Judd-Ofelt, radiative properties of Sm$^{3+}$ ions doped PVA+PEG complex polymer films from spectral analysis

V Vinay Krishna$^1$, S Hima Bindu$^2$, D Siva Raju$^{3,4}$ and Ch Linga Raju$^3$*

$^1$ Department of Electronics & Instrumentation Technology, Acharya Nagarjuna University, Nagarjuna Nagar- 522510, A.P, India.
$^2$ Departments of Physics, National Institute of Technology Warangal, Warangal-506004, Telangana, India.
$^3$ Departments of Physics, Acharya Nagarjuna University, Nagarjuna Nagar-522510, A.P, India.
$^4$ Indian Institute of Science Education and Research Tirupati, Tirupati- 517501, A.P, India

* E-mail: drchlraj_phy@yahoo.com

Abstract. A trivalent rare earth ion Sm$^{3+}$ (1-5 mol %) doped Poly (vinyl alcohol) (PVA) and Poly (ethylene glycol) (PEG) complex polymer blends were synthesized by using solution casting technique. The spectroscopic characteristics behaviour and Judd-Ofelt (J-O) intensity parameters, oscillatory strengths and radiative properties of the prepared polymer blends were investigated with the help of optical absorption and photoluminescence spectral studies. Well defined UV-VIS-NIR optical absorption bands pertaining Sm$^{3+}$ ions are observed in optical absorption spectrum and these bands has been assigned to their respective electronic transitions. The theoretical oscillatory strengths ($f_{cal}$) and Judd-Ofelt (J-O) network framing theory were adopted to evaluate J-O intensity parameters $\Omega_{a}(a=2,4,6)$ from the experimental oscillatory strengths ($f_{exp}$). The covalent characteristic nature of the Sm$^{3+}$ ions with surrounding ligands within the host polymer matrix was confirmed through bonding parameter ($\delta$). The coordinated environment of Sm$^{3+}$ ions and the key significant J-O intensity parameters are used for calculation of spectroscopic radiative properties. Photoluminescence spectrum is obtained and the highly intensified emission peak is observed for the transition $^4G_{5/2}\rightarrow^6H_{7/2}$ at 595 nm under 401 nm excitation wavelengths. The CIE colour coordinate diagram shows that the present complex polymer films incorporated with Sm$^{3+}$ ions are acting as perfect and highly stable material for active reddish-orange emissions.

1. Introduction
In recent decades an extensive research and development is going on lanthanide Ln$^{3+}$ ions doped glass materials for their enhanced physical, chemical and novel optical properties. Apart from that, the present scenario is interested towards lanthanide ions doped organic luminescent polymeric materials which are themselves acting as interesting materials to the researchers in the area of material science and engineering [1]. Polymers are excellent class of host materials and they gain high priority because of their longer life, high stabilities and easy processing nature [2]. The polymers can be synthesized in an easy manner, which is the major advantage for development of luminescent and opto-electronic device
applications like laser action mechanisms, optical communication transmissions and optical fiber amplifiers [3].

The blended complex polymer materials gained high significance and importance in research and development of novel materials. The complex host polymer materials are responsible for incorporation of the lanthanide ions of higher concentrations and are turned to best polymer host matrix for optical devices and luminescent display devices [4]. The coordination complex formation between two dissimilar polymers gives raise to the formation of hydrogen bonds. Polyvinyl alcohol (PVA) is selected as primary host polymer material because the functional carbonyl groups of polymer PVA forms coordinated complexes. Apart from that, polymer PVA is non-toxic and highly water soluble polymer consisting of good thermal and mechanical strengths. In addition to that it is having high biodegradable nature. The secondary polymer is polyethylene glycol (PEG) which is non toxic water soluble polymer and possessing good thermal stability [5-6]. The formation of complexation between polymers PVA and PEG results in formation of highly stable complex polymer blends which are capable of incorporation of lanthanide ions [7].

