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Degenerate four-wave mixing determination of third-order optical nonlinearities of three mixed ligand nickel(II) complexes

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ABSTRACT

Three mixed ligand nickel(II) complexes were synthesized and characterized by UV–visible, IR, MS and elemental analysis. Their off-resonant third-order nonlinear optical properties were measured using femtosecond laser and degenerate four-wave mixing technique. The third-order nonlinear optical susceptibilities $\chi^{(3)}$ were 3.20–3.51 × 10⁻¹³ esu. The nonlinear refractive indexes n_2 were 5.89–6.45 × 10⁻¹² esu. The second-order hyperpolarizabilities γ of the molecules were 3.20–3.50 × 10⁻³¹ esu. The response times were 55–81 fs. The results show that these complexes have potential nonlinear optical applications.

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1. Introduction

The design and synthesis of materials exhibiting large thirdorder nonlinear optical (NLO) properties has been the focal point of a large amount of recent research in great part due to their potential applications in optical communication, optical data storage, optical information processing, optical computing and so on. Unlike second-order NLO materials, the structure-property relationships of third-order NLO materials are a little vague. Several design principles have been adopted during the past few decades to improve third-order optical nonlinearities of materials. One attractive approach is the formation of organometallic and coordination materials by combining of conjugated organic molecules with transition metal [1–5]. Many conjugated organic molecules such as stilbene derivatives [6], azobenzene derivatives [7], anthraquinone derivatives [8], squaraine derivatives [9] and triphenylamine derivatives [10] have been proven to be effective third-order NLO materials. Compared to purely organic materials, organometallic and coordination materials can combine the advantages of architectural flexibility, ease of fabrication and tailoring, and high NLO properties of organics with good transmittancy, temporal and thermal stability of inorganics. Such materials also have enhanced second-order hyperpolarizabilities γ of the molecules by introducing a metal atom.

In recent years, many nickel complexes have received considerable attention as third-order NLO materials due to their rich photophysical and photochemical properties [11-18]. A Japanese patent shows that the conjugated organic molecules, phenanthro [9,10-d]imidazole derivatives, can exhibit high third-harmonic generation and rapid response [19]. So they are highly promising candidates for third-order NLO materials. Their analogs, imidazo[4,5-f][1,10]phenanthroline (IP) and its 2-aryl-substituted derivatives (**PIP**, **TIP**), also have π -conjugated electron systems and are able to act as bidentate ligands towards transition metals such as nickel because of the replacement of phenanthrene by phenanthroline (**phen**). We present here three mixed ligand nickel(II) complexes **a**-**c** (Fig. 1), where different conjugated ligands (**phen**, **IP**, **PIP**, **TIP**) are bonded to the central nickel ion in the form of octahedral coordination geometry. Their structures were characterized by UV-visible, IR, MS and elemental analysis. By using femtosecond laser, the off-resonant third-order optical nonlinearities of the complexes were measured with degenerate four-wave mixing (DFWM) technique. The relationships between molecular structure and optical property were analyzed. To our knowledge, it is the first study of the NLO properties for these complexes and the complex **c** is new.

2. Experimental

2.1. Materials

The compound 1,10-phenanthroline-5,6-dione was prepared according to the literature method [20]. Other materials were commercially available and of reagent grade. All of them were used without further purification.



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Fig. 1. Structures of the ligands and the nickel(II) complexes **a-c**.

2.2. Physical measurements

FT-IR spectra were recorded on a Vector 22 spectrometer using KBr pellets. ¹H NMR spectra were collected on a AVANCE III 500 MHz apparatus, with TMS as internal standard and DMSO- d_6 as solvent. UV–visible spectra were recorded on a Shimadzu UV-2550 UV–visible spectrometer. Elemental analyses were conducted on a Thermo Finnigan Flash EA 1112 apparatus. Mass spectra were taken on a Therm LCQ TM Deca XP plus ion trap mass spectrometry instrument. Melting points were measured on an X-4 micromelting point apparatus without correction.

