Applied Chemical Engineering (2025) Volume 9 Issue 2 ISSN: 2578-2010 (O)
doi: 10.59429/ace.v9i2.5912

RESEARCH ARTICLE

Spectral and Non-Linear Optical Properties Investigation of Mixtures of (Fluorescein, Eosin, and Rhodamine B) Organic Laser Dyes

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ABSTRACT

This study investigates the spectral and nonlinear optical characteristics of a new mixture of three organic laser dyes : (Fluorescein Orange, Eosin Yellow, and Rhodamine B) dissolved in chloroform solvent at varying concentrations (2×10-5, 4×10-5, 6×10-5, and 8×10-5) M. A diode-pumped solid-state laser with a power of 84mW and a 457nm wavelength has been used for nonlinear measurements using the Z-Scan method. With a UV-VIS spectrophotometer, the transmission and absorption spectra of each sample were measured. All of the samples' closed-aperture Z-scans confirmed self-defocusing behavior, and the open-aperture Z-scan confirmed two-photon absorption. According to the findings, the nonlinear absorption coefficient and nonlinear refractive index increased with concentrations. The fluorescence spectra of the dye combination at a concentration of (8×10^{-5} M) were the most intense among all tested concentrations .The findings showed that there was a clear link between concentration and absorption intensity :when concentration went up, absorbance went up as well. The research also found that larger concentrations led to a lower quantum efficiency and a longer fluorescence lifespan. These results indicate that the dye combination has favorable properties, positioning it as a good candidate for use in photonic and nonlinear optical devices.

Keywords: Eosin dye, quantum efficiency, photonic applications, nonlinear refractive index, self-focusing.

ARTICLE INFO

Received: 24 February 2025
Accepted: 13 April 2026
Available online: 18 June 2026

1. Introduction

The organic dyes are used as an active medium of a laser which have high absorption bands within the visible region of the electromagnetic spectrum. Extended conjugated systems with alternating single and double bonds in their molecular structures are presented in the dye [1]. These dye molecules can dissolve in an organic solution or in a solid matrix. A chromophore is any material that absorbs visible and ultraviolet photons. Light is absorbed when the dye makes an electrical transition from the ground state to the excited state, which gives the dye color [2]. Chromophores are the chemical substances that give molecules their color. The dye's color originates from its ability to absorb visible wavelengths (300-900nm) [3] . These dyes' high fluorescence allows for fluorescence spectroscopy to analyze their linear characteristics [4]. While the dyes have been shown to be laser compatible in solid, fluid, or gaseous forms, their most significant effects, such as laser media, have been observed in liquid and solid states. [5].Due to its objectivity in a wide range of domains, non-linear optical (NLO) features have been widely focused on in recent theoretical and experimental research. [6]. The rate of energy transfer during fluorescence emission has numerous applications in photochemistry, physics, and biology. An additional significant application of energy transfer is in dye lasers, where it serves to mitigate photo quenching effects and consequently enhance laser efficiency [7]. To the best of our knowledge, this study is the first to report the use of a ternary dye mixture comprising (Fl, Eo-Y, and R B) under the present experimental conditions. No previous investigations have addressed the combined incorporation of these three dyes within a single system for this type of application. The synergistic interaction between the dyes is expected to play a significant role in enhancing the optical and nonlinear properties of the material. Accordingly, this work introduces a promising strategy that may open new avenues for advanced optical applications, particularly in areas such as optical limiting and photonic devices

2. Theory

The following equation gives us the substance's greatest absorbance [8]:

$$n = n_o + n_2 I \tag{1}$$

Where (I) represents incoming intensity, (α_o) linear absorption coefficient, and (β) intensity-related nonlinear absorption coefficient. To find the linear refractive index at high intensity using Eq. (2) [9]:

$$\alpha = \alpha_o + \beta I \tag{2}$$

Where, (n_o) is the linear refractive coefficient, and (n_2) is the nonlinear refractive index. To examine the nonlinear optical characteristics, Z-scan technique determines the nonlinear refractive index in closed-aperture shapes, us Eq. (3) [10]:

$$n_2 = \frac{\Delta\phi_\circ}{I_o L_{eff}} \tag{3}$$

Where, ($\Delta\Phi_o$) is the phase shift that is nonlinear [11]:

$$\Delta T_{p-v} = 0.406 |\Delta \Phi_o| \tag{4}$$

The difference between the normalized transmittances at peaks and valleys is represented by ΔT_{p-v}. Where, $k = 2\pi/\lambda$, where (λ) denotes the spectrum of the beam, (I_o) represents the intensity level at the focal point [12]:

$$\mathbf{I_o} = \frac{2P_{peak}}{\pi\omega_\circ^2} \tag{5}$$

Where ($\omega_\circ$) is the beam radius at the focal point equal 0.025 mm and (L_{eff}) signifies the effective length of the sample provide the following formula [12]:

$$L_{eff} = \frac{(1 - \exp^{-\alpha_o L})}{\alpha o} \tag{6}$$

The linear absorption coefficient (α_o) can be obtained by the formula [13]:

$$\alpha_o = \frac{\ln(\frac{1}{T})}{t} \tag{7}$$

Where (t) is the sample's thickness,(T) is the transmittance, and (n_o) is the linear refraction index which is given by the equation [14]:

$$n_o = \frac{1}{T} + \sqrt{(\frac{1}{T2} - 1)} \tag{8}$$

Transmittance is the relative percent of light that passes through the solvent. Thus, if half the light is transmitted, it can be said that the solution has 50% transmittance [14].

$$T\% = (\frac{I}{I_o}) \times 100\% \tag{9}$$

The nonlinear absorption coefficient (β) is given by the following [15]:

$$\boldsymbol{\beta} = \frac{2\sqrt{2}\ \mathbf{T(z)}}{\mathbf{I_o}\boldsymbol{L_{eff}}} \tag{10}$$

