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Monolithic NLO chromophores with different pendant groups and matrix-assisted-poling effect: synthesis and chractorization

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Abstracts

Realization of the large electro-optic (EO) activity for organic nonlinear optical (NLO) chromopores with high first order hyperpolarizability requires simultaneous optimization for molecular structure. In this work, we investigated the influences of different pendant groups in chromophore's side chains on the performance of EO materials. A series of NLO chromophores **F1-F3** based on the same conjugated structure but with different pendant groups have been synthesized and systematically investigated. Due to the disperse-red type pendant groups, chromophore **F3** shows excellent film-forming ability and relatively high glass transition temperature without blending with optically inactive polymer matrix. The Variable Angle Spectroscopic Ellipsometry (VASE) measurement proves the neat **F3** film displays a higher index of refraction value and weak absorption at 1310 nm and 1550 nm, which is beneficial for reducing the operation voltage and optical loss of modulator. Due to the effective isolating ability of pendant groups, the best EO coefficient of the poled **F3** film reaches to 81pm/V, which is two times larger than the value of the same type chromophore in guest-host material. This result, together with high index of refraction and low optical loss, will shed light on a new perspective for the design of new monolithic organic EO materials. Keywords: nonlinear optic; chromophore; pendant group; matrix-assisted; poled polymer

1. Introduction

Organic electro-optic (EO) materials have drawn much attention due to their attractive commercial applications in computing, telecommunications, and sensing such as phased array radar, electronic/photonic integrated circuits, terahertz spectroscopy, etc.[1-8] Compared with traditional inorganic and semiconductor materials, the organic EO materials have faster intrinsic response times and lower dielectric constants than lithium niobate leading to higher modulation bandwidth and efficiency.[9-13] The EO coefficient (r_{33}) of organic material mainly depends on three critical parameters: EO chromophore's first molecular hyperpolarizability, β_{zzz} , number density, N, and the acentric order parameter, $\langle \cos^3 \theta \rangle$. The r_{33} value were calculated by the following equation:

$$r_{33} = 2 \frac{N\beta_{zzz}F_L(3-\lambda_{max}^2/\lambda^2)}{3n^4(1-\lambda_{max}^2/\lambda^2)} (\cos^3\theta)$$
(1)

Where *n* is the material's index of refraction and the ratio $\lambda_{max}^2/\lambda^2$ refers to the wavelength at maximum absorbance to the wavelength of the incident light field. The local field correction $F_L = ((\eta_0^2(\eta_{\omega}^2+3))/(\eta_{\omega}^2+2\eta_0^2))((\eta_{\omega}^2+2)/3)^2)$ is the product of Lorentz and Onsager field factors for the static- and frequency-dependent refractive indices of the material.[14]

In the past decade, many researches have mainly focused on the design of chromophore with improving high β_{zzz} .[3, 7, 15-26] Generally, the improvement of β_{zzz} will be accompanied with the increase of molecular dipole moment. Extensive experimental and theoretical studies have shown that the chromophore's aggregation, which was mainly caused by the strong intermolecular electrostatic interaction among chromophores with high dipole moment, hinders chromophore getting acentric order under poling electric field.[25-28] The chromophores should be systematically modified to reduce dipole-dipole aggregation. Recently, the nonlinear optical (NLO) chromophore's design methodology with enhanced *N* and $\langle cos^3 \theta \rangle$ has been turned into a hot research spot in the

area of organic EO materials.[29-38] Several successful monolithic EO materials have been reported in which the pendant groups are incorporated into chromophore's side-chain to promote intermolecular cooperativity over nanometer length scales. Jen *et al.* have introduced arene-perfluoroarene interaction which is known as a strong face-to-face interaction into NLO chromophore design to create tightly packed molecular assemblies leading to a new class of supramolecular materials. [12, 39-41] Dalton *et al.* have systematically researched the chromophore self-assembly from coumarin-coumarin intermolecular interactions. [29, 42-46] Due to the large steric hindrance of pendant groups, the chromophore will be well isolated with other neighbor chromophores to avoid detrimental anti-parallel aggregation.[22, 47-50] This kind of side-chain chromophores generally exhibit excellent film-forming ability and moderate glass transition temperature (T_g), which mean they can be used to fabricated EO device without polymer host. For the Mach–Zehnder EO modulator, the voltage required to produce a π -phase shift of light, V_{π} , is a key parameter for energy consumption and thermal management, which is given by

