Investigations on structural, photo-physical and photometric parameters of metal based quinoline complexes for OLEDs

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Abstract. This paper includes the synthesis of bluish-green light emitting metal based hydroxyl quinoline complexes namely, Mgq2, Baq2 and MgxBaq1-xq2 (Mg: Magnesium, Ba: Barium, q: 8-hydroxy quinoline, x = 0.1, 0.2, ..., 0.9) by simple precipitation method at different values of pH and stoichiometry. It’s noteworthy to state that we are the first one to report novel complexes based on Ba (Baq2 and Mg0.5Ba0.5q2). The inquisition of these complexes was carried out to probe structural, photo physical and photometric parameters by FTIR, photoluminescence (PL) spectra and 1931 CIE colour calculator, respectively. These investigations reveal that pH value and stoichiometry have feeble effects on the emission wavelength and intensity. Investigations further reveal that among all the synthesized complexes, Baq2 (at pH 6.5) emits intense blue light in various environments. Thus, barium based quinoline complexes have the potential to sustain their emission features in solid state as well as in acidic and basic medium- one of the characteristic features which are highly essential for the fabrication of OLEDs by vacuum as well as solution techniques.

Keywords: Quinoline complexes, pH, stoichiometry, bluish green emission, OLED.

1. Introduction

Light-emitting devices (LEDs) have created in the field of light emitting optoelectronic devices nearly 50 years ago; nevertheless, during the past one and half decade they were just popular as an indicator in traffic signals, electronic appliances and many more [1,2]. These LEDs slowly emerged in numerous wavelengths including ultraviolet, visible (including violet, pink and white, apart from red, green and blue) and infrared regions of electromagnetic spectrum. The energy band gap (Eg) dictates the emissive wavelength of the diode, based on relation E=hc/λ. This functional feature of LEDs validated them into numerous diverse areas including displays, sensor applications, automotive uses, medical applications, as illuminators, in horticulture, solid state lighting technology medicine [3] and even for decorative purpose to name a few. LED bulbs- a combination of point source LEDs, in spite of being mercury free, long lasting and energy saving, they are restricted by technology, they shift colour in due course of time and temperature, also cause light pollution [4]. Hence, one of the newest kinds of LED lighting and displays emerged as organic light emitting diodes (OLEDs), which make use of organic phosphor...
capable of emitting light when facilitated with current [5]. These diodes/displays are popular sources, flexible with remarkable visual appeal. Organic phosphor that is used as emissive material in OLEDs have the potential to emit light in various environments (solid state, either in acidic or basic media) without much alteration in its emission wavelength. Based on these facts, volumes and volumes of research have been carried out since 1987 by C.W. Tang on aluminium based quinoline namely, tris(8-hydroxyquinoline) aluminium (III) (Alq3) complex which emit green light and he even succeeded in developing a single layer OLED out of Alq3[6]. Since then, two-layer, three layer and later multilayer OLEDs emerged and now they are playing a leading role in small as well as large panel displays that can be either rigid or flexible, based on the application [7-12]. OLEDs based on this organic metal chelates have gained momentum due to their elevated thermal stability, ability to transport electrons and emissive properties of the material [13, 14]. Therefore in the present study, 8-hydroxyquinolate metal complexes, namely Mgq2, Baq2 and MgBa(1-x)q2 were synthesized by economical synthesis procedure and the investigations have been carried out under various environments.

2. Experimental

Metal based quinoline complexes namely, Mgq2, Baq2 and MgBa(1-x)q2 were synthesized by cost effective and less time consuming precipitation technique at room temperature.