At present, the Sm\(^{3+}\) ions doped complex polymeric materials gained much more importance in the application of optoelectronic, photonic devices applications, laser action systems, optical communications and electro-luminescent display devices. The Sm\(^{3+}\) ions are exhibit strong emission mechanisms in UV-Vis-NIR regions [8]. Moreover, The Sm\(^{3+}\) ions exhibit strong emission mechanism in visible region, because the presence of electronic transitions between 4f-4f states of their outer most orbitals [9]. The high stability, good optical and luminescence mechanisms of Sm\(^{3+}\) ions allows these complex polymer blends to be a good host material for incorporation of active Ln\(^{3+}\) ions for designing variety of photonic and luminescent device applications [10].

2. Material Synthesis

The universally accepted solution casting technique is used for synthesis of complex polymer blends. In the first step of preparation, PVA (polyvinyl alcohol), PEG (polyethylene glycol) and Sm\(_2\)Cl\(_6\)H\(_2\)O (samarium chloride hexa hydrate) are used. Initially 5 mol\% of PVA and 1 mol\% of PEG stock aqua solutions were prepared. Then the PVA and PEG polymer solutions are added in pre-defined ratios for obtaining a uniform complex polymer film of PVA and PEG. From here onwards the (PVA+PEG) polymers are turns into blends of PVAPEG polymer matrix.

Then we prepared 1-5 mol \% of samarium dopant ion aqua solution as mentioned above. Then add the Sm\(^{3+}\) ions aqua solutions to complex PVAPEG polymer blends in fixed ratios and stirred it with the help of a magnetic stirrer for obtaining a uniform and clear final solution. Then poured it into petri dishes for evaporation at room temperature. After complete evaporation, peeled it from the petri dishes. Finally, the rare earth ions doped complex polymer films of having uniform thickness are obtained and are used for carrying out various spectroscopic characterization techniques.

The optical absorption spectra of complex polymers blends are recorded in the wavelength of 200 nm to 2500 nm using JASCO V-670 spectrophotometer. The photoluminescence (PL) spectrum recorded by using Jobin Yvon spectroflurometer of model FL3-11. All these experimental recordings were carried out at room temperature.
3. Optical Absorption Spectral Studies

The optical absorption of spectra of PVAPEG: 0-5 mol % of Sm³⁺ ions are recorded in UV-VIS –NIR region and are shown in figure 1(a) and 1 (b). The 4f-4f electronic transitions involves the movement of electrons from ground state ⁶H⁵/₂ to various excited states represented as ⁶H⁵/₂ → ⁴D³/₂ (343 nm), ⁴D³/₂ (363 nm), ⁶P⁷/₂ (375 nm), ⁶P³/₂ (401 nm), ⁶F⁹/₂ (1084 nm), ⁶F⁷/₂ (1242 nm), ⁶F₃/₂ (1472 nm) and ⁶F₁/₂ (1584 nm) respectively [11]. In UV-VIS region the majority of electronic transitions are occurred due to induced electric dipoles. The intensities of these electronic transitions are weak, because they are spin forbidden, and there is an exception for only one transition ⁶H⁵/₂ → ⁶P₃/₂ (401 nm) which is spin allowed (ΔS=0). In NIR region, the electronic transitions are distinctly intensive, because of effective shielding mechanism of 4f electrons by the filled 5s and 5p shells. The broad band appeared at 278 nm is a characteristic peak of PVA and is arises may be due to activator-host lattice interactions [12-13].