$$V_{\pi} = \frac{\lambda d}{2n^3 r_{33} L \Gamma} \tag{2}$$

Where λ is the optical wavelength, *n* is the index of refraction, *d* is the electrode gap, *L* is the electrode length (interaction length of the electrical and optical fields), and Γ is the electrical/optical overlap integral. The monolithic materials display higher index of refraction compared with chromophore/polymer system, which is useful for V_{π} decrease. Pendant groups interactions covalently linked to chromophores with large dipole moments effectively prevent phase separation which is common in guest-host materials with high chromophore concentration. What's more, monolithic EO materials exhibit some other important properties, such as better solubility, lower optical loss, etc.[8]

In this work, we design and synthesize three "FTC" (thiophene bridge) type chromphores with different pendant groups in side chains. The hydroxyl group, bulky *tert*-butyl-diphenyl-silyl group (TBDPS) and disperse-red 1 (DR1) are chosen as pendant functional parts. DR1 is a common dye widely used in textile industry and NLO

materials, which has large steric hindrance and weak dipole-dipole interaction with each other. Meanwhile, the weak intermolecular interaction between DR1s would be helpful for improving the film-forming ability and T_{g} s of monolithic materials. The abilities of assisting chromophore-poling are compared. Apart from chromophore **F1**, the other two chromophores (**F2** and **F3**) were spin-coated into thin films without polymer matrix. The structural-directing side chains act as the matrix which can effectively improve the chromophore concentration and index of refraction, and reduce the optical loss. For reasonable comparison, previously reported chromophores **EZ-FTC** was used as bench chromophores.[18, 51] Four chromophores' structures were presented in Figure 1. These NLO chromophores all choose 2-dicyanomethylene-3-cyano-4,5,5-dimethyl-2,5-dihydrofuran (TCF) as electron acceptors. ¹H and ¹³C NMR and MALDI-TOF were carried out to demonstrate the preparation of these chromophores. The Variable Angle Spectroscopic Ellipsometry (VASE) is used to measure the optical constants of films. Thermal properties, photophysical properties, density functional theory (DFT) calculations and EO performances of these chromophores were systematically studied and compared to illustrate the influences of different side-chain groups on rational monolithic EO material design.



2. Experimental section

2.1 Materials and instruments

All chemicals are commercially available and are used without further purification unless otherwise stated. *N*, *N*-dimethyl formamide (DMF) was distilled over calcium hydride and stored over molecular sieves (pore size 3Å). Acetone was dried with anhydrous MgSO₄, then distilled and stored over molecular sieves (pore size 3Å). The 2-dicyanomethylene-3-cyano-4-methyl-2,5-dihydrofuran(TCF) acceptor was prepared according to the

literature.[52] ¹H and ¹³C NMR spectra were determined by Advance Bruker NMR spectrometer (400 MHZ). The MS spectra were obtained on MALDI-TOF (Matrix Assisted Laser Desorption/Ionization of Flight) on BIFLEXIII (Broker Inc.) spectrometer. Electric field poling and Teng-Man ellipsometry were carried out on a home built instrument. The UV-Vis experiments were performed on Cary 5000 photo spectrometer. Cyclic-Voltammetry(CV) was carried out at 10^{-3} M in acetonitrile versus Ag/AgCl, glassy carbon working electrode, Pt counter electrode, 20 °C, 0.1 M Bu₄NPF₆, 100 mV s⁻¹ scan rate, ferrocene internal reference $E_{1/2} = +0.43$ V. The thermogravimetric analysis (TGA) was determined by TA5000-2950TGA (TA co) with a heating rate of 10 °C min⁻¹ under the protection of nitrogen. The film thickness was measured by Ambios Technology XP-1. The VASE analysis was performed using J. A. Woollam M-2000 instrument. Data were acquired at 55°, 65° and 75°; and fitting was done using Woollam CompleteEASE software.