2.1. Precursors

Following precursors of analytical grade (AR) were employed during the synthesis of metal based quinoline complexes are tabulated in Table 1.

| Reagents and solvents | Molecular formula | Make | Molecular weight (g/mole) | Melting point (°C) | Boiling point (°C) |
|-----------------------|-------------------|------|--------------------------|-------------------|-------------------|
| 8-hydroxyquinoline    | C27H18AlN3O3      | Aldrich Chemicals | 145.16                  | 192 - 194°C       | 267               |
| Magnesium Nitrate     | Mg(NO3)2          | Aldrich Chemicals | 256.14                  | 88.9              | 330               |
| Barium Nitrate        | Mg(NO3)2          | Aldrich Chemicals | 261.35                  | 592               |                   |
| Acetic acid           | CH3COOH           | Alfa Aesar Chemicals | 60.05                  | 16-17             | 117.9             |
| Ammonia solution      | NH4OH             | Aldrich Chemicals | 35.04                   | -91.5             | 24.7              |
| Double distilled water| H2O               | Labogens          | 18.02                   | 0                 | 100               |

2.2. Synthesis

Firstly 25 ml of double distilled water and 25 ml acetic acid were taken in a beaker. Later, 5 g of 8-hydroxyquinoline (8 Hq) was added into a mixture of double distilled water and acetic acid. This mixture was stirred well at about 40°C on a hot plate so as obtain vibrant orange homogeneous transparent solution (say solution I). In another beaker, 0.5660g of Mg (NO3)/0.5775 g of Ba (NO3) was dissolved in doubled distilled water, stirred well at a temperature of 40°C on a hot plate till clear
milky white solution was obtained (say solution II). Solution I and II were mixed for 10 min and then NH₄OH solution was added drop by drop to this mixture with continuous stirring till yellowish green precipitate was obtained. After the formation of precipitate, pH of the solution was noted. The precipitate was collected at various pH values at an interval of 0.5 from pH 5.5 to 8.0 so as to study the role of pH on the intensity of the obtained precipitate. Precipitate was then washed with double distilled water for 3 to 4 times and the precipitate was set aside in an oven at 45°C for 45 min so as to evaporate the left-over water molecules or any other solvents or moisture if any. By following the same procedure and by considering the same stoichiometry of magnesium and barium, MgₓBa₁₋ₓq₂ was synthesized [15].

![Figure 1. Synthesis procedure of metal based quinoline complexes](image)
Three-dimensional structure of the precursors employed during the synthesis, and the so formed complexes are shown in Figure 2 (a-e)

![Figure 2](image)

(a)

(b)

(c)

(d)

(e)

Figure 2. 3D structure of (a) 8-hydroxy quinoline (b) Mg(NO₃)₂, (c) Ba(NO₃)₂ (d) Mgq₂ and (e) Baq₂.

3. Result and discussion

The Fourier transform infrared (FT-IR) spectrum of metal based quinoline complexes were carried out on SHIMADZU Model 8101A infrared spectrophotometer, photo-luminescence spectra was carried out on HITACHI F-4000 spectrofluorometer and 1931 Commission International de l'Eclairage (CIE) system software was used to explore CIE coordinates and Colour correlated temperature (CCT).
3.1. Fourier Transform Infrared (FT-IR) spectra

FTIR is an analytical technique, which authenticates the molecular structure of the synthesized complexes by portraying the sharp characteristic absorption peaks (in the infrared region, as the name suggests) of the sample under investigation. These absorption peaks help to identify the empirical molecular structure of the synthesized complexes, namely, Mgq2, Baq2 and MgxBaq2(1-x)q2 (at x = 0.5). In the present investigation, FTIR spectra was carried out in the range of 4000-800 cm⁻¹.

![FTIR spectra of Mgq2](image)

