Z^2 / Z_0^2) + 1]} \quad (6)$$

where T is the transmittance through the aperture, which is a function of the sample position Z , the nonlinear refractive index is calculated from the peak to valley difference of the normalized transmission (experiment-ally) by the following formula [6]:-

$$n_2 = \Delta\Phi_0 / I_0 L_{eff} k \quad (7)$$

$$\Delta T_{p-v} = 0.406 \Delta\Phi_0 \quad (8)$$

where: ΔT_{p-v} : change in normalized transmittance between peak and valley, which its equal $|T_p - T_v|$ [10], $\Delta\Phi_0$ nonlinear phase shift, $k = 2\pi n / \lambda$, λ : is the wavelength of the beam. L_{eff} : the effective length of the sample, can be determined from the following formula [7]:-

$$L_{eff} = (1 - \exp^{-\alpha_0 t}) / \alpha_0 \quad (9)$$

where,
t: the sample length,

$$\alpha_0 = \frac{1}{t} \ln \frac{1}{T} \quad (10)$$

where, T is the transmittance. In equation (7), I_0 is the intensity at the focal spot given by [9]:

$$I_0 = \frac{P}{\pi \omega_0^2} \quad (11)$$

where : ω_0 , the beam radius at the focal point, P : the power of the laser beam.

2.2 Open-Aperture Z-Scan:

An open-aperture Z -Scan measures the change in power intensity of a beam, focused by lens L in Fig. 3, in the far field at detector PD , which captures the entire beam. The change in power intensity is caused by multi-photon absorption in the sample S as it travels through the beam waist. In the focal plane where the intensity is greatest, the largest nonlinear absorption is observed. At the “tails” of the Z -scan signature, where $|Z| \gg Z_0$, the beam intensity is too weak to elicit nonlinear effects. The higher order of multi-photon absorption present in the measurement depends on the wavelength of light and the energy levels of the sample [1].

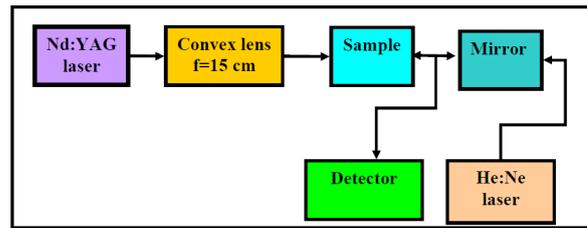


Fig. 3: Open-aperture Z -Scan of experimental work.

Clearly, even with nonlinear absorption, a Z -scan with a fully open aperture is insensitive to nonlinear refraction (film sample approximation). The Z -scan traces with no aperture are expected to be symmetric with respect to the focus ($Z = 0$) where they have a minimum transmittance or maximum transmittance. In fact, the coefficients of nonlinear absorption can be easily calculated from such transmittance curves [9]. The total transmittance is given by [7]:-

$$T(z) = \sum_{m=0}^{\infty} \frac{\left[\frac{\beta I_0 L_{eff}}{1 + (Z / Z_0)^2} \right]^m}{(m + 1)^{3/2}} \quad (13)$$

where Z : - is the sample position at the minimum transmittance, m :- integer. $T(z)$:- the minimum transmittance. The two terms in the summation are generally sufficient to determine the nonlinear absorption coefficient β .

3. Experimental Work

The experimental work based on the testing the olive oil transmission spectrum using UV-VIS spectrophotometer. Fig.4 shows the transmission spectrum of olive oil. The optical transmission of olive oil shows a variable behavior of the transmission as a function of the incident wavelength. The transmission behavior olive oil is about (44.28)% at wavelength of 532 nm, while it

was (72.94)% at 1064 nm as shown in Fig. 4. The transmission spectrum shows the maximum peak at (850) nm.