Where T(z) is the lowest normalized transmittance at the focal point, at (Z=0). Based on the results of the fluorescence spectra, the formula can be used to determine the fluorescence lifespan and quantum yield (Φ_f) and the fluorescence lifetime based on the findings of the fluorescence spectra is [16]:

$$\tau_F = \frac{\boldsymbol{a} \times \boldsymbol{\tau_{fRB}}}{\boldsymbol{a_{RB}}} \tag{11}$$

The lifetime of the standard chemical (τ_{fRB}) is derived by integrating the fluorescence curve of the laser organic dye [17]:

$$\Phi \boldsymbol{f} = \frac{\int \mathbf{F(\upsilon)d\acute{\upsilon}}}{\int \boldsymbol{\varepsilon}\mathbf{(\upsilon)d\acute{\upsilon}}} \tag{12}$$

Where, ∫ F(v') dv' is the area under the curve, while the area under the absorption curve is denoted by ∫ε (v') dv'.

3. Materials and Chemical

Fluorescein Orange, Eosin Yellow, and Rhodamine B are among the brightest xanthene dyes [18]. These organic dyes show a strong fluorescence and photo stability. Due to their self-association behavior in solutions and various applications, these members of the xanthene family have become more well-known. They are widely used for biomedical imaging, histological staining, and fluorescence microscopy, as well as in laser systems. Eosin Yellow ($C_{20}H_6Br_4Na_2O_5$) with a molecular weight of (691.9 g/mol) , Fluorescein Orange ($C_{20}H_{12}O_5$) with a molecular weight of 332.31 g/mol, and Rhodamine B ($C_{28}H_{31}N_2O_3Cl$) with a molecular weight of 479.02 g/mol. The dyes were purchased from Sigma-Aldrich (Germany) with purities above 99%. Figure 1. shows the molecular structure of the dyes[19].

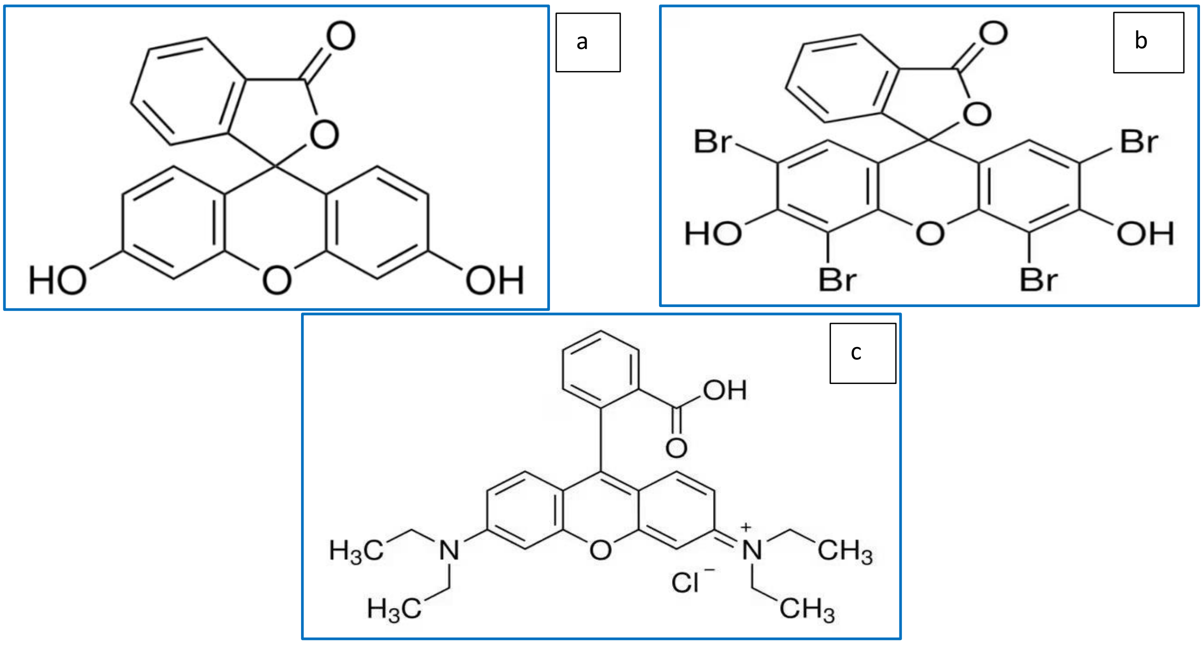

Figure 1. The Molecular Structure of : (a)Fluorescein Dye,(b)The Molecular Structure of Eosin Organic Dye, (c) The Molecular Structure of Rhodamine B dye [19].

3.1. Preparing solutions

Chloroform solvent was used to create concentrated stock solutions (10^{-3} M) of each organic laser dye Fluorescein Orange, Eosin Yellow, and Rhodamine B. A German electric balance (model BL 210 S) with a precision of four decimal places was used to precisely weigh the color powders. Subsequent working solutions of lower concentrations were prepared by dilution of the stock solution according to the following equation [20] :

$$\mathbf{W} = \frac{\mathbf{M}_{W} \times V \times C}{1000} \tag{13}$$

Where (W) represents the weight of the dissolved substance in gram, (M_w) is the Molecular weight of the material in g/mol, (V) is the solvent volume in mL, and (C) is the concentration in M. The dilution formula used to prepare the solution is [20]:

$$C_1V_1 = C_2V_2 \tag{14}$$

Where (C_1) and (V_1) denote the concentration and volume of the stock solution, while (C_2) and (V_2) represent the desired concentration and volume of the diluted mixture solution of the three dyes: Eosin, Fluorescein, and Rhodamine B, were prepared at four different concentrations (2×10^{-5}, 4×10^{-5}, 6×10^{-5}, and 8×10^{-5} M).Equal quantities (1 mL) of each dye solution were added to create a ternary mixture. mixes at the appropriate quantities, as shown in Figure 2.