**Figure 3.** FTIR spectra of Mgq2

All the three spectra clearly portray scattering below 800 cm⁻¹, which may be due to crystalline nature of the complexes, hence not recorded. The FTIR spectra of Mgq2 reveal OH- stretching vibration in-between 3600-3000 cm⁻¹. The absorption peaks at 2387.87 and 1951.96 cm⁻¹ can be allocated to the stretching modes of methylene groups in Mgq2 [16]. A broad peak range 2400-2000 reveals the presence of strong O=C=O stretching. Vibrations at 1604.77, 1577.77 and 1500.62 cm⁻¹ can be assigned to quinoline group of the synthesized complex. The bands at 1469.76 and 1423.47 cm⁻¹ can be ascribed to pyridyl and phenyl groups. Aromatic amine resonances (C–N–C) can also be observed in-between 1370–1250 cm⁻¹ [17]. The peaks at 742.59 and 790.81 cm⁻¹ are allied with in-plane ring deformation as portrayed in figure 3, confirming the formation of Mgq2 complex. No major differences were found in FTIR spectra of Baq2 and MgxBaq2(1-x)q2 (at x = 0.5) in comparison with the FTIR spectra of Mgq2 complex.
Minor differences in the FTIR spectra of Baq₂ may be due to presence of Ba (an alkaline earth metal with atomic number 56 and atomic radii 268 pm) instead of Mg (an alkaline earth metal with atomic number 12 and atomic radii 173 pm) as well as Mg and Ba with equal stoichiometry in coordination with 8-hydroxy quinoline as shown in figure 4 and 5, confirming the formation of Baq₂ and MgₓBa₁₋ₓq₂ (at x = 0.5) complexes, respectively.

Figure 4. FTIR spectra of Baq₂

Figure 5. FTIR spectra of MgₓBa₁₋ₓq₂ (at x = 0.5)
3.2. Photo-luminescence spectra with varying pH

Figure 6 shows the emission and excitation (photo-luminescence) spectra of Mgq₂ at various values of pH, ranging in-between 5.5 to 8.0, at an interval of 0.5. Excitation spectra of Mgq₂ at different values of pH displays broad excitation peak with a weak shoulder. At pH 5.5, Mgq₂ complex shows excitation at 422nm with a weak shoulder at 389nm. Similarly, the complex at pH 6.0, 6.5, 7.0, 7.5 and 8 displays a sharp peak at 427, 427, 430, 428 and 427 nm with a weak shoulder at 384,382, 381, 380 and 380nm, respectively. Mgq₂ complex emits blue light, which falls in the visible spectrum of electromagnetic spectrum at 484, 484, 485, 488, 488 and 486 nm, for pH 5.5, 6.0, 6.5, 7.0, 7.5 and 8, respectively. Maximum excitation as well as emission wavelength was observed in the complex synthesized at pH = 7.5, which may be due to hydrogen ion concentration in the solution that is in coherence with the quinoline containing magnesium. Even with the variation in pH, the nature and position of bands remained almost unaltered. However, a slight decrease in intensity was observed when the pH of the complex was gradually incremented or decremented by 0.5 starting from pH 5.5 till 8.0(excluding pH=7.5), suggesting its sensitivity to pH at one particular value of pH [18]. The variation of intensity with pH is observed as 7.5 > 8.0 > 6.5 > 6.0 > 7.0 > 5.5.

![PL spectra of Mgq₂](image)

**Figure 6.** PL spectra of Mgq₂ at various values of pH

Baq₂ complex also maintained the same trend, however at pH 6.5, it shows maximum excitation wavelength at 395 nm with a weak shoulder at 348 nm. Even at pH 7.5, the peak position remained at 395 and 348 nm. Surprisingly, the shoulder disappears at pH 5.5, 6.0, 7.0, and 8, while the maxima peak displays at 472, 473, 470 and 471 nm, respectively. Baq₂ complex also emits blue light, which falls in the visible spectrum of electromagnetic spectrum at 472, 473, 460, 470, 472 and 471 nm, for pH 5.5, 6.0, 6.5, 7.0, 7.5 and 8, respectively. Maximum excitation as well as emission wavelength was observed in the complex synthesized at pH = 6.5, which may be due to hydrogen ion concentration in the solution that is in coherence with the quinoline containing barium. The variation of intensity with pH is observed as 6.5 > 7.5 > 7.0 > 5.5 > 6.0 > 8.0 as shown in figure 7 PL spectral data of Mgq₂ and Baq₂ at various values of pH are tabulated in Table 2.
Figure 7. PL Spectra of Baq₂ at different values of pH.