2.3. Synthesis

2.3.1. 1H-Imidazo[4,5-f][1,10]phenanthroline (**IP**)

A mixture of 1,10-phenanthroline-5,6-dione (1.05 g, 5 mmol), formaldehyde (0.18 g, 6 mmol), ammonium acetate (7.7 g, 100 mmol), and glacial acetic acid (16 mL) was heated under reflux with stirring for 3 h. The cooled solution was diluted with H₂O and neutralized with concentrated aqueous ammonia. The precipitate was collected and recrystallized from DMF to give a light yellow crystalline powder. Yield: 0.8 g, 72.7%. m.p. >310 °C (Lit. m.p. >310 °C [21]). ¹H NMR (500 MHz, DMSO-d₆), δ (ppm): 13.75

(s, 1H), 9.03 (dd, 2H, J_1 = 4.3 Hz, J_2 = 1.5 Hz), 8.83 (dd, 2H, J_1 = 8 Hz, J_2 = 1.5 Hz), 8.47 (d, 1H), 7.83 (dd, 2H, J_1 = 8 Hz, J_2 = 4.3 Hz).

2.3.2. 2-Phenyl-1H-imidazo[4,5-f][1,10]phenanthroline (PIP)

This ligand was synthesized as above using benzaldehyde. The product was a yellow granular crystal. Yield: 1.2 g, 81.1%. m.p. >310 °C (Lit. m.p. >310 °C [21]). ¹H NMR (500 MHz, DMSO-d₆), δ (ppm): 13.79 (s, 1H), 9.05 (dd, 2H, J_1 = 4.3 Hz, J_2 = 1.8 Hz), 8.95 (dd, 2H, J_1 = 7.6 Hz, J_2 = 1.8 Hz), 8.30–8.32 (m, 2H), 7.86 (dd, 2H, J_1 = 7.6 Hz, J_2 = 4.3 Hz), 7.64 (dd, 2H), 7.53–7.56 (m, 1H).

2.3.3. 2-(2-Thienyl)-1H-imidazo[4,5-f][1,10]phenanthroline (TIP)

This ligand was synthesized as above using 2-thiophenecarboxaldehyde. The product was a brown-yellow crystalline powder. Yield: 0.58 g, 76.8%. m.p. >320 °C (Lit. m.p. >320 °C [22]). ¹H NMR (500 MHz, DMSO-d₆), δ (ppm): 13.78 (s, 1H), 9.04 (dd, 2H, $J_1 = 4.4$ Hz, $J_2 = 1.5$ Hz), 8.86 (dd, 2H, $J_1 = 7.9$ Hz, $J_2 = 1.5$ Hz), 7.93 (dd, 1H, $J_1 = 3.8$ Hz, $J_2 = 0.8$ Hz), 7.84 (dd, 2H, $J_1 = 7.9$ Hz, $J_2 = 4.4$ Hz), 7.78 (dd, 1H, $J_1 = 4.8$ Hz, $J_2 = 0.8$ Hz), 7.30 (dd, 1H, $J_1 = 4.8$ Hz, $J_2 = 3.8$ Hz).

2.3.4. (1H-Imidazo[4,5-f][1,10]phenanthroline-κΝ7,κΝ8)bis(1,10phenanthroline-κΝ1,κΝ10)-nickel(2+) (**a**)