Figure 2. Organic laser dyes mixture with different concentrations.

3.2. Devices used

3.2.1. UV-Visible Spectroscopy

A Shimadzu 1800 UV-visible spectrophotometer was used to evaluate linear optical parameters. This device uses two light sources: a tungsten lamp at (390-1100) nm and a deuterium lamp at (190-390) nm. Specialized software was used to determine optical constants based on wavelength, transmittance, and absorbance measurements.

3.2.2. Fluorescence Measurement

Fluorescence spectra of dye samples were acquired using a FluoroMate FS-2 spectrometer. A Shimadzu RF-5301PC fluorophotometer was used to take further fluorescence emission measurements. Samples were placed in a quartz cuvette (1 × 1 × 5 cm) at a 90° angle from the incoming excitation beam. This optical configuration was specifically chosen to minimize the influence of distributed excitation light. The computer-controlled apparatus covers a wavelength range of 220-900 nm and allows for specific change to excitation and emission wavelengths, scanning parameters, monochromatic slit width, and detector settings. The acquired fluorescence spectra were examined to assess optical properties, The collected fluorescence spectra were processed and analyzed to evaluate the optical behavior of the dye mixtures.

3.2.3. Z-scan measurement

The Z-scan strategy is a straightforward and fundamental method for characterizing nonlinear absorption and refraction. It works using single beam technology. It refers to the process of passing a sample through a Gaussian beam focused in the central region. Wavefront disturbance caused by self-focusing or non-self-focusing will lead to nonlinearity in the Kerr scale. The power of the beam crossing a small aperture in the far field varies depending on the position of the sample. By estimating the output power with respect to the sample position, implemented using either methods with closed or open apertures, as shown in Figure 3. [21].

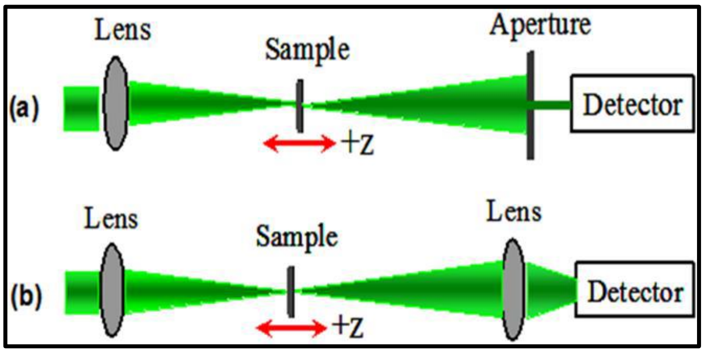

Figure 3. The setup of closed aperture Z-scan (a) closed aperture Z-scan and (b) open aperture z-scan [22]

4. Results and Discussion

4.1. FT-IR Spectra

The FT-IR spectra for fluorescein powder indicates the stretching bond indicated by the peak at (2118) cm-1 indicate carbon-hydrogen bond (C-H), the peak at (1321) cm-^{1} indicate (O-H), and the peak at (1562) cm^{-1} indicate (C=C) Carbon-carbon bonds are covalent bonds formed between two carbon atoms. The peak at (1163) cm^{-1} indicates (C-O), whereas the range (839-759) cm^{-1} indicates the (C-C) group, which agrees with the [23].

As shown in Figur4. to Figure 6. depicts the stretching bond, represented by the range (3741-2870)cm^{-1}, for the bond (N-H).The signal at (3063) cm^{-1} indicates a carbon-hydrogen bond (C-H).The peak at (2840) cm^{-1} indicates (C-H) stretching. The peak at (2321) represents (O=C=O) carbon dioxide stretching. The peak at (1688) cm^{-1} indicates (C=O), The signal at (1642) cm^{-1} indicates a carbon-nitrogen bond, which is a covalent link between carbon and nitrogen (C=N), whereas the peak at (1465) cm^{-1} indicates a hydrogen bond. The peak at (1165)cm^{-1} indicates the carbon-oxygen bond, which is a polar covalent link between carbon and oxygen, which agrees with the reference [24].

The FT-IR spectrum of Eosin -Y shows the main functional groups of the dye: in 3400 cm^{-1}: Broad O–H stretching, indicating hydroxyl groups or hydrogen bonding. in the (~1710–1730) cm^{-1} (C=O): Carbonyl stretching, confirming carboxyl/lactone groups. in the 1610 cm^{-1}: Aromatic C=C stretching from the benzene rings. In the 1260 cm^{-1} and 1100 cm^{-1}:(C–O) and (C–O–C) stretching, related to ether or phenolic groups. Below 800 cm^{-1}: Fingerprint region of aromatic ring substitutions. These peaks confirm the typical structure and purity of Eosin Y dye, which agrees with the [25].