-----Figure 2-----

2.2 Synthesis

Chromophore F1

A screw cap vial was charged with **5** (0.317 g, 1.00 mmol) and ethanol (20 mL, 200 proof). After **5** were completely dissolved, TCF (0.24 g, 1.20 mmol) was added at once. Then , the vial was capped and the reaction mixture were stirred at 60 °C for 6 h. The reaction was monitored by TLC. Finally, the solution was cooled to room temperature and solvent was removed under reduced pressure. The crude product was purified using silica gel chromatography eluting with dichloromethane/ethyl acetate (v/v: 95/5) to remove unwanted materials. Changing the eluent system to 5% methanol in DCM, 0.38 g product was obtained as dark blue solid. Yield: 76%. ¹H NMR (400 MHz, DMSO- d_6) δ (ppm) 8.17 (d, *J* = 15.6 Hz, 1H), 7.47 (d, *J* = 8.7 Hz, 2H), 7.25 (d, *J* = 15.9 Hz, 2H), 7.23 (s, 1H), 7.18 (d, *J* = 15.9 Hz, 1H), 6.72 (d, *J* = 8.7 Hz, 2H), 6.57 (d, *J* = 15.6 Hz, 1H), 4.70 (t, *J* = 5.4 Hz, 2H), 3.56 (t, *J* = 5.4 Hz, 2H), 3.46 (t, *J* = 5.4 Hz, 2H), 3.00 (s, 3H), 1.76 (s, 6H). ¹³C NMR (100 MHz, DMSO- d_6) δ (the solid to be consisted as the temperature and the temperature at temperature at the temperature at temperature at the temperature at the temperature at temperature at the temperature at temperature at the temperature at temperature atemperature at temper

DMSO) δ (ppm) 177.43, 174.85, 154.30, 152.63, 150.45, 138.57, 135.13, 132.68, 129.41, 128.86, 123.57, 116.10, 113.47, 112.25, 111.43, 98.63, 95.49, 58.64, 58.22, 26.07. HRMS (ESI) (M+, C₂₈H₂₆N₄O₃S): calcd: 498.17256; found: 498.17252.

Chromophore F2

In a 25 mL round bottom flask were combined F1 (0.125 g, 0.25 mmol), imidazole (0.068 g, 1.00 mmol), and dry DMF (10 mL). After completely dissolved, TBDPS-Cl (1.37 g, 1.00 mL) was added, the solution was stirred for another 3h at room temperature. The mixture was then diluted with ethyl acetate, washed with DI water, dried over MgSO₄. Solvent was removed under reduced pressure. The crude material was purified using silica gel chromatography eluting with hexanes/ethyl acetate (v/v: 5/1) to afford 0.20 g of dark blue solid. Yield: 85%.¹H NMR (400 MHz, CDCl₃) δ (ppm) 7.77 (d, *J* = 15.5 Hz, 1H), 7.64 (m, 4H), 7.62 (d, *J* = 9.0 Hz, 2H), 7.48 – 7.27 (m, 16H), 7.04 (d, *J* = 15.8 Hz, 1H), 6.92 (d, *J* = 15.8 Hz, 1H), 6.86 (s, 1H), 6.57 (d, *J* = 8.9 Hz, 2H), 6.51 (d, *J* = 15.5 Hz, 1H), 4.79 (s, 2H), 3.83 (t, *J* = 5.9 Hz, 2H), 3.55 (t, *J* = 5.9 Hz, 2H), 3.01 (s, 3H), 1.61 (s, 6H), 1.07 (s, 9H), 1.04 (s, 9H). ¹³C NMR (100 MHz, CHCl₃) δ (ppm) 176.05, 174.23, 173.32, 162.61, 153.10, 151.16, 150.25, 135.57, 133.27, 132.72, 127.90, 123.63, 112.65, 112.14, 96.95, 36.50, 31.43, 19.08. HRMS (ESI) (M+, C_q:H_q:N₄O₃S): calcd: 942.45426; found: 942.45421.

Chromophore F3

An oven dried 100mL flask was charged with **F1** (0.125 g, 0.25 mmol), 1,3-dicyclohexylcarbodiimide (0.25 g, 0.60 mmol), DPTS (0.69 g, 0.044 mmol). This mixture was dissolved in a mixture of freshly distilled DCM (20 mL). The reaction was stirred overnight, washed with NaCl (sat'd) and then DI water. The organic phase was separated and dried over MgSO₄ and concentrated in vacuo. The dark blue crude residue was then purified by silica gel column chromatography (5% THF/DCM) to yield 0.22g of dark blue solid. Yield: 68%. ¹H NMR (400 MHz, CDCl₃) δ (ppm) 8.24 (d, *J* = 1.4 Hz, 2H), 8.21 (d, *J* = 1.4 Hz, 2H), 7.94 (d, *J* = 15.6 Hz, 1H), 7.85 – 7.77 (m, 8H),