A mixture of nickel dichloride hexahydrate (0.24 g, 1 mmol), **phen** (0.4 g, 2.2 mmol) and methanol (20 mL) was heated under reflux with stirring for 2 h. A solution of **IP** (0.26 g, 1.2 mmol) in methanol (15 mL) was then added and further stirred under reflux for 3 h. The reaction mixture resulted was cooled to room temperature, and a saturated aqueous sodium perchlorate solution was added. The precipitate was collected and recrystallized from DMF twice to give a pink crystalline powder. Yield: 0.7 g, 79.2%. FT-IR (KBr), v (cm⁻¹): 3395 (v_{NH} , v_{OH}), 3050 ($v_{=CH}$), 1614 ($v_{c=C}$), 1514, 1422, 1122 (v_{CIO4}), 855 ($\delta_{=CH}$), 725 ($\delta_{=CH}$), 625 (δ_{CIO4}). Anal. Calc. for C₃₇H₂₄Cl₂N₈NiO₈·2.5H₂O: C, 50.31; H, 3.31; N, 12.69. Found: C, 50.45; H, 3.23; N, 12.42%. ESI-MS (CH₃CN): m/z 637.1 ([M-2CIO₄-H]⁺), 319.3 ([M-2CIO₄]²⁺).

2.3.5. (2-Phenyl-1H-imidazo[4,5-f][1,10]phenanthroline- κ N7, κ N8) bis(1,10-phenanthroline- κ N1, κ N10)-nickel(2+) (**b**)

This complex was synthesized using a procedure similar to that described for **a**, with **PIP** instead of **IP**. The product was a light yellow crystalline powder. Yield: 0.5 g, 53.1%. FT-IR (KBr), v (cm⁻¹): 3433 (v_{NH} , v_{OH}), 3045 ($v_{=\text{CH}}$), 1639 ($v_{\text{C=C}}$), 1518, 1455, 1118 (v_{CIO4}), 809 ($\delta_{=\text{CH}}$), 725 ($\delta_{=\text{CH}}$), 634 (δ_{CIO4}). Anal. Calc. for C₄₃H₂₈Cl₂N₈NiO₈·1.5H₂O: C, 54.86; H, 3.32; N, 11.90. Found: C, 54.95; H, 3.57; N, 12.24%. ESI-MS (CH₃CN): m/z 357.3 ([M–2CIO₄]²⁺).

2.3.6. [2-(2-Thienyl)-1H-imidazo[4,5-f][1,10]phenanthroline-κΝ7,κΝ8] bis(1,10-phenanthroline-κΝ1,κΝ10)-nickel(2+) (**c**)

This complex was synthesized using a procedure similar to that described for **a**, with **TIP** instead of **IP**. The product was a light yellow crystalline powder. Yield: 0.6 g, 63.9%. FT-IR (KBr), v (cm⁻¹): 3341 (v_{NH} , v_{OH}), 3070 ($v_{=\text{CH}}$), 1606 ($v_{\text{C=C}}$), 1522, 1422, 1126 (v_{CIO4}), 850 ($\delta_{=\text{CH}}$), 727 ($\delta_{=\text{CH}}$), 629 (δ_{CIO4}). Anal. Calc. for C₄₁H₂₆Cl₂N₈Ni O₈S·H₂O: C, 52.48; H, 3.01; N, 11.94. Found: C, 52.70; H, 3.33; N, 12.33%. ESI-MS (CH₃CN): m/z 719.0 ([M-2ClO₄-H]⁺), 360.4 ([M-2ClO₄]²⁺).

2.4. Nonlinear optical measurements

The third-order NLO properties were measured using femtosecond DFWM technique, with a Ti: Sapphire laser. Fig. 2 shows the experimental setup. The pulse width was determined to be 80 fs on a SSA25 autocorrelator. The operating wavelength was centered at 800 nm. The repetition rate of the pulses was 1 KHz. During the measurement, the laser was very stable (rms < 0.1%). The input beam was split into two beams k_1 and k_2 with nearly equal energy by use of a beam splitter, then focused on the sample. The beam k_2 passed through a delay line driven by a stepping motor in order that the optical path length difference between the k_2 and k_1 beams could be adjusted during the measurement. The angle between the beams k_1 and k_2 was about 5°. When k_1 and k_2 were overlapped spatially in the sample, the generated signal beam k_3 or k_4 passed through an aperture, recorded by a photodiode and then analyzed by a Lock-in amplifier and computer.