Table 2. PL spectral data of Mgq₂ and Baq₂ at various values of pH

| pH | λ_{ext} (nm) | λ_{emi} (nm) |
|----|--------------|--------------|
|    | Shoulder peak | Main peak    |
| Mgq₂ complex |          |              |
| 5.5 | 389          | 422          | 484          |
| 6   | 384          | 427          | 484          |
| 6.5 | 382          | 427          | 485          |
| 7   | 381          | 430          | 488          |
| 7.5 | 380          | 428          | 488          |
| 8   | 380          | 427          | 486          |
| Baq₂ complex |          |              |
| 5.5 | -            | 399          | 472          |
| 6   | -            | 398          | 473          |
| 6.5 | 348          | 395          | 460          |
| 7   | -            | 398          | 470          |
| 7.5 | -            | 395          | 472          |
| 8   | -            | 399          | 471          |
3.3. Photo-luminescence spectra with varying stoichiometry

We also made an attempt to vary stoichiometry of the combination of magnesium and barium nitrate during the synthesis of binuclear MgₓBa₁₋ₓq₂ complex at pH 7 [19]. The reason for selecting pH 7 is due to the fact that Mgq₂ exhibited its maximum intensity at pH 7.5, while Baq₂ exhibited its maximum intensity at pH 7.5. The average of both, which is going to be 7 is preferred. The composition of the chemical constituents considered during the synthesis of MgₓBa₁₋ₓq₂ complexes are tabulated in Table 3.

Table 3. The composition of the chemical constituents for the synthesis of MgₓBa₁₋ₓq₂ complexes.

| S.No. | MgₓBa₁₋ₓq₂ complex | 8-hydroxy quinoline (g) | Mg(NO₃)₂ (g) | Ba(NO₃)₂ (g) |
|-------|---------------------|------------------------|--------------|-------------|
| 1.    | x= 0.1              | 0.0188                 | 0.1732       |             |
| 2.    | x= 0.2              | 0.0377                 | 0.1540       |             |
| 3.    | x= 0.3              | 0.0566                 | 0.1344       |             |
| 4.    | x= 0.4              | 0.0754                 | 0.1155       |             |
| 5.    | x= 0.5              | 0.0943                 | 0.0962       |             |
| 6.    | x= 0.6              | 0.1132                 | 0.0770       |             |
| 7.    | x= 0.7              | 0.1320                 | 0.0577       |             |
| 8.    | x= 0.8              | 0.1509                 | 0.0385       |             |
| 9.    | x= 0.9              | 0.1698                 | 0.0192       |             |

The photo-luminescence spectra of MgₓBa₁₋ₓq₂ complexes displays the fact that when the stoichiometry of both the complexes is same i.e. when x = 0.5, the excitation and emission spectra registered maximum intensity due to the relaxation of an excited electron from the S₁-S₀ level [20]. However, for various x values of magnesium nitrate and barium nitrate quinoline based complexes, their PL spectra registers slightly different excitation and emission wavelengths and divergent intensities as shown in Fig.8. Thus, it can be inferred that when x < 0.5, the intensity was greater as compared to the intensity when x > 0.5. However, every value of x portrays emission in blue region of visible spectrum. The earlier reports state the fact that the emission intensity of quinoline samples decreased with noticeable shift with an increase in atomic number of the centre metal ion. The electron cloud between the centre metal and ligands would influence the luminescence intensity, however independent of the emission wavelength.
3.4. Photo-luminescence spectra in formic acid

The PL spectra of solvated metal based quinoline complexes were recorded in formic acid at molar concentration of $10^{-3}$ mol/L. It was observed that the PL spectra of the solvated complex is hypsochromically shifted by around 20-25 nm as that of in solid state. This can be attributed to the solvent-solute interaction in the solution.
Figure (i) shows the emission spectra of Mgq_2 in Formic Acid with peaks at 423nm and 465nm. Figure (ii) displays the emission spectra of Baq_2 in Formic Acid with peaks at 275nm and 450nm.
Figure 9. PL spectra of (i) Mg$q_2$, (ii) Ba$q_2$ and (iii) Mg$_{0.5}$Ba$_{0.5}$q$_2$ in formic acid