![Figure 1. (a) UV-VIS region (b) NIR region optical absorption spectrum of PVAPEG: 0-5 mol % of Sm³⁺ ions doped polymer blends.](image)

3.1 Oscillatory Strengths and Nephelauxetic Ratio

The prominent method used for determining the effectiveness of the absorption bands is to calculate the oscillatory strengths for each transition which is directly proportional to the area under the absorption peaks [15]. The optical electronic transitions and their corresponding experimental and calculated oscillatory strengths of PVAPEG: 1-5 mol % of Sm³⁺ from its initial ground state to final excited state are evaluated from the absorption spectra and are shown in the table 1. By observing all these oscillatory strengths there is vast variations and deviations in the experimental oscillatory strengths and calculated oscillatory strengths. This is may be due to uncertainty in the prediction and determination of area under absorption band [16]. The mode of bonding between lanthanide-oxygen (Ln-O) were examined by nephelauxetic ratio (β) and bonding parameter (δ). The nephelauxetic phenomenon arises because of overlapping between metal and ligands, which leads to formation of metal ligand bonds. The bonding will be either covalent or ionic depending up on the value of (δ). If the (δ) is positive then they forms covalent bonding otherwise it is Ionic [14]. The nephelauxetic ratio (β) and bonding parameter (δ) are calculated and are given in table 1. The positive values of the ‘δ’ denotes that Sm³⁺ ions bondings in the present polymer blends are covalent in nature.
Table 1. The optical absorption transitions, experimental ($f_{\text{exp}}$), calculated ($f_{\text{cal}}$) oscillator strengths ($\times 10^{-6}$), nephelauxetic ratio ($\beta$), bonding parameter ($\delta$) of PVAPEG: 1-5 mol % of Sm$^{3+}$ ions doped polymer blends.

| S. No | Transition | PVAPEG:1Sm | PVAPEG:2Sm | PVAPEG:3Sm | PVAPEG:4Sm | PVAPEG:5Sm |
|-------|------------|------------|------------|------------|------------|------------|
|       | $f_{\text{exp}}$ | $f_{\text{cal}}$ | $f_{\text{exp}}$ | $f_{\text{cal}}$ | $f_{\text{exp}}$ | $f_{\text{cal}}$ | $f_{\text{exp}}$ | $f_{\text{cal}}$ | $f_{\text{exp}}$ | $f_{\text{cal}}$ | $f_{\text{exp}}$ | $f_{\text{cal}}$ |
| 1     | $^4D_{5/2}$ | 7.14       | 3.18       | 6.46       | 2.08       | 4.05       | 1.91       | 6.28       | 2.12       | -           | -           |
| 2     | $^4D_{3/2}$ | -          | -          | -          | -          | 1.78       | 1.80       | -          | -          | 2.10       | 1.11       |
| 3     | $^6P_{7/2}$ | 10.03      | 2.98       | 5.607      | 1.70       | 3.45       | 0.21       | 6.83       | 0.35       | 4.69       | 0.37       |
| 4     | $^6P_{3/2}$ | 12.53      | 16.98      | 12.15      | 10.91      | 10.49      | 9.88       | 12.75      | 11.82      | 7.30       | 6.44       |
| 5     | $^4M_{17/2}$ | -          | -          | -          | -          | 0.66       | 0.01       | -          | -          | -          | -          |
| 6     | $^4I_{11/2}$ | -         | -          | -          | -          | 1.35       | 0.01       | -          | -          | 1.96       | 0.04       |
| 7     | $^4M_{15/2}$ | -          | -          | -          | -          | 0.83       | 0.03       | -          | -          | 1.81       | 0.10       |
| 8     | $^4F_{5/2}$ | 3.40       | 0.15       | 3.56       | 0.01       | 3.27       | 0.01       | 3.98       | 0.01       | 1.96       | 0.01       |
| 9     | $^6F_{7/2}$ | 0.74       | 0.13       | 0.36       | 5.88       | 3.32       | 3.42       | 4.04       | 3.98       | 2.39       | 2.56       |
| 10    | $^6F_{3/2}$ | 57.20      | 63.90      | 15.89      | 15.62      | 23.61      | 23.47      | 24.66      | 24.27      | 18.05      | 18         |