The experiments were performed at 22 °C. The samples dissolved in DMF at concentrations of 5×10^{-4} mol/L were placed in a 1 mm thick quartz cell. The solvent DMF has no nonlinear signal under the light intensity adopted. So the third-order optical nonlinearities measured come from the ligands and the complexes themselves.

3. Results and discussion

3.1. Synthesis and characterization

Among three nickel(II) complexes **a–c**, **c** was first synthesized by our research group. **a** and **b** have been previously reported [23]. Two steps are included in the published synthetic route: (1) The synthesis of $[Ni(phen)_2Cl_2]$ according to the literature method [24]. (2) The complexation reaction of $[Ni(phen)_2Cl_2]$ with the appropriate ligands. In this paper, we adopted a simple one-pot synthetic method. The desired complexes **a–c** were isolated as the perchlorates and purified by recrystallization in relatively high yield. They were characterized by FT-IR spectra, electrospray ionization MS and elemental analysis. But they could not be further characterized by ¹H NMR spectra due to their paramagnetic properties.

3.2. The third-order NLO properties

The UV–visible absorption spectra of two ligands (**phen**, **IP**) and three complexes **a–c** in DMF solutions are displayed in Figs. 3 and 4. Their maximum absorption peaks appear at 227 nm, 254 nm, 270 nm, 280 nm and 295 nm, respectively, which are attributed to intraligand π – π * transitions. Above 400 nm, their DMF solutions are essentially transparent. The laser wavelength (800 nm) used in the experiment of DFWM is out of the absorption region. Thus their off-resonant third-order optical nonlinearities can be measured.

The third-order nonlinear optical susceptibility $\chi^{(3)}$ is measured via a comparison with that of a reference sample CS₂, calculated from the DFWM signal (*I*), the linear refractive index (*n*), the sample thickness (*L*) and absorption correction factor using the following equation [25]:

$$\chi_s^{(3)} = \left(\frac{I_s}{I_r}\right)^{1/2} \frac{L_r}{L_s} \left(\frac{n_s}{n_r}\right)^2 \frac{\alpha L \exp(\alpha L/2)}{1 - \exp(-\alpha L)} \chi_r^{(3)}$$
(1)

where the subscripts "s" and "r" represent the parameters for the sample and CS₂. And α indicates the linear absorption coefficient. The fraction $\frac{\alpha l.exp(\alpha L/2)}{1-exp(-\alpha L)}$ comes from the sample absorption and equals to 1 approximately while the sample has little absorption around the employed laser wavelength. The values of $\chi_r^{(3)}$ and n_r for CS₂ are 6.7 × 10⁻¹⁴ esu and 1.632, respectively [26].

The nonlinear refractive index n_2 in isotropic media is estimated through the equation [27]:

$$n_2(\text{esu}) = 12\pi \chi^{(3)}/n^2 \tag{2}$$

where *n* is the linear refractive index of solution, measured by 2WAJ Abbe refractometer.



Fig. 2. Experimental setup of DFWM.

γ



Fig. 3. UV-visible absorption spectra of the ligands (phen, IP) in DMF.



Fig. 4. UV-visible absorption spectra of the complexes a-c in DMF.

The second-order hyperpolarizability γ of a molecule in isotropic media is related to the solution $\chi^{(3)}$ by [28]:

$$=\chi^{(3)}/Nf^4\tag{3}$$

where *N* is the number density of the solute per milliliter, related to the molar concentration *c* by $N = N_A c$ with N_A being Avogadro's number. And f^4 is the local field correction factor which is $[(n^2 + 2)/3]^4$ (*n* is the linear refractive index of solution).