Spectral data of PL spectra is tabulated in Table 5. Mg$q_2$ displays blue emission at 465 nm, when excited at 423 nm as shown in figure 9 (i). Upon excitation of Ba$q_2$ at 275 nm, the emission spectra display a sharp emission peak at 450nm as shown in figure 9 (ii). figure 9 (iii) shows, that PL spectra of Ba$_{0.5}$ and Mg$_{0.5}$. at excitation of 425nm and emission at 482 nm [22]. Photo-luminescence data of the synthesized complexes solvated in formic acid are tabulated in Table 5. Thus, the luminescence wavelength is tuned to lower wavelengths, however lie in blue-bluish green region. These results prove the potential of the synthesized complexes to sustain in various environments like in solid state, acidic and basic environment with slight variations in emission wavelength and intensity. Hence, these complexes can be used in fabrication of OLEDs by solution techniques rather than the conventional vacuum technique, which is laborious and costly offence.

Table 5. Photo-luminescence data of the synthesized complexes solvated in formic acid

| Complex in Formic acid | $\lambda_{\text{ext}}$ (nm) | $\lambda_{\text{emi}}$ (nm) |
|-----------------------|-----------------|-----------------|
| Mg$q_2$               | 423             | 465             |
| Ba$q_2$               | 275             | 450             |
| Ba$_{0.5}$ Mg$_{0.5}$ q$_2$ | 425           | 482             |

3.5. Photometric evaluation

The colour emitted by the light source is generally analysed in terms of commission International de l’ Eclairage (CIE) system by using chromatic coordinates (x, y) [23,24]. Figure 10 portrays the CIE coordinates of Mg$q_2$ and Ba$q_2$ at different values of pH, while figure 11 and 12 displays the CIE coordinates of solvated complexes in formic acid and for different stoichiometry of Mg and Ba, respectively. The determined coordinates of CIE and colour correlated temperature (CCT) are tabulated in Table 6, which reflect the fact that their emission lies in bluish green region, that is in coherence with the PL spectral data.
Figure 10. CIE Coordinate of (a) Mgq₂ and (b) Baq₂ at different values of pH
Figure 11. CIE Coordinate of (a) Mg$q_2$ and (b) Ba$q_2$ and (c) Ba$_{0.5}$ Mg$_{0.5}$ q$_2$ in formic acid

Figure 12. CIE Coordinate of Ba$_x$ Mg$_{(1-x)}$ for different values of x
Table 6. Photometric parameters of the synthesized complexes in various environments

| Parameter       | CIE Coordinates (x,y) | CCT    |
|-----------------|-----------------------|--------|
| **Mgq₂**        |                       |        |
| pH = 5.5        | (0.1512, 0.3418)      | 26581  |
| pH = 6          | (0.1504, 0.3468)      | 24810  |
| pH = 6.5        | (0.1501, 0.3422)      | 26581  |
| pH = 7          | (0.1546, 0.3704)      | 18520  |
| pH = 7.5        | (0.1523, 0.3685)      | 19266  |
| pH = 8          | (0.1536, 0.3601)      | 20394  |
| **Baq₂**        |                       |        |
| pH = 5.5        | (0.1458, 0.2199)      | Undefined |
| pH = 6          | (0.1479, 0.2322)      | Undefined |
| pH = 6.5        | (0.1447, 0.1477)      | Undefined |
| pH = 7          | (0.1444, 0.2193)      | Undefined |
| pH = 7.5        | (0.1453, 0.2328)      | Undefined |
| pH = 8          | (0.1517, 0.2369)      | Undefined |
| **Mgq₂**        | In Formic acid        | (0.1614, 0.2842) | Undefined |
| **Baq₂**        | In Formic acid        | (0.1487, 0.2163) | Undefined |
| **Mg₀.₅Ba₀.₅q₂**| In Formic acid        | (0.1623, 0.0147) | Undefined |
| **MgₓBa₁₋ₓq₂**  | x = 0.1               | (0.1585, 0.2771) | Undefined |
|                 | x = 0.2               | (0.1482, 0.3046) | Undefined |
|                 | x = 0.3               | (0.1503, 0.3066) | 91054 |
|                 | x = 0.4               | (0.1474, 0.3122) | 74978 |
|                 | x = 0.5               | (0.1469, 0.3130) | 68337 |
|                 | x = 0.6               | (0.1193, 0.2895) | Undefined |
|                 | x = 0.7               | (0.1224, 0.2966) | Undefined |
|                 | x = 0.8               | (0.1198, 0.3028) | Undefined |
|                 | x = 0.9               | (0.1248, 0.2911) | Undefined |