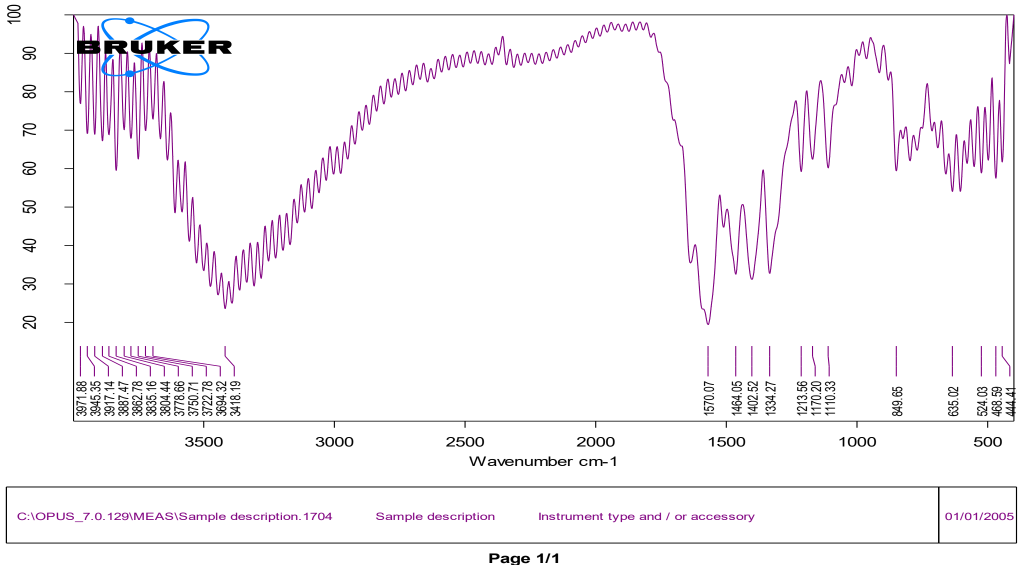

Figure 4. FT-IR spectrum for Fluorescein dye as powder.

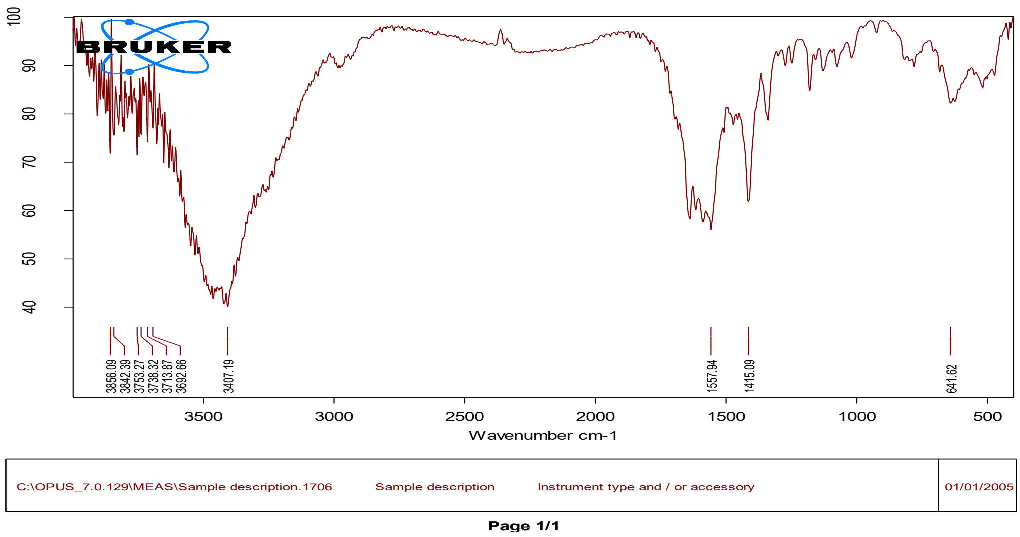

Figure 5. FT-IR spectra of Rhodamine B dye as powder.

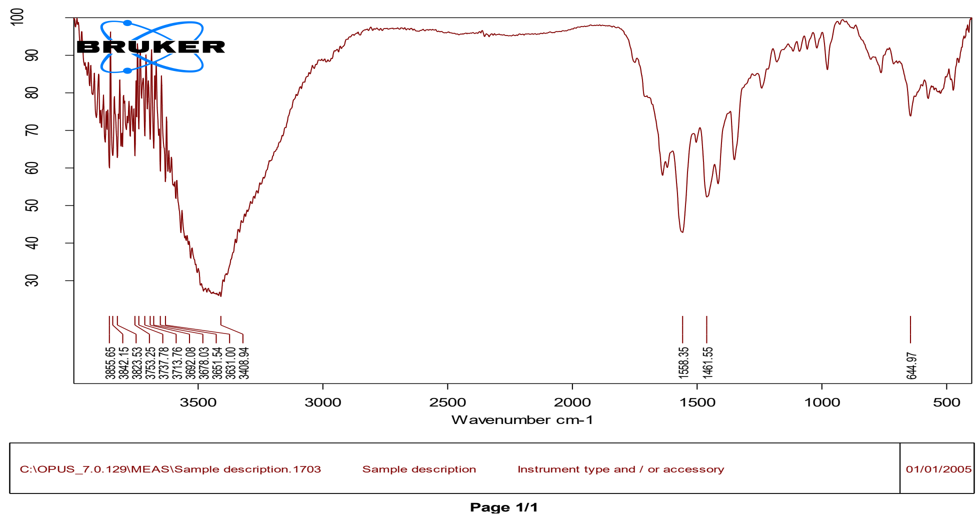

Figure 6. FT-IR spectra of Eosin dye as powder.