7.27 (d, J = 8.9 Hz, 2H), 7.11 (s, 1H), 6.92 (d, 1H), 6.87 (d, 1H), 6.73 (d, J = 3.5 Hz, 2H), 6.69 (d, J = 3.5 Hz, 2H), 6.60 (d, J = 8.9 Hz, 2H), 6.48 (d, J = 15.6 Hz, 1H), 5.10 (d, 4H), 4.28 – 4.17 (m, 4H), 4.05 (m, 2H) 3.64 – 3.52 (m, 4H), 3.44 (m, 4H), 2.95 (s, 3H), 2.58 (dd, 3H), 1.68 (s, 6H), 1.55 (m, 4H), 1.22 – 1.13 (m, 6H). ¹³C NMR (100 MHz, CDCl₃) δ (ppm) 182.82, 173.16, 172.18, 171.19, 162.35, 156.71, 152.19, 151.24, 147.45, 143.86, 135.09, 130.91, 128.92, 126.27, 124.69, 122.67, 112.10, 111.49, 99.00, 61.65, 60.42, 48.70, 45.67, 38.75, 28.87, 26.52, 21.07, 14.22, 12.31. HRMS (ESI) (M+, C₆₈H₆₆N₁₂O₁₃S): calcd: 1290.45930; found: 1290.45928.

3. Results and discussion

3.1. Synthesis and characterization

Synthetic approaches for the chromophores **F1-F3** were showed in Figure 2. All reactions were performed under nitrogen protection. TCF acceptor was prepared according to the literature. The synthesis of compounds **1** and **5** have been reported previously.[14, 22, 53] The compound **1** was introduced to the core through esterification in the presence of DCC (*N*,*N'*-dicyclohexylcarbodiimide) and DPTS (4-(dimethylamino) pyridinium 4-tosylate), which yield the functionalized side-chain chromophore **F3**. The resulting material was then purified by silica gel column chromatography. All the chromophores were completely characterized by ¹H-NMR, ¹³C-NMR, MS, UV-Vis spectroscopic analysis and the data obtained were in full agreement with the proposed formulations.





The nature of the intramolecular charge transfer (ICT) absorption and solvatochromic behavior of F1-F3 were investigated using UV-Vis absorption measurements in aprotic solvents with different polarities. The Figure 3 displays the spectra of F1-F3 in three solvents and films with different dielectric constants. The spectra data are

summarized in Table 1. The shape and position of the ICT band of this type of chromophore mainly depends on the dielectric properties of the solvents and the side chains of chromophores. Different from the other two chromophores, F3 shows two apparent ICT absorption peaks (469 nm and 644nm in chloroform) in UV-Vis spectra. The one in low wavelength represented the absorption of two disperse-red units in side chains and the one in high wavelength belongs to FTC conjugated structure. Three chromophores show similar solvatochromic behaviour in solvents with different dipole moment. When the solvents changing from acetone to chloroform, the λ_{max} of F1 shifted from 632 nm to 645 nm, which is the smallest red-shift compared with others. UV-Vis spectra in thin films (Figure 3) were also measured. The characteristic absorption band of the film will be broader than solutions because of material inhomogeneity and chromophore interactions in film.[12, 35, 54, 55] In the neat films, the pendant groups are acted as the matrix where chromophores are dispersed in. The change of the matrix dielectric constant will also result in red- or blue-shifts of absorption peak for a chromophore. DR1 group possesses a higher dielectric constant compared with bulky TBDPS group, which results in the largest red-shift of absorption peak of F3 when the surrounding environment changing from chloroform solution to neat films. The electrochemical properties of three chromophores were studied by cyclic voltammetry (CV). As shown in Figure 4, all three chromophores exhibited the similar oxidation potential, reduction potential and a lower energy gap, which was attributed to the same conjugating structures. The results also indicated that the modification of the pendant groups has little influence on the chromophores' ICT ability, which could affect the β_{zzz} value and further materials' macroscopic EO activities.