4. Conclusions

We successfully synthesized as well as investigated metal based quinoline complexes at different values of pH and stoichiometry by employing simple precipitation method. FTIR spectra confirm the formation of the desired quinoline complexes. Maximum excitation as well as emission wavelength was observed at pH 7.5 and 6.5 in Mgq₂ and Baq₂, respectively. However, the nature and position of bands remained almost unaltered. An attempt has been made to vary stoichiometry of the combination of magnesium and barium nitrate during the synthesis of binuclear MgₓBa₁₋ₓq₂ complex at pH 7. It
can be inferred that when $x < 0.5$, the intensity was greater as compared to the intensity when $x > 0.5$. However, every value of $x$ portrays emission in blue region of visible spectrum. The PL spectra of solvated metal based quinoline complexes were recorded in formic acid at molar concentration of $10^{-3}$ mol/L portrays hypsochromic shift by around 20-25 nm as that of in solid state. Photometric evaluation reflects the fact that their emission lies in bluish green region that is in coherence with the PL spectral data. Hence, these complexes can be used in fabrication of OLEDs by solution techniques rather than the conventional vacuum technique, which is laborious and costly offence. In conclusion, though all the synthesized complexes sustain well in various environments like in solid state, acidic and basic environment with slight variations in emission wavelength and intensity, the best among them is Ba$q$ (at pH 6.5).