$\delta_m=2.379$ $\delta_m=1.655$ $\delta_m=0.954$ $\delta_m=1.040$ $\delta_m=1.094$
$\bar{\beta}=0.873$ $\bar{\beta}=0.847$ $\bar{\beta}=0.811$ $\bar{\beta}=0.836$ $\bar{\beta}=0.882$
$\delta=0.144$ $\delta=0.179$ $\delta=0.233$ $\delta=0.194$ $\delta=0.133$

3.2 Judd-Ofelt (J-O) Theory

The extent and magnitude of electrical dipole oscillator strengths are evaluated from Judd-Ofelt theory. All the Judd-Ofelt parameters $\Omega_\lambda$ ($\lambda=2, 4, 6$) exhibited the same trend that is $\Omega_2>\Omega_4>\Omega_6$. The J-O intensity parameter $\lambda_2$ depends on the Ln-O covalency as well as asymmetry around Sm$^{3+}$ ion site [17]. In practical cases the higher values of $\lambda_2$ denotes the presence of covalent bonding between lanthanide ions and surrounding environment metal ligands. The $\lambda_4$ and $\lambda_6$ parameters give the characteristic properties like viscosity and rigidity of the host polymer blends. The ratio between the $\lambda_4$ to $\lambda_6$ is the spectroscopic quality factor, which is a significant parameter to determine the stimulated emission for active laser medium [18]. The calculated J-O intensity parameters and spectroscopic quality factor of Sm$^{3+}$ ions doped complex host polymer blends are furnished in table 2.

Table 2. The Judd-Ofelt parameters ($\Omega_{\lambda, (1-2, 4, 6)} \times 10^{-20}$) of PVAPEG: 1-5 mol % of Sm$^{3+}$ ions doped polymer blends.

| S. No | Sample Name   | $\Omega_2$ | $\Omega_4$ | $\Omega_6$ | $\Omega_4/\Omega_6$ | Trend     |
|-------|----------------|------------|------------|------------|----------------------|-----------|
| 1     | PVAPEG:1 Sm    | 2.548      | 1.872      | 0.765      | 2.44                 | $\Omega_2>\Omega_4>\Omega_6$ |
| 2     | PVAPEG:2 Sm    | 1.874      | 0.591      | 0.327      | 1.80                 | $\Omega_2>\Omega_4>\Omega_6$ |
| 3     | PVAPEG:3 Sm    | 2.786      | 1.584      | 1.462      | 1.08                 | $\Omega_2>\Omega_4>\Omega_6$ |
| 4     | PVAPEG:4 Sm    | 2.452      | 1.784      | 1.687      | 1.05                 | $\Omega_2>\Omega_4>\Omega_6$ |
| 5     | PVAPEG:5 Sm    | 1.562      | 0.672      | 0.425      | 1.58                 | $\Omega_2>\Omega_4>\Omega_6$ |
4. Photoluminescence
The photoluminescence spectra of PVAPEG: 1-5 mol % Sm³⁺ ions doped complex polymer blends are recorded in the wavelength of 550-720 nm under 401 nm excitation wavelengths. The recorded excitation and emission spectrums are shown in the figure 2 (a) and 2 (b). The excitation spectrum consist of total nine bands which are assigned ⁶H⁵/₂→⁶P⁷/₂ (374 nm), ⁶H⁵/₂→⁴L⁵/₂ (389 nm), ⁶H⁵/₂→⁶P₃/₂ (401 nm), ⁶H⁵/₂→⁶P₅/₂ (416 nm), ⁶H⁵/₂→⁴M₅/₂ (437 nm), ⁶H⁵/₂→⁶F₅/₂ (450 nm), ⁶H⁵/₂→⁶I₃/₂ (464 nm), ⁶H⁵/₂→⁴I₁/₁₂ (472 nm), and ⁶H⁵/₂→⁴I₀/₂ (481 nm) respectively. Among all these transitions, the transition ⁶H⁵/₂→⁶P₃/₂ (401 nm) found to be more intensive and is used for recording emission spectra. The emission spectra consist of four intense bands assigned namely ⁴G₅/₂ → ⁶H₅/₂ (560 nm), ⁴G₅/₂ → ⁶H₇/₂ (596 nm), ⁴G₅/₂ → ⁶H₉/₂ (642 nm) and ⁴G₅/₂ → ⁶H₁₁/₂ (716 nm) [19]. Among them, the transition at ⁴G₅/₂ → ⁶H₇/₂ (596 nm) is highly sharpened that may be used for reddish orange-emissions applications.