------Figure 4------

3.3 VASE analysis

To investigate the optical absorption behavior of EO films, VASE analysis was performed to measure the optical constants (real index of refraction, *n*, and absorption coefficient, κ) of chromophore films (as shown in Figure 5). At two of the important wavelengths for telecom (1310 nm, 1550 nm), **F3** film shows the largest *n* value ($n_{1310} = 1.79$, $n_{1550} = 1.77$) compared with **F2** and **F1** at 25 wt% in PMMA host polymer ($n_{1310} \approx n_{1550} = 1.56$). According to the equation 2, the operation voltage (V_{π}) is inversely proportional to value of $n^3 r_{33}$, so increasing *n* can significantly decrease the power requirements and solve the thermal management problems of the device. Meanwhile, the films show extremely weak absorption at the wavelengths 1310 nm and 1550 nm, which is significant for reducing the optical loss of device.

-----Figure 5------

3.4 Thermalphysical analysis

The thermal stability of chromophores were investigated by TGA. The decomposition temperatures (T_d , temperature at which 5% mass loss occurs during heating) are summarized in Table 2. Chromophores **F1-F3** show higher T_d values (above 200 °C) which is similar with the chromophore **EZ-FTC** (Figure 6). The T_ds of three chromophores are high enough to meet the requirement of device fabrication.



The T_{gs} were measured by DSC and showed in Figure 7. Although **F1** shows the highest T_{g} , the lack of flexible groups leads to poor film-forming ability by spin-coating method which can't afford the flat films for electric-field poling. **F3** exhibits the moderate higher T_{g} value (83.5 °C) compared with **F2** which has T_{g} values of 62.0 °C. The

weak dipole-dipole interactions between **DR1** groups in side chains are the reason of material's T_g improvement. Nearly neutral TBDPS groups can only act as bulky groups to isolate chromophores.

3.5 EO performance

In order to evaluate their EO activities, the monolithic EO chromophores were spin-coated into thin films on indium-tin oxide (ITO) glass substrates from 1,1,2-trichloroethane solution and poled by electric field. F2 and F3 exhibited excellent film-forming abilities and get neat films with high quality. However, F1 failed to get satisfactory films due to the strong molecular rigidity and lack of flexible groups. Therefore, F1 was doped into PMMA with 25 wt% for film preparation. The EO films were poled by contact-poling apparatus and measured by Teng-Man simple reflection method[56, 57] The r_{33} values were calculated by the following equation:

$$r_{33} = \frac{3\lambda I_m (n^2 - \sin^2 \theta)^2}{4\pi V_m I_c n^2 (n^2 - 2\sin^2 \theta) \sin^2 \theta} \propto \frac{I_m}{I_c}$$
(3)

Where I_c is the output beam intensity, I_m is the amplitude of the modulation, V_m is the modulating voltage.

The poling electric-field is 180 V/µm. The poling data are also summarized in Table 2. Figure 8 shows the I_m , I_c , temperature, and the current (real-time) monitored by Teng-Man. I_m is a signal intensity related to the change in index of refraction on poling and proportional to $r_{33} - r_{13}$.[46] As shown in Figure 8, **F2** and **F3** showed the similar behaviour in poling process. Figure 8 also shows the curves of current and I_m/I_c with time and temperature. When film was heated to T_g under a poling field, there is a sudden rise in I_m/I_c , which indicates the start of poling. At the same time, the current increases quickly. It is common for the increase of current or current spiked upon poling process and severe in neat chromophore systems. Due to the relatively large electric resistance, lower poling current increase was observed in **F1**/PMMA films. According to equation 2, the r_{33} is proportional to the value of I_m/I_c because others are constants that only have relationships with apparatus and the original refractive indices of

the materials. The results also indicated that the rise of I_m/I_c value occurs in reaching F3's T_g , which shows similar law with I_m/I_c and current.