4.2. The absorption spectra

Figure 7. displays the absorption spectra of three organic dyes, namely Fl, E-Y, and RB dissolved in chloroform solvent. The absorption spectra were measured within the wavelength range of (300–900 nm). Where all dyes exhibited noticeable absorption in the visible region (400–600 nm).The Fluorescein dye absorption exhibited a main absorption peak around (440–460 nm), corresponding to electronic transitions of type $\pi \rightarrow \pi^*$ within its conjugated aromatic structure. The absorbance intensity of this dye was relatively low compared to the other dyes, and it absorbs mainly in the blue-green region, which results in greenish-yellow fluorescence emission. The E-Y spectra revealed a high absorption band about (515-530) nm, suggesting absorption in the green area of the spectrum. E-Y had a higher absorbance than Fluorescein, suggesting more π-electron conjugation and interactions. When stimulated, this dye often produces orange fluorescence. The absorption maxima of RB dye is at (555-565) nm, which corresponds to the yellow-green region of the visible spectrum. RB had the highest absorbance intensity among the three dyes, suggesting a strong light-matter interaction and an extended conjugated π-system. This dye is famous for its strong red fluorescence emission. (Fluorescein, Eosin-Y, and Rhodamine B) showed a red shift in absorption maxima (λ_{max}), suggesting increased molecule conjugation and delocalization of π-electrons. This activity reduces the energy difference between the HOMO and LUMO energy levels, causing absorption to shift toward longer wavelengths [26]. The absorption spectra of ternary mixtures of the organic laser dyes Fluorescein, Eosin Y, and Rhodamine B dissolved in chloroform at varies concentrations (2×10^{-5}, 4×10^{-5}, 6×10^{-5}, and 8×10^{-5}M) are shown in Figures 8. An increase in the relative spectral intensity was observed with higher concentrations of the donor dye, which can be attributed to an enhanced probability of energy transfer and the possible formation of dye–dye complexes. The spectral amplitude of the mixtures also increased with donor concentration, indicating improved energy transfer efficiency. The broadest spectral response was obtained at 8×10^{-5} M, corresponding to a balanced proportion of donor and acceptor molecules, The result agree with Safa A. Jabbar et al [27].

Figures (4 and 5) show that the first absorption band appears in the UV region (300–350 nm), which is related to $\pi \rightarrow \pi^*$ electronic transitions associated with aromatic rings and conjugated double bonds. dye concentration, following the Beer-Lambert law [28]. Two absorption bands were detected in the visible region: one about 330 nm (near the UV edge) and another at 530-550 nm, which accounts for the dye solution's hue. The band at 540 nm represents $n \rightarrow \pi^*$ transitions or extended π-conjugation, which absorbs green-yellow light and emits its equivalent visible light [29].

The red curve has the highest absorbance, suggesting bigger effective concentration or stronger intermolecular interactions at these wavelengths. The blue curve exhibited the lowest absorbance, perhaps due to reduced dye concentration, weaker connections, or suppression of electronic transitions. The transmittance spectra showed variations in optical transmission based on input wavelength, with higher concentrations often leading to lower transmittance at certain wavelengths, this agree with Albouchi, F and Abdelmajid, J [30].

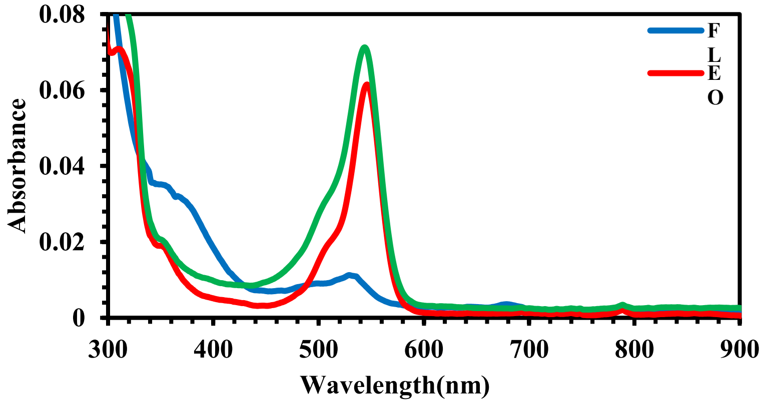

Figure 7. Absorbance Spectra for the Three Organic Pure Dyes: (Fluorescein Eosin- Y, and Rhodamine B) dissolved in Chloroform Solvent.

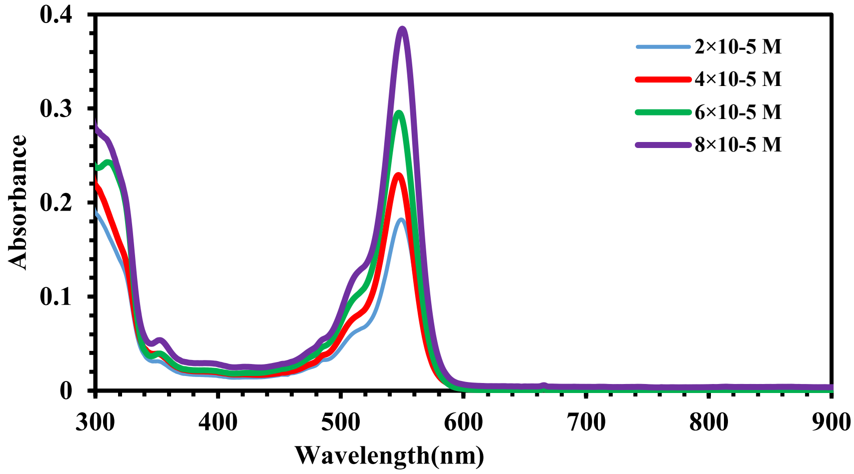

Figure 8. Absorbance Spectra for a Mixture of Three Organic Dyes at different concentrations dissolved in Chloroform Solven

4.3. The Fluorescence Spectra

Figure 9. The study compares the fluorescence spectra of three organic dyes (Fl, E-Y, and RB) in the (400-900) nm wavelength range. These spectra show each dye's emission properties as well as spectral interactions that imply probable energy transfer between them. The Fluorescein dye exhibits a strong fluorescence emission peak around (520 nm), corresponding to the green region of the visible spectrum E-Y shows a broader fluorescence band with a maximum near (550–560 nm), located at the yellow-green region. Meanwhile, R B presents the most intense fluorescence among the three dyes, with an emission peak around (580–600 nm), falling in the orange-red region of the spectrum. A noticeable spectral overlap exists between the emission bands of these dyes.