Figure 2. (a) Excitation (b) Emission spectra of complex PVAPEG: 1-5 mol % of Sm³⁺ ions doped polymer blends.

4.1 Radiative Properties
The Judd-Ofelt intensity parameters are used to analyze the radiative characteristic properties of emission spectrum of PVAPEG: 1-5 mol % Sm³⁺ ions doped complex polymer blends. The stimulated emission cross-section (σₑ) can be used to analyze the potential laser transitions of lanthanide ions doped complex polymer blends. An efficient and better laser action mechanism must and should have large stimulated emission cross-section [20]. High gain bandwidth (σₑ × Δλₑ) is the prominent characteristic to indentify the better and stable laser materials [21]. The calculated values of radiative properties such as peak emission wavelength (λₑ), effective line width (Δλₑ, nm), radiative transition probability (Aₑ, s⁻¹), total radiative transition probability (Aₑ, s⁻¹), radiative transition probability (Aₑ, s⁻¹), radiative branching ratios (βₑ), experimental branching ratio (βₑ) for the PVAPEG: 1-5mol % of Sm³⁺ ions doped polymer blends are given in the table 3. Similarly the emission properties such as stimulated emission cross-section (σₑ × 10⁻²² cm²) gain bandwidth parameter ((σₑ × Δλₑ)×10⁻²³ cm⁻³) for PVAPEG: x mol % of Sm³⁺ (x=1-5mol %) polymer films are given in the table 3.
Table 3. The Emission properties like peak emission wavelength (\(\lambda_p, \text{nm}\)), effective line width (\(\Delta\lambda_p, \text{nm}\)), radiative transition probabilities (\(A_R, s^{-1}\)), radiative branching ratios (\(\beta_R\)), measured branching ratios (\(\beta_m\)), total radiative transition probabilities (\(A_T, s^{-1}\)), %), stimulated emission cross-section (\(\sigma_e \times 10^{-22} \text{cm}^2\)), gain band width parameter (\((\sigma_e \times \Delta \lambda_p) \times 10^{-22} \text{cm}^2\)) of PVAPEG:1-5mol % of Sm\(^{3+}\) ions doped polymer blends.