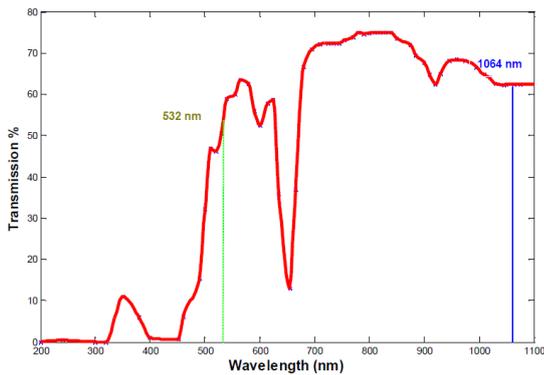


Fig. 4: UV-VIS transmission of olive oil

The linear absorption coefficient of olive oil α_0 was determined for both wavelengths using eq. (10) as shown in table (1).

λ nm	Thickness t	Transmission%	α_0 cm ⁻¹
532	10mm	47.13	0.752
1064	10mm	62.37	0.472

Table 1 linear absorption and refractive index of olive oil, the values of α_0 and n_0 were determined using equations respectively

The olive oil solution was filled into the glass cuvette 1mm thickness. The cuvette was hand made in the laboratory, which consists from five slides of glass as shown in Fig. 5.

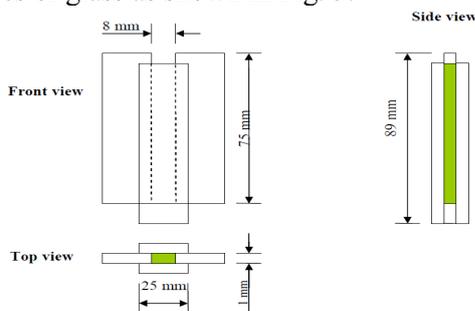


Fig.5 The sample cuvette

The nonlinear refractive index and nonlinear absorption coefficient of olive oil were measured by the z-scan techniques. Both nonlinear refractive index and nonlinear absorption coefficient are associated with the real susceptibility and imaginary parts of susceptibility respectively. Two techniques had been used to measure the nonlinear optical properties of olive oil, closed-aperture which is used to measure the nonlinear refractive index and open-aperture which is used to measure the nonlinear absorption

coefficient. Each technique applied on two cases of wavelength, case I: 532 nm and case II: 1064 nm.

3.1 Nonlinear refractive index:

In order to investigate the nonlinear refractive index, there were two cases chosen; at 532 nm and at 1064 nm. In case I, fig.6 shows the closed-aperture z-scan curves, at 532 nm, which represents the normalized transmittance as a function of position z

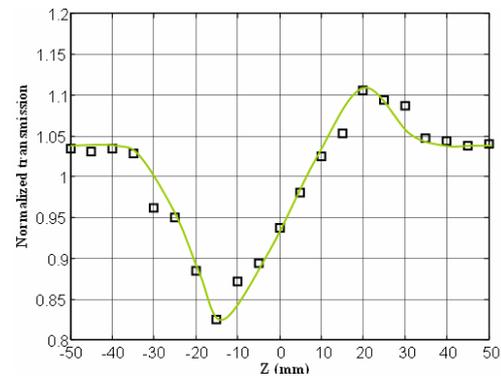


Fig.6 : Normalized transmittance versus position at 532 nm wave length, 50 mW input power for closed-aperture

In case II, the closed-aperture z-scan curves were determined at 1064 nm as in different powers. In the closed-aperture transmittance curves, the peaks to valley values ΔT_{p-v} were shown in Table 2

λ (nm)	Power (mW)	ΔT_{p-v}
532	50	0.246
1064	80	0.222
	100	0.3228
	120	0.398
	140	0.467

Table 2: The peak to valley values of normalized transmittance curves.

The sample nonlinearity was calculated from the difference between the heights (peak) and the lowest value (valley) transmission values denoted as ΔT_{p-v} . After the sample passes through the waist and moves toward the aperture, it decreases the beam divergence and thus increases the transmission through the aperture. The self-focusing arising from the kerr effect in olive oil solution, which appears in the peak and valley transmittance of each of z-scan trace.