The emission spectrum of Fluorescein overlaps with that of Eosin-Y, and in turn, Eosin-Y overlaps with Rhodamine B. This sequential overlap supports the possibility of resonance energy transfer (FRET) between the dyes in the order Fluorescein → Eosin Y → Rhodamine B. In such a process, Fluorescein acts as the energy donor, Eosin-Y as both intermediate donor and acceptor, and Rhodamine B as the final energy acceptor[31].

The ternary mixture of Eosin, Fluorescein, and Rhodamine B dyes dissolved in chloroform at varies concentrations (2×10^{-5}, 4×10^{-5}, 6×10^{-5}, and 8×10^{-5} M) in Figure 10. exhibits a broad fluorescence spectrum in the range of (500–700nm). The observed emission results from the relaxation of excited dye molecules back to their ground states, which produces the characteristic Stokes shift [32].As the concentration increases, the fluorescence intensity is enhanced and a noticeable red shift occurs, which can be attributed to molecular interactions and reabsorption processes within the medium [33].

The fluorescence lifetime (τ_f) and quantum yield (Φ_f) were calculated using absorbance and emission data. Higher concentrations result in prolonged fluorescence lifetimes and decreased fluorescence quantum yield, which is linked to aggregation and intermolecular energy transfer in dye mixtures (see Table 1).

Figure 11. illustrates the spectral overlap between the absorption and fluorescence spectra of the three dyes: Fl, E-Y, and RB. The spectra show how energy transfer can occur among these dyes through their overlapping regions. Fluorescein's absorption spectrum ranges from (450-500)nm, Eosin-Y shows its absorption peak near (520–550 nm) and emits fluorescence around (550–570nm). Rhodamine B absorbs light between (550–600 nm) and fluoresces in the red region around (580–620)nm. A clear spectral overlap can be seen between the fluorescence of Fluorescein and the absorption of Eosin-Y, indicating that Eosin-Y can act as an energy acceptor when Fluorescein serves as an energy donor. Similarly, the fluorescence of E-Y overlaps with the absorption of R B, suggesting another possible energy transfer from E-Y to R B. This stepwise overlap

(Fluorescein → Eosin Y → Rhodamine B) demonstrates the possibility of resonance energy transfer between these dyes. Therefore, these observations are limited to spectral evidence and cannot be considered as direct confirmation of resonance energy transfer. [34].

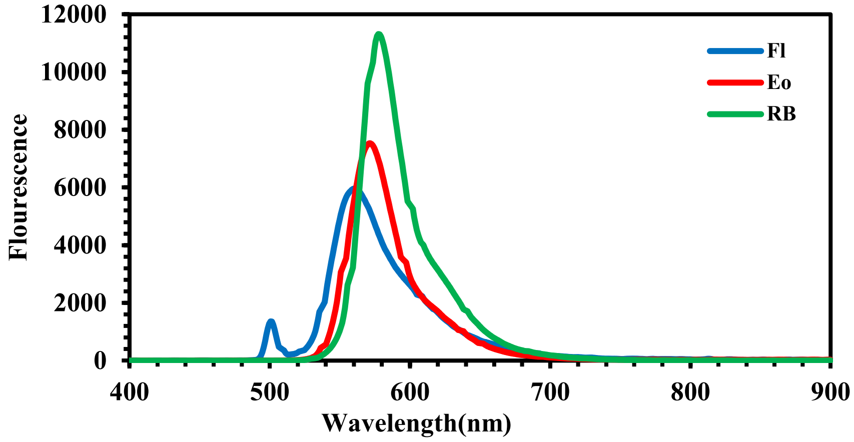

Figure 9. Fluorescence spectra for Pure (Fluorescein, Eosin -Y, and Rhodamine B) organic laser dyes.

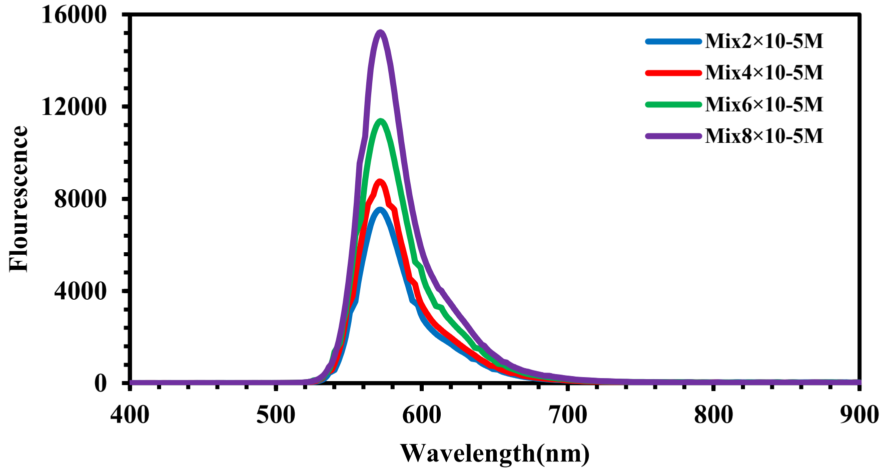

Figure 10. Fluorescence spectra for a Mixture of (Fluorescein, Eosin-Y, and Rhodamine B) organic dyes at different concentrations.