-----Table 2-----

-----Figure 8-----

Due to low blending concentration and the lack of bulky groups to inhibit anti-parallel aggregation, **FL**/PMMA exhibits the lowest r_{33} value (23 pm/V) though the **F1** has the same conjugate structure with other three chromophores. In contrast to **F2** and **F3**, **F1**'s D- π -A stucture is exposed to others due to the poor performance of hydroxyl groups to isolate the chromophores with each other. The geometric optimization was carried out on three chromophores using B3LYP method at 6-311G* level, and was shown in Figure 9. **F1** shows a bare D- π -A structure with perfect planarity which lead to unfavourable anti-parallel aggregations. As to **F2** and **F3**, there are large bulky groups in donor and bridge parts to change the planar D- π -A conjugating system into 3D structures. Anti-parallel aggregation would be hard to occur in neat EO films. After contact poling, the **F3** film shows large improvement in EO activity (81 pm/V at 1310 nm) compared with **EZ-FTC** (39 pm/V), **F2** (56 pm/V). Meanwhile, according to previous report, the r_{33} value of DR1/PMMA system is only about 3.7 pm/V, which is not the root-cause of r_{33} value change.[58] Combination with the higher index of refraction, the $n^3 r_{33}$ value of poled **F3** reached to 464 pm/V, five times larger than the value of **F1**/PMMA (89 pm/V).

------Figure 9------

4. Conclusion.

Three organic NLO chromophores modified by different pendant groups in side chains have been synthesized and systematically characterized by NMR, MS, UV-Vis spectra and EO activities test. Thermogravimetric analysis

showed good thermal and thermoxidative stabilities of the three chromophores. **F2** and **F3** showed good solubility and comparability with polymer which were crucial to make high quality EO films. The effects of solvatochromic behavior on the UV-Vis absorption were also investigated to comparative discuss the influences of different pendant groups on the ICT absorption of the conjugated structure. Meanwhile, VASE measurement was carried out to analyze the index of refraction and the absorption coefficients at 1310 nm and 1550 nm. The chromophore **F3**, functionalized with **DR1** as pendant groups, exhibits relatively high T_g and the index of refraction ($n_{1310} = 1.79$, $n_{1550} = 1.77$). The poled monolithic chromophore thin film of **F3** displays large r_{33} value which is two times larger than **EZFTC** in traditional guest-host system. Together with higher index of refraction, the $n^3 r_{33}$ value of poled **F3** is about 464 pm/V, much larger than the poled **F1**/PMMA film. These results are useful for designing new monolithic EO materials with high EO activity and index of refraction to improve the performance of device.

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Figure captions:

Figure 1. The structures of chromophores.

Figure 2. The synthesis routes of chromophores.

Figure 3. The UV-Vis spectra of chromophores.

Figure 4. The Cyclic-Voltammetry curves of chromophores.

Figure 5. Optical constants of chromophores in films.

Figure 6. TGA curves of chromophores.

Figure 7. DSC traces of chromophores.

Figure 8. The poling curves of EO films on ITO.

Figure 9. Optimized chromophores structures..

Table 1. Optical constants, UV-Vis and CV data

	$\lambda_{max}\!/nm^a$	$\lambda_{max}\!/\!nm^b$	$\lambda_{max}\!/\!nm^c$	$\lambda_{max}\!/\!nm^d$	E_{ox}/V^e	E_{red}/V^e	$\Delta E \! / \! e V^e$	\mathbf{n}^{f}	n ^g
F1	632	632	645	643	0.430	-0.663	1.093	1.57	1.56
F2	640	636	671	661	0.372	-0.737	1.109	1.74	1.74
F3	624	620	644	687	0.435	-0.656	1.091	1.79	1.77

^a measured in toluene. ^b measured in acetone. ^c measured in chloroform. ^d measured in film. ^e 10⁻³ M in acetonitrile versus Ag/AgCl, glassy carbon working electrode, Pt counter electrode, 20 °C, 0.1 M Bu₄NPF₆, 100 mV s⁻¹ scan rate, ferrocene internal reference $E_{1/2} = +0.43$ V. ^f is the index of refraction at 1310 nm. ^g is the index of refraction at 1550 nm.

	Density(wt%) ^a	Tg∕°C	T_d /°C	T_p /°C ^b	$r_{33}/(\text{pm/V})^{c}$				
F1	25%	111.9	256	105	23				
F2	49%	62.0	233	63	56				
F3	36%	83.5	224	83	81				
^a is the weight percent of the active part of the NLO chromophore (D- π -A conjugated part) in films. ^b are the poling									

Table 2. Thermalphysical properties and poling data of chromophores

temperatures. ^c are measured by Teng-Man ellipsometry (Home made instrument).



















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Highlights

- 1. Three novel chromophores with different pendant groups were synthesized.
- 2. The effects of different pendant groups on the performance were investigated.
- 3. The highest electro-optic activity of poled films reached to 81 pm/V.