The dependence of DFWM signal intensity on the delay time of the input beam is shown in Fig. 5. The curves are obtained via fitting the time convolution between autocorrelation function of pulse and single exponent decline function $\exp\left(\frac{t}{-T_2}\right)$. The response times of the samples can be obtained from Fig. 5.

The values of $\chi^{(3)}$, n_2 , γ and response times for the samples deduced and calculated from the experimental results are listed in Table 1.

The γ values obtained for the mixed ligand nickel(II) complexes **a-c** are large, and comparable with those of some known NLO organometallic and coordination materials (for example, 6.5×10^{-32} - 1.9×10^{-31} esu for 1,3-dithiole-2-thione-4,5-dithiolate complexes at 1064 nm [29,30], 1.21×10^{-31} esu for a heterometal cluster containing iron at 532 nm [31], 2.6×10^{-34} - 1.7×10^{-32} esu for alkynylruthenium complexes at 800 nm [32], 2.8×10^{-33} - 1.04×10^{-32} esu for fullerene-containing organometallics [33], 1.0×10^{-31} esu for azo-nickel chelate compound at 830 nm [34]). Though a sufficient understanding of the effect of molecular structure on the third-order NLO response is still lacking, many studies have indicated that delocalized π -conjugated electron systems play an important role in determining the third-order NLO properties of organic materials [35-40]. Thus the ligands phen and IP who possess two-dimensional delocalized π -conjugated electron systems exhibit the γ values in the order of 10^{-31} esu. Compared with metal-free ligands **phen** and **IP**, the γ value of the nickel(II) complex a is distinctively greater. This may be due to the fact that the electron configuration of Ni²⁺ is d⁸, the overlapping between the d orbitals of central nickel ion and π -electron orbitals of ligands can allow the three ligands to be in electronic communication with one another through the nickel, leading to a larger polarizable system, and finally better NLO properties.

Among three nickel(II) complexes **a–c**, **b** possesses higher γ value compared to **a** whereas **c** shows the highest γ value. This result denotes that the extended π delocalization of the ligands exerts an effect on the third-order NLO properties of the complexes. By introducing the benzene ring in 2-position of the



Fig. 5. DFWM signal versus delay time for the ligands (phen, IP) and the complexes a-c in DMF solution.

Table 1 The values of $\chi^{(3)}$, n_2 , γ and response times for the ligands (**phen**, **IP**) and the complexes **a–c**.

Sample	n	$\chi^{(3)}$ (10 ⁻¹³ esu)	n_2 (10 ⁻¹² esu)	γ (10 ⁻³¹ esu)	Response time (fs)
phen	1.4306	1.75	3.23	1.76	37
IP a	1.4319	1.96 3.20	3.61 5.89	1.96 3.20	39 57
b	1.4308	3.35	6.18	3.36	55
с	1.4327	3.51	6.45	3.50	81

imidazole unit, the electron delocalization of the ligand **PIP** is enhanced owing to the increase of the conjugation length. In contrast to the benzene ring (151 kJ/mol), the thiophene ring has lower delocalization energy (121 kJ/mol), which results in stronger intramolecular charge transfer and higher degree of electron delocalization of the ligand **TIP**. So the greater the electron delocalization of the ligands is, the larger the γ values of the complexes will be. In addition, the bathochromic shift of the π - π * absorption band in the complexes **a-c** also implies the increase in the degree of π electron delocalization, which in turn leads to the better third-order optical nonlinearity.

Fig. 5 shows that the nickel(II) complexes **a**–**c** possess ultrafast response times which are in the range of 55–81 fs. Such instantaneous responses also ensure that the measured NLO responses are mainly contributed from the delocalized electrons [41].

4. Conclusions

Three mixed ligand nickel(II) complexes were prepared using a simple one-pot synthetic method. Their structures were characterized by UV–visible, IR, MS and elemental analysis. The off-resonant third-order NLO properties were investigated by the DFWM technique with the laser duration of 80 fs at the wavelength of 800 nm. The large ($\gamma = 3.20-3.50 \times 10^{-31}$ esu) and ultrafast ($\tau = 55-81$ fs) nonlinearities showed by these complexes originate from the extensive electronic delocalization and polarization.