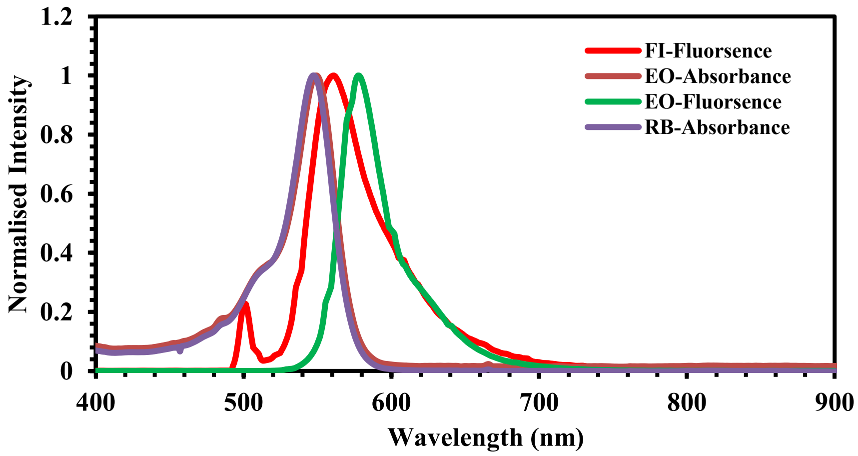

Figure 11. Spectral overlap and Energy Transfer Path among fluorescein, Eosin and Rhodamine B.

Table 1. The Optical Properties of Pure and Mixture dyes at different concentrations.

Organic Dye	Concentration (M)	λmax (Absorbance)	λmax (Fluorescence)	τf (ns)	Φf (%)
Fl dye	8×10^{-3}	545	561.2	0.25	**91**
Eo dye	8×10^{-3}	549	577.4	0.03	**89**
Rb dye	8×10^{-3}	547	571.7	0.04	**87**
Mixture of (FL+Eo+RB)	2×10^{-5}	549	571.6	0.04	**96**
	4×10^{-5}	547	571.1	0.04	**94**
	6×10^{-5}	547	571.7	0.05	**93**
	8×10^{-5}	550	571.7	0.05	**92**

4.4. Nonlinear optical properties

Using the experimental Z-scan data, values of β and n_2 were extracted for the organic dye mixture in chloroform at various concentrations. Table2. show that the values of nonlinear refractive index (n_2) for all samples of mixture. The values of nonlinear parameters (n_2 and β) for solutions are decreased with decreasing the concentrations, as decreasing the values of linear parameters (α_o and n_o). This is due to decreasing number of molecules per volume unit at low concentrations [35].

Figure 12. depicts the connection between Normalized Transmission of Light and the location, denoted Z(mm), over a center point. The characteristic "valley" form, also known as a Z-scan curve, is a hallmark of nonlinear optical measurements, revealing how the material's properties vary with light intensity. although they all exhibit a similar asymmetrical response around the zero position, the RB sample has the most substantial variance in transmission. The data graphically depicts how the three materials interact with a focused light beam while being transported via its focal plane.

Figure 13. depicts an open-aperture Z-scan of three pure dye solutions to investigate their nonlinear absorption coefficient. It has been determined that two photons absorb. Transmittance behaves linearly at various frequencies. Distances from the sample point's distant field (-Z). The transmittance curve in the nearby field (Z = 0) mm at the focal point) begins to drop and finally approaches the minimum value.The region of nonlinear optical response was observed within a range of approximately −2 mm to +2 mm around the focal plane.

The closed-aperture transmittance curve exhibits a characteristic peak–valley profile, confirming a negative nonlinear refractive index ($n_2 < 0$), which is associated with a self-defocusing effect, as illustrated in Figure 14.

Shown in Figure 15. reveal a nearly linear transmission pattern at larger negative Z values. As the sample approaches the focal point (Z = 0 mm), the transmittance gradually decreases, reaching a minimum value (T_{min}). Beyond the focus, at (+ Z). positions, the transmission begins to increase again, approaching the linear regime. This behavior is attributed to two-photon absorption, where simultaneous absorption of two photons occurs as the sample passes through the beam waist, giving rise to the observed intensity variations, his behavior agrees with the study's point of Saleh et al [36].

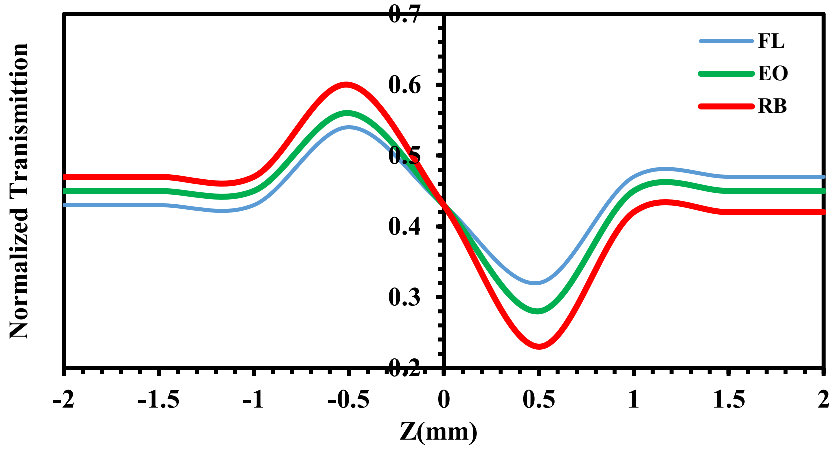

Figure 12. Closed-aperture Z-Scan data pure dyes (Fl, E-Y and RB) in chloroform solvent

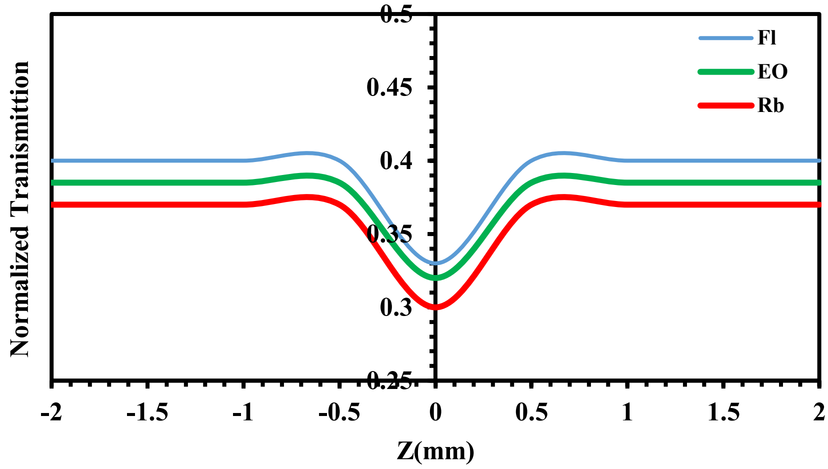

Figure 13. open aperture Z-Scan data for pure dyes (Fl, E-Y and RB) in chloroform solvent