| S. No | Sample Name | Transition | \(\lambda_p\) | \(\Delta \lambda_p\) | \(A_R\) | \(\beta_R\) | \(\beta_m\) | \(A_T\) | \(\sigma_e\) | \(\sigma_e \times \Delta \lambda_p\) |
|-------|-------------|------------|---------------|-----------------|--------|-----------|-----------|------|----------|-----------------|
| 1     | PVAPEG:1Sm  | \(^6H_{5/2}\) | 560           | 4.42            | 62.14  | 0.09      | 0.16      | 1.73 | 7.64     |
|       |             | \(^6H_{1/2}\) | 595           | 12.14           | 312.18 | 0.46      | 0.55      | 0.90 | 10.92    |
|       |             | \(^6H_{0}\)  | 642           | 8.44            | 216.12 | 0.31      | 0.15      | 675.58| 0.91      | 7.68             |
| 2     | PVAPEG:2Sm  | \(^6H_{5/2}\) | 660           | 5.21            | 85.14  | 0.12      | 0.42      | 1.27 | 6.61     |
|       |             | \(^6H_{1/2}\) | 594           | 11.81           | 360.14 | 0.47      | 0.68      | 1.08 | 12.75    |
|       |             | \(^6H_{0}\)  | 641           | 9.10            | 232.04 | 0.30      | 0.20      | 1.07 | 9.73     |
|       |             | \(^6H_{1/2}\) | 660           | 5.54            | 92.09  | 0.12      | 0.14      | 1.81 | 10.02    |
| 3     | PVAPEG:3Sm  | \(^6H_{5/2}\) | 660           | 5.61            | 72.05  | 0.11      | 0.09      | 1.91 | 10.71    |
|       |             | \(^6H_{1/2}\) | 594           | 1.88            | 301.09 | 0.45      | 0.68      | 1.03 | 12.23    |
|       |             | \(^6H_{0}\)  | 642           | 9.04            | 207.04 | 0.31      | 0.17      | 1.62 | 14.64    |
| 4     | PVAPEG:4Sm  | \(^6H_{5/2}\) | 660           | 4.35            | 82.07  | 0.12      | 0.04      | 3.46 | 15.05    |
|       |             | \(^6H_{1/2}\) | 595           | 13.13           | 347.09 | 0.44      | 0.70      | 1.76 | 10.68    |
|       |             | \(^6H_{0}\)  | 642           | 9.30            | 252.03 | 0.32      | 0.26      | 0.96 | 12.60    |
|       |             | \(^6H_{1/2}\) | 660           | 4.22            | 97.05  | 0.12      | 0.02      | 1.63 | 15.15    |
| 5     | PVAPEG:5Sm  | \(^6H_{5/2}\) | 595           | 13.24           | 364.42 | 0.45      | 0.47      | 1.30 | 48.32    |
|       |             | \(^6H_{1/2}\) | 641           | 12.27           | 261.19 | 0.32      | 0.29      | 3.65 | 48.32    |

4.2 Chromaticity Colour Coordinates
An appropriate mechanism for analyzing the colour luminescence of any polymeric materials is examining through the CIE colour chromaticity coordinates [22]. The chromaticity colour coordinates x, y of the present Sm\(^{3+}\) ions doped polymer samples were obtained from the photoluminescence spectra. These colour chromaticity coordinates are highly helpful for evaluating the exact emission colour of the polymer samples. The colour chromaticity coordinates x, y are given in the table 4. The figure 3, depicts the chromaticity diagram of the polymer materials for different concentrations of Sm\(^{3+}\) ions. From the figure 3, it is observed that all the samarium ion concentrations shows reddish-orange region in CIE diagram. This proves that the prepared polymer films act as promising materials for electro luminescent colour displays and solid-state lightening applications in reddish orange emissions at 401 nm wavelength.
Table 4. The CIE colour chromaticity coordinates of the PVAPEG: 1-5 mol % of Sm$^{3+}$ ions doped polymer blends.

| S. No | Sample Name | CIE (X) | CIE (Y) |
|-------|-------------|---------|---------|
| 1     | PVAPEG:1 Sm | 0.649371| 0.350294|
| 2     | PVAPEG:2 Sm | 0.644539| 0.355103|
| 3     | PVAPEG:3 Sm | 0.644119| 0.355521|
| 4     | PVAPEG:4 Sm | 0.644233| 0.355406|
| 5     | PVAPEG:5 Sm | 0.642445| 0.357186|

Figure 3. CIE colour chromaticity diagram of PVAPEG: 1-5 mol % of Sm$^{3+}$ ions doped polymer blends.