The closed-aperture z-scan defines variable normalized transmittances values as shown in table 2, which is used to determine the nonlinear

phase shift eq.(6). The linear refractive index n_o , the maximum peak on-axis irradiance at 532 nm & 1064 nm wavelengths and the minimum beam waist radius at the focal point were determined for both wavelengths equals 180 μm for 1064nm and 50.67 μm for 532nm (Table (3)) which In addition, the nonlinear refractive index was determined at different nonlinear phase shift .

λ (nm)	Power (mW)	n_o	I_o (mW/cm ²)	$\Delta\Phi$ (rad)	n_2 (cm ² /W)
532	50	1.478	98.25×10^3	0.66	2.45×10^{-7}
1064	80	1.46	157.2×10^3	0.54	3.5×10^{-6}
	100		196.5×10^3	0.795	4.07×10^{-6}
	120		235.8×10^3	0.972	4.18×10^{-6}
	140		275×10^3	1.15	4.24×10^{-6}

Table 3: nonlinear refractive index and nonlinear phase shift versus incident power.

Fig. 7 depicts the change in refractive index versus incidence intensity. It is shows that the change in the refractive index increased when the incidence intensity increased.

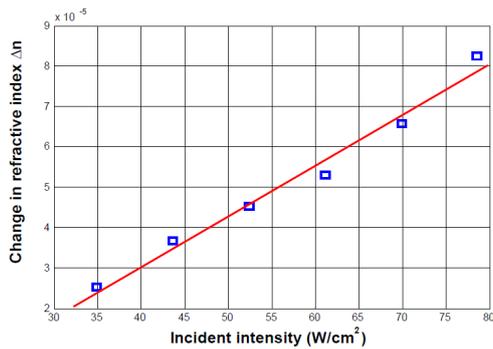


Fig. 7: Variation in change in refractive index with incidence intensity.

The thermo-optic coefficient dn/dT was determined, when thermal conductivity $K = 0.17$ W/m.K as shown in Fig. 8.

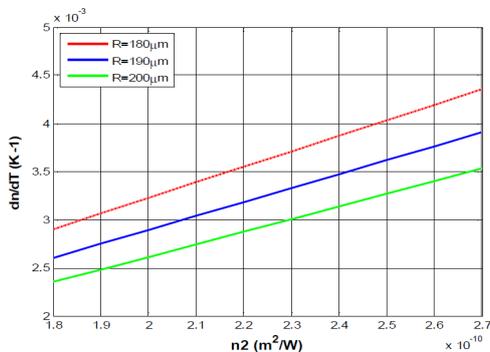


Fig. 8: Thermo-optic coefficient versus nonlinear refractive index and radius of beam R.

The experimentally measured n_2 of olive oil were compared with other nonlinear liquid materials, such as Toluidine Blue O dye. This material had a

nonlinear refractive index 1.4×10^{-7} cm²/W at 532 nm wavelength [12]. Also the nonlinear refractive index of olive oil nearest at 1064 nm wavelength near to the nonlinear refractive index for different nematic liquid crystals in the near IR range [10]. Qualitatively, these values were in good agreement with our experimental values of olive oil. The highest nonlinearity of olive oil can be used in photonic devices applications (e.g. Liquid-filled photonic crystal fiber).

3.2 Nonlinear absorption coefficient:

In order to investigate the nonlinear absorption coefficient, two wavelengths were considered 532 nm and 1064 nm. In case I, Fig. 9 shows the open-aperture z-scan curves, which represents the normalized transmission as a function of position z.

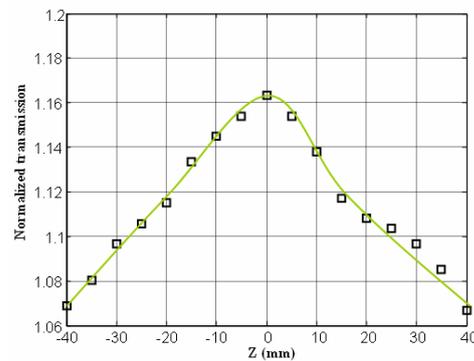


Fig. 9: Normalized transmittance versus position at 532 nm wave length, 50 mw input power for open-aperture.