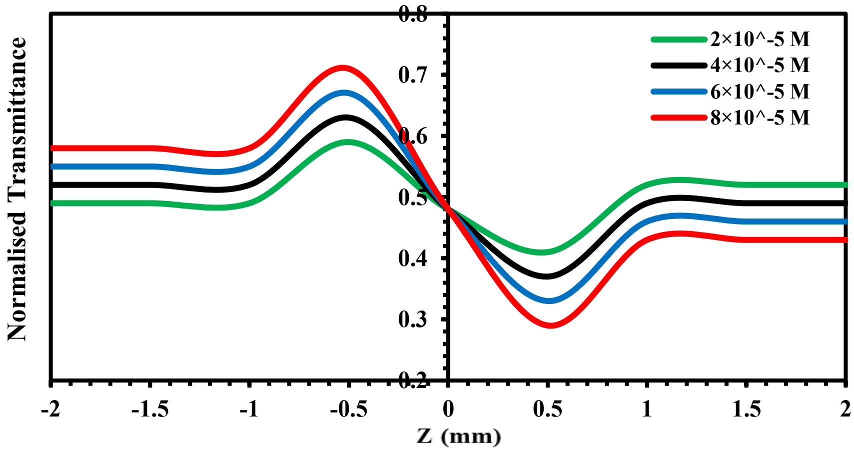

Figure 14. closed aperture Z-scan data for mixture of three organic dyes at different concentration in chloroform solvent.

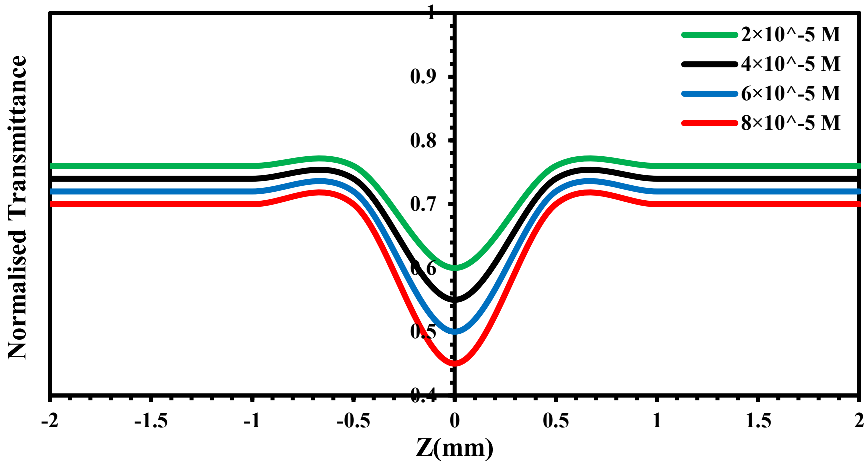

Figure 15. Open aperture Z-scan data for mixture of three organic dyes at different concentration in chloroform solvent.

Table 2. The optical properties of pure dyes (Fl, E-Y, and R B) and mixture quantities at λ = 457 nm in chloroform solvent are linear and nonlinear.

Organic Laser Dyes	C Mol/L	T%	$\alpha_\circ$ cm^{-1}	n_o	ΔTp−v	n_2 cm^2/mW	T(z)	β cm/mW
Fl dye	8×10^{-3}	0.984	0.016	1.0326353	0.22	1.8×10^{-10}	0.33	4.1×10^{-3}
E-y dye	8×10^{-3}	0.981	0.0185	1.0375992	0.28	2.4×10^{-10}	0.32	4.3×10^{-3}
Rb dye	8×10^{-3}	0.976	0.0234	1.0478198	0.37	2.9×10^{-10}	0.30	5.0×10^{-3}
Mixture of (Fl + Ey+ Rb)	2×10^{-5}	0.961	0.038	1.080164	0.30	3.2×10^{-10}	0.60	5.2×10^{-3}
	4×10^{-5}	0.955	0.045	1.094275	0.34	3.4×10^{-10}	0.55	5.4×10^{-3}
	6×10^{-5}	0.946	0.055	1.115771	0.38	$3,6\times10^{-10}$	0.50	5.6×10^{-3}
	8×10^{-5}	0.934	0.067	1.142942	0.41	4.0×10^{-10}	0.45	6.0×10^{-3}

5. Conclusion

The research found that the absorbance spectra of (Fl, E-Y, and RB) became stronger as the concentration went up. In the same way, the fluorescence spectra of the mixture show a positive correlation with concentration, which means that the intensity of the fluorescence goes up as the concentration increases. as the concentration was larger, the quantum efficiency went down, perhaps because the radiative and fluorescence lifetimes were longer. The fluorescence spectra of the dye combination at a concentration of (8×10^{-5} M) were the most intense among all tested concentrations . in nonlinear properties closed-aperture measurements revealed a peak–valley signature, indicating negative nonlinear refraction associated with a defocusing effect, whereas open-aperture data confirmed the presence of two-photon absorption. The combined dye system exhibited a gradual enhancement in both linear and nonlinear optical coefficients with increasing concentration, attributed to efficient energy transfer from the donor to the acceptor dyes within the blend. Overall, the findings highlight that this novel dye combination represents a promising candidate material for potential applications in nonlinear optical systems.

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