5. References

[1] Aderhold J, Davy dov Y Yu, Fedler F, Klausing H, Mistele D, Rotter T, Semchinova O, Ste mmer J and Graul J 2001 J. Cryst. Growth 222 701
[2] Zhao M, Liao H, Molokeev, M S, Zhou Y, Zhang Q, Liu Q and Xia Z, Emerging ultra-narrow-band cyan-emitting phosphor for white LEDs with enhanced color rendition. Light: Science & Applications, 8(1) (2019) 1-9.
[3] Dong Y, Wang Y K, Yuan F, Johnston A, Liu Y, Ma D, Choi M J, Chen B, Chekini M, Baek S W and Sagar L K, Bipolar-shell resurfacing for blue LEDs based on strongly confined perovskite quantum dots. 2020 Nature Nanotechnology, 15(8) 668-674.
[4] Rattanakul, S. and Oguma, K., Inactivation kinetics and efficiencies of UV-LEDs against Pseudomonas aeruginosa, Legionella pneumophila, and surrogate microorganisms. 2018 Water Research, 130 31-37.
[5] N.Thejo Kalyani, Swart H, Dholbe S J, Artificial lighting: origin-Impact and Future Prospective; Principles and Applications of Organic Light Emitting Diodes; 2017 Elsevier: Imprint Woodhead Publishing Series in Electronic and optical materials, United Kingdom Ch. 4. 87-114.
[6] N.Thejo Kalyani, Dholbe S J, “Organic Light Emitting Diodes: Novel Energy Saving Lighting Technology -A review” 2012 Renewable and Sustainable Energy Reviews: 16 2696-2723.
[7] Tang C W, and Van Slyke S A, Organic electroluminescent diodes, 1987 Appl. Phys. Lett., 51 913-915.
[8] Kid J, and Iizimi Y, Fabrication of highly efficient organic electroluminescent devices, 1998 Appl. Phys. Lett., 73(19) 2721-2724.
[9] Chan I and Hong F, Improved performance of the single-layer and double-layer organic light emitting diodes by nickel oxide coated indium tin oxide anode, 2004 Thin Solid Films, 450 (2) 304-311.
[10] Lim J, Jeong C, Lee J, Yeom G, Jeong H, Choi S, Lee I, and Lee W, Synthesis and characteristics of bis(2,4-dimethyl-8-quinolinolato) (triphenylsilanolato) aluminum (III): A potential hole-blocking material for the organic light-emitting diodes, 2006 J. Organometallic Chemistry, 691 (12) 2701-2707.
[11] Ma D, Wang G, Hu Y, Zhang Y, Wang L, Jing X, Wang F, Lee C, and Lee S, A dinuclear aluminum 8-hydroxyquinoline complex with high electron mobility for organic light-emitting diodes, 2003 Appl. Phys. Lett. 82(2) 1296-1299.
[12] Omar W, Haverinen H, and Horn O, New Alq3 derivatives with efficient photoluminescence and electroluminescence properties for organic light-emitting diodes, 2009 Tetrahedron, 65(47) 9707-9712.
[13] Sapochak L, Benincasa F, Schofield R, Baker J, Riccio K, Fogarty D, Kohlmann H, Ferris K and Burrows P, Electroluminescent Zinc (II) Bis(8-hydroxyquinolino) (III) Complexes, 2004 J. Org. Chem., 69(5) 1723-1725.
[14] Tao J, Wang R, Yu H, Chen L, Fang D, Tian Y, Xie J, Jia D, Liu H, Wang J and Tang F, Highly transparent, highly thermally stable nanocellulose/polymer hybrid substrates for flexible OLED devices. 2020 ACS Applied Materials & Interfaces, 12(8) 9701-9709.
[15] Suchitra J P, Kala A, Devi V B, Sagadevan S and Selvin R, Synthesis and Optical Characterization of Cd (mq) Nanoparticles for Organic Light Emitting Diode Application. 2018 Sensor Letters, 16 (12) 938-943.
[16] Shinde P, Pandharipande S, N. Thejokalyani, Dholbe S J, Exploration of photophysical properties of green light emitting bis(8-hydroxyquinoline) zinc (Znqz) metal chelate under various environments; 2018 Optik 162 131-140.
[17] Liu J, Zhong X, Wu S, Li Y, Xu Y and Zeng H, Green synthesis and characterization for 8-hydroxyquinoline magnesium. 2019 Materials Research Express 6(5) 055101.
[18] Pohl R, A. Montes V, Shinar J, and Anzenbacher P, Red–Green–Blue Emission from Tris(5-aryl-8-quinolinolato) Al (III) Complexes, 2004 J. Org. Chem., 69(5) 1723-1725.
[19] Kalyani N T, Chitnis D and Dholbe S J, Judd-Ofelt analysis on pH sensitive Eu (taa) 3bipy and Eu (dmh) 3phen hybrid organic complexes in various organic solvents for solution processed OLEDs. 2019 Materials Science for Energy Technologies, 2(3) 589-599.
[20] Chitnis D, Kalyani N T and Dholbe S J, Structural and Optical Investigation of Novel Europium Hybrid Organic Complex for OLEDs and Solid-State Lighting; 2017 Journal of Materials Physics and Chemistry 5(1) 1-10.
[21] Bem D B, Swart H C, Luyt A S, Biggs M M and Dejene F B, Synthesis and Characterization of Long Persistence Strontium and Barium Aluminate Phosphors. Durban conference, SAIP UKZN, 7 - 10 July 2009.
[22] Kalyani N T, Atram R G and Dhoble S J, Synthesis and characterization of Y_{1-x}Eu_x(DBM)_3(Phen) and La_{1-x}Eu_x(DBM)_3(Phen) complexes for solid state lighting 2016 *International Journal of Luminescence and applications* **6** (2) 139-145.

[23] Chitnis D, Kalyani N T and Dhoble S J, Exploration of spectroscopic properties of solvated tris(thenoyltrifluoroacetone) (2,2′-bipyridine) europium (III) red hybrid organic complex for solution processed OLEDs and displays; 2017 *Journal of Luminescence*, **185** 61–71.

[24] Mullemwar S Y, Zade G D, Kalyani N T and Dhoble S J, Blue light emitting P-Hydroxy DPQ phosphor for OLEDs, 2016 *Optik* **127** 10546–10553.