5. Conclusions
The present paper reports the results of optical, photoluminescence characteristics of different concentrations of Sm$^{3+}$ ions doped PVAPEG complex polymer blends. The covalent bonding nature of Sm$^{3+}$ ions with surrounding ligands have been confirmed through bonding parameters (6). Similarly the Judd-Ofelt (J-O) parameters $\Omega_{\lambda}(\lambda = 2,4,6)$ were evaluated from the optical absorption spectra and the highest value of $\lambda_2$ indicates that more covalent bonding nature of Sm$^{3+}$ ions with ligands. The radiative properties of Sm$^{3+}$ ions in the polymer matrix PVAPEG are useful for selection of active laser material for lasing applications. The peak stimulated emission cross-section of $^4G_{5/2} \rightarrow ^6H_{9/2}$ transition of Sm$^{3+}$ ions in the PVAPEG: Sm$^{3+}$ (5 mol %) of complex polymer blend founded to be highest. Intense reddish orange emission at 595nm corresponding to $^4G_{5/2} \rightarrow ^6H_{9/2}$ transition was observed in Sm$^{3+}$ ion doped PVAPEG polymer blends under 401 nm excitation which may be used for laser active medium for photonic devices and lighting displays. The CIE colour coordinate diagram confirms that the polymer blends can be used as potential applications in active reddish-orange emission laser materials, electro-luminescent displays devices and solid-state lighting applications.
References

[1] Obula Reddy M, Chandra Babu B 2015 *Indian J. Mater. Sci.* Article ID 927364.
[2] Adiyodi A K, Jyothy P V, Toney T F, Gijo Jose, Unnikrishnan NV 2007 *Optoelectron. Adv. Mater. Rapid Commun.* 1 281
[3] Lawrence M B, Desa J A E, Aswal V K, Rai R 2014 *Bull. Mater. Sci.* 37 301
[4] Naveen Kumar K, Kang M, Bhaskar Kumar G, Ramakaram Y C 2016 *Opt. Mater.* 54 6
[5] Rajavardhana Rao T, Omkaram I, Veera Brahram K, Linga Raju Ch 2013 *J. Mol. Struct.* 1036 94
[6] Rajavardhana Rao T, Omkaram I, Sumalatha B, Veera Brahram K, Linga Raju Ch 2012 *Ionics* 18 695
[7] Naveen Kumar K, Vijayalakshmi L, Ramakaram Y C 2015 *Opt. Mater.* 45 148
[8] Gagandeep Kaur, Rai S B 2011 *J. Phys. D: Appl. Phys.* 44 425306
[9] Nayab Rasool Sk, Rama Moorthy L, Jayasankar CK 2013 *Opt. Commun.* 311 156
[10] Naveen Kumar K, Chandra Babu B, Buddhudu S 2015 *J. Lumin.* 161 456
[11] Saman Q. Mawlud, Muhafar M. Ameen, Md. Rahim Sahar, Zahra Ashur Said Mahraz, Kasim F. Ahmed 2017 *Opt. Mater.* 69 318
[12] Hima Bindu S, Rajavardhan Rao T, Linga Raju Ch 2015 *Phys. Scr.* 90 065802
[13] Sivaiah K, Buddhudu S 2012 *Indian J. Phys.* 86 1079
[14] Srihari T, Jayasankar CK 2017 *Opt. Mater.* 66 35
[15] Shanmuga Sundari S, Marimuthu K, Sivaraman M, Surendra Babu S 2010 *J. Lumin.* 130 1313
[16] Karthikeyan B 2006 *Chem. Phys. Lett.* 432 513
[17] Linganna K, Basavapooroornima Ch, Jayasankar CK 2015 *Opt. Commun.* 344 100
[18] Sd. Zulfiqar Ali Ahamed, Madhukar Reddy C, Deva Prasad Raju B 2013 *Spectrochim. Acta Part A* 103 246
[19] Naveen Kumar K, Rudramadevi B H, Buddhudu S 2014 *Indian J. Pure Appl Phys.* 52 588
[20] Basavapooroornima Ch, Jayasankar CK 2014 *J. Lumin.* 153 233
[21] Hima Bindu S, Siva Raju D, Vinay Krishna V, Rajavardhana Rao T, Veera Brahram K, Linga Raj Ch 2016 *Opt. Mater.* 62 655
[22] Vimal G, Mani P, Biju P R, Joseph C, Unnikrishnan N V, Ittyachen M A 2014 *Spectrochim. Acta Part A* 122 624