In case II, the open-aperture z-scan curves results were determined at different input power, at 1064 nm for different powers. From the results of the open-aperture z-scan, the nonlinear behavior of the transmission curves in good agreement with the result reported by Kandasamy et al. [11]. The transmittance is sensitive to the nonlinear absorption as a function of input power intensity. The change in intensity is caused by saturation absorption in the sample as it travels through the beam waist. In the focal plane where the intensity is greatest, the largest nonlinear absorption is observed. At the far field of the Gaussian beam, where $|z| \gg z_0$, the beam intensity is too weak to elicit nonlinear effects. A symmetric peak value is contributed to the negative nonlinear absorption coefficient β , indicates that the sample shows a bleaching-like behavior (saturation of absorption). Table 4 shows that (T_{max}) values increased with increasing input power at 1064 nm. Also, the value of normalized transmission at 1064nm and 120mW input power is approximately the same value of normalized transmission at 532nm and 50mW input power. The open-aperture z-scan defines variable transmittance values, which is used to determine the nonlinear absorption

coefficient this can be shown in Table 5. The variation of β is inversely proportional to the input intensity, the nonlinear absorption showed the intensity dependence. Since the olive oil exhibit the saturation of absorption as a function of the input intensity. The value of β also depends on the wavelength. In contrast, the value of β in case II is greater than case I. In contrast these values of β of olive oil with other material. It shows that the olive oil having high nonlinear absorption coefficient. This can be shown in Toluidine Blue O dye, which had nonlinear absorption coefficient β equal to (- 2.5 μ m/W) at 532 nm [12].

λ (nm)	Power (mW)	T_{max}
532	50	1.163
1064	80	1.136
	100	1.151
	120	1.167
	140	1.171

Table 4: The peak value (T_{max}) of normalized transmittance curves.

λ (nm)	Power (mW)	β (m/W)
532	50	- 7.26 $\times 10^{-4}$
1064	80	- 0.002
	100	- 0.0018
	120	- 0.0016
	140	- 0.0014

Table 5: Nonlinear absorption coefficients versus input power.

4. Conclusions:

It is found that olive oil behaved " Blue-shift" when it is excited at visible region and this behavior is an indicator of two photon absorption. Furthermore this material is birefringence. These points lead to study the nonlinear optical properties of olive oil. The concluded information obtained from this project results are described: 1) The nonlinear refractive index of olive oil n_2 versus input powers and wavelengths is determined using z-scan technique, which are equal $n_{2,average}=3.99 \times 10^{-6} W/cm^2$ for 1064nm wavelength and $n_2=2.45 \times 10^{-7} W/cm^2$ for 532nm wavelength. Also, the nonlinear phase shift θ is found to be equal to 0.66 rad at 532nm wavelength and $\theta_{average}=1.05$ rad at 1064nm wavelength. 2) Olive oil has a saturation effect for both wavelengths 532nm and 1064nm in CW regime. Therefore, the nonlinear absorption coefficient is determined using z-scan technique which are $\beta_{average}=-0.0017$ m/W for 1064nm

and $\beta=-7.26 \times 10^{-4}$ m/W for 532nm wavelength. 3) The olive oil have a high nonlinear refractive index and nonlinear absorption compared with other material (i.e Toluidine Blue O dye in Acetonitrile have nonlinear refractive index $n_2=1.4 \times 10^{-7} W/cm^2$ and nonlinear absorption coefficient $0.34 \times 10^{-3} cm/W$), which can be a promising candidate for photonic device application. 4) No nonlinear response was observed in olive oil using He:Ne laser of 5mW output power. The nonlinear response could be seen at 50mW input power when Nd:YVO4 laser is used at 532nm wavelength.

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