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References

- [1] G. Li, Y.L. Song, H.W. Hou, L.K. Li, Y.T. Fan, Y. Zhu, X.R. Meng, L.W. Mi, Inorg. Chem. 42 (2003) 913–920.
- [2] Z.B. Liu, Y. Zhu, Y.Z. Zhu, J.G. Tian, J.Y. Zheng, J. Phys. Chem. B 111 (2007) 14136–14142.
- [3] Z.H. Chen, C. Zhong, Z. Zhang, Z.Y. Li, L.H. Niu, Y.J. Bin, F.S. Zhang, J. Phys. Chem. B 112 (2008) 7387–7394.
- [4] C.E. Powell, M.P. Cifuentes, M.G. Humphrey, A.C. Willis, J.P. Morrall, M. Samoc, Polyhedron 26 (2007) 284–289.
- [5] R. Rangel-Rojo, K. Kimura, H. Matsuda, M.A. Mendez-Rojas, W.H. Watson, Opt. Commun. 228 (2003) 181–186.
- [6] N. Kobko, A. Masunov, S. Tretiak, Chem. Phys. Lett. 392 (2004) 444-451.
- [7] T.C. He, Y.G. Cheng, Y.B. Du, Y.J. Mo, Opt. Commun. 275 (2007) 240-244.
- [8] Q.H. Meng, W.F. Yan, M.J. Yu, D.Y. Huang, Dyes Pigm. 56 (2003) 145-149.
- [9] M.L. Yang, Y.S. Jiang, Chem. Phys. 274 (2001) 121-130.
- [10] Z.J. Liu, X.Q. Xiong, J.G. Qin, H.M. Gong, Q.Q. Wang, J. Mol. Struct. 934 (2009) 86–90.
- [11] X.B. Sun, Y.L. Wang, Q. Ren, F.J. Zhang, Y. Gao, H.L. Yang, L. Feng, X.Q. Wang, D. Xu, Opt. Mater. 29 (2007) 1305–1309.
- [12] H. Fukui, H. Nagai, R. Kishi, T. Minami, H. Takahashi, T. Kubo, M. Nakano, Synth. Met. 159 (2009) 2416–2418.
- [13] Y.Z. Gu, F.X. Gan, S.Q. Wang, H.J. Xu, Opt. Commun. 197 (2001) 501-505.
- [14] Z.F. Dai, X.L. Yue, B.X. Peng, Q.G. Yang, X.C. Liu, Chem. Phys. Lett. 317 (2000) 9–12.

- [15] P.F. Zhang, Y.M. Xu, F.T. Zheng, Y. Yang, Laser Technol. 30 (2006) 155–157.
- [16] Y.H. Wang, X.A. Zhang, P.H. Cheng, Y.Z. Gu, J. Henan Univ. (Nat. Sci.) 34 (2004) 19-21
- [17] Z.Y. Tian, W.T. Huang, D.B. Xiao, S.Q. Wang, Y.S. Wu, Q.H. Gong, W.S. Yang, J.N. Yao, Chem. Phys. Lett. 391 (2004) 283–287.
- [18] J. Tedim, S. Patrício, R. Bessada, R. Morais, C. Sousa, M.B. Marques, C. Freire, Eur. J. Inorg. Chem. 2006 (2006) 3425–3433.
- [19] A. Hidetomo, Y. Yasuhiko, M. Kazuhiro, Y. Yoshihiro, Jpn. Pat. 05273616, 1993.
 [20] W. Paw, R. Eisenberg, Inorg. Chem. 36 (1997) 2287–2293.
- [21] J.Z. Wu, L. Wang, G. Yang, T.X. Zeng, L.N. Ji, Chem. J. Chin. U 17 (1996)
- 1010-1015. [22] R.M.F. Batista, S.P.G. Costa, M. Belsley, C. Lodeiro, M.M.M. Raposo, Tetrahedron
- 64 (2008) 9230–9238.
- [23] Q.L. Zhang, J.H. Liu, H. Xu, X.Z. Ren, J.Z. Liu, L.N. Ji, Acta Sci. Nat. Univ. Sunyatseni 42 (2003) 21–24.
- [24] C.M. Harris, E.D. Mckenzie, J. Inorg. Nucl. Chem. 29 (1967) 1047-1068.
- [25] Y. Yang, M. Samoc, P.N. Prasad, J. Chem. Phys. 94 (1991) 5282-5290.
- [26] M.E. Orczyk, M. Samoc, J. Swiatkiewicz, P.N. Prasad, J. Chem. Phys. 98 (1993) 2524–2533.
- [27] S.A. Jenekhe, S.K. Lo, S.R. Flom, Appl. Phys. Lett. 54 (1989) 2524–2526.
- [28] B.K. Mandal, B. Bihari, A.K. Sinha, M. Kamath, L. Chen, Appl. Phys. Lett. 66 (1995) 932-934.
- [29] X.B. Sun, X.Q. Wang, Q. Ren, G.H. Zhang, H.L. Yang, L. Feng, Mater. Res. Bull. 41 (2006) 177–182.
- [30] H.L. Yang, X.Q. Wang, Q. Ren, G.H. Zhang, X.B. Sun, L. Feng, S.F. Wang, Z.W. Wang, Opt. Commun. 256 (2005) 256–260.
- [31] J. Lu, C.H. Lü, J.H. Yu, J.Q. Xu, Y. Li, X. Zhang, T.G. Wang, Q.X. Yang, Polyhedron 23 (2004) 755–761.
- [32] M.P. Cifuentes, C.E. Powell, M.G. Humphrey, G.A. Heath, M. Samoc, B. Luther-Davies, J. Phys. Chem. A 105 (2001) 9625–9627.
- [33] Y.C. Liu, Y.H. Kan, S.X. Wu, G.C. Yang, L. Zhao, M. Zhang, W. Guan, Z.M. Su, J. Phys. Chem. A 112 (2008) 8086–8092.
- [34] H. Xiang, Z.Y. Tian, S.F. Wang, Z.W. Wang, Z. Li, H. Yang, J.N. Yao, Q.H. Gong, Chin. Phys. B. 17 (2008) 2535–2538.
- [35] C. Videlot-Ackermann, T. Isoshima, A. Yassar, T. Wada, H. Sasabe, D. Fichou, Synth. Met. 156 (2006) 154–161.
- [36] S.C. Yin, H.Y. Xu, W.F. Shi, L. Bao, Y.C. Gao, Y.L. Song, B.Z. Tang, Dyes Pigm. 72 (2007) 119–123.
- [37] D. Udayakumar, A.J. Kiran, A.V. Adhikari, K. Chandrasekharan, G. Umesh, H.D. Shashikala, Chem. Phys. 331 (2006) 125–130.
- [38] H.Y. Xu, S.C. Yin, W.J. Zhu, Y.L. Song, B.Z. Tang, Polymer 47 (2006) 6986-6992.
- [39] J.M. Lu, S.J. Ji, N.Y. Chen, Z.R. Sun, X.L. Zhu, W.P. Shi, Z.G. Wang, J. Appl. Polym. Sci. 89 (2003) 2611–2617.
- [40] P. Poornesh, K. Ravi, G. Umesh, P.K. Hegde, M.G. Manjunatha, K.B. Manjunatha, A.V. Adhikari, Opt. Commun. 283 (2009) 1519–1527.
- [41] C.K. Wu, P. Agostini, G. Petite, F. Fabre, Opt. Lett. 8 (1983) 67-69.