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# Synthesis and Polymerization of Liquid Crystals Containing Vinyl and Mercapto Groups

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Liquid-crystalline monomers containing two vinyl groups, two mercapto groups, or a 1:1 combination of the two have been synthesized and characterized in terms of their mesomorphic properties. These monomers can be photopolymerized in situ in an appropriate ratio of vinyl and mercapto groups to form highly ordered liquid-crystalline main-chain polymers. During polymerization in the nematic phase the appearance changes from clear in the highly aligned birefringent state to opaque. This effect is probably due to scat-

tering which is caused by the disturbance of the macro alignment as a result of the polymerization shrinkage and/or phase separation. In some cases, the reaction mixtures pass from the nematic to the crystalline state which results in a reduction in the degree of conversion and also in a change in the microcrystalline state. Crystallization can be suppressed by promoting asymmetry of the molecular structure which leads to a higher degree of conversion.

## Introduction

Polymers with a well-defined molecular order are of interest because of their optical and electro-optical properties. A convenient method for producing thin films of these polymers involves photo-initiated chain-crosslinking of liquid-crystalline monomers<sup>[1][2]</sup>. The different liquid-crystalline states of low-molecular-mass reactive mesogens show a wide variety of molecular order, all of which may be used for fixation in the polymerization process<sup>[3][4]</sup>. Various known techniques for establishing monolithic molecular order in liquid crystals can be applied or can be combined with one another to create films with complicated molecular architectures that are optically free of defects<sup>[5][6]</sup>. The monomers have a large degree of freedom in their molecular structure allowing the tailoring of the properties in the monomeric state and the mechanical and optical properties of the films.

The first reports of bulk photopolymerization of reactive liquid crystals were related to monoacrylates forming liquid-crystalline side-chain polymers<sup>[7][8]</sup>. The linear polymers formed exhibited various mesophases, although their transition temperatures differed from those of the initial monomer. Liquid-crystalline phase transitions therefore took place during the polymerization process or during cooling to ambient temperature and the molecular order changed as a result of the polymerization. To overcome this problem, bulk photopolymerization of polyfunctional liquid-crystalline monomers was attempted (photosetting liquid crystals). Early experiments involved the free-radical-based photopolymerization of monolithically ordered nematic liquid-crystalline diacrylates, which resulted in stable polymers, denoted as liquid-crystalline networks, having the same texture and almost the same degree of molecular

orientation<sup>[1]</sup>. However, the use of liquid-crystalline diepoxides<sup>[9][10]</sup> and liquid-crystalline divinylethers<sup>[11][12]</sup> polymerized using photocationic mechanisms leads essentially to the same results.

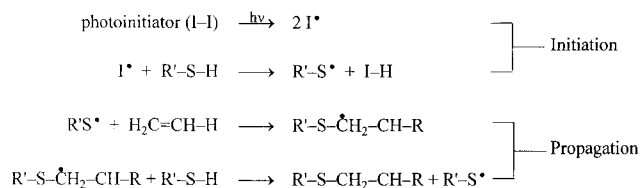
A limitation of side-chain liquid-crystalline networks is that when the polymerization is carried out in the easy-to-process nematic (N) phase, the order parameter  $S$  remains below 0.8; this imposes limits on the anisotropy of, for instance, the optical properties. The limitation of  $S$  is mainly attributed to steric factors in the networks. Although thermal vibrations of the mesogenic cores are thought to become restricted when embedded in the network structure, which should lead to higher values of  $S$  (also because their virtual transition to the isotropic state has been shifted to higher temperatures), the distribution of their long axes remains rather wide as their tendency to parallelism is hindered by the polymer chain. This hypothesis is supported by the fact that  $S$  tends to decrease even more with (a) shorter spacers between the polymer chain and the mesogenic core, and (b) bulky substituents at the core moieties<sup>[1]</sup>. This hypothesis is further supported by the fact that higher  $S$  values were found for epoxide networks, in which the mesogenic crosslinks are separated by a periodicity of three atoms in the polymer chain, than for liquid-crystalline acrylate and vinyl networks with a polymer chain periodicity of two atoms. It is known that, because of the larger aspect ratio of a liquid-crystalline main-chain polymer, in general, a higher value of  $S$  can be realized than with a liquid-crystalline side-chain polymer<sup>[12]</sup>.

It is therefore of both theoretical and practical interest to design liquid-crystalline monomers which upon photopolymerization align the mesogenic cores in a main-chain type of molecular arrangement. This principle is schematically

shown in Figure 1, which compares: (a) the photoinduced chain-crosslinking reaction with (b) a photoinduced liquid crystal main-chain formation. In the first process the polymer chain grows in a more or less perpendicular manner, independently of the stiff cores, whereas in the latter process the stiff cores are incorporated in the polymer chains themselves. It is expected that the latter process yields photoformed polymers with a higher value of *S* and hence a greater degree of optical anisotropy.

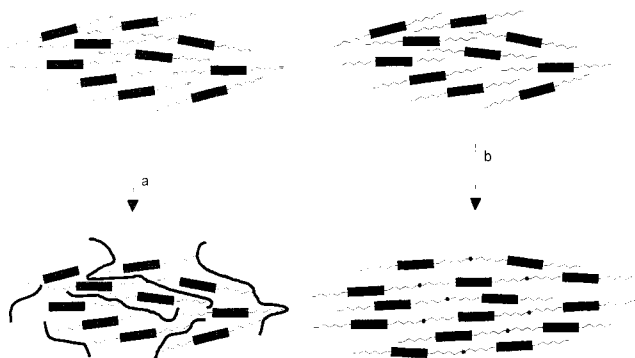
The photo-induced addition of thiols to olefins is a well-known reaction for non-liquid-crystalline systems, which leads to linear<sup>[13][14]</sup> or crosslinked<sup>[15]</sup> polymers, depending on the monomer functionality. The general reaction involving a photo-dissociating initiator is shown in Scheme 1.

Scheme 1. General reaction scheme showing the formation of sulphide bonds by photoinduced addition of mercapto groups to vinyl groups



The new materials described in this paper are designed so that groups R and R' are responsible for the mesomorphic behaviour; they have to be polyfunctional to form polymers. With a functionality of two, linear polymers are formed; higher functionalities lead to polymer networks. Here we have restricted ourselves to a functionality of two, with the aim of obtaining linear polymers. With this restriction two different systems may be used: (a) monomer blends consisting of a 1:1 ratio of di-vinyl and di-mercapto liquid-crystalline monomers, or (b) a monomer which carries both the mercapto and the vinyl functionality. If groups R and R' are appropriately chosen both systems yield liquid-crystalline polymers which have the same chemical structure. This paper describes the synthesis and the properties of these types of monomer systems and their photopolymerization behaviour.

Figure 1. Schematic presentation of (a) the photo-induced chain crosslinking of liquid crystals and (b) photo-induced liquid-crystalline main-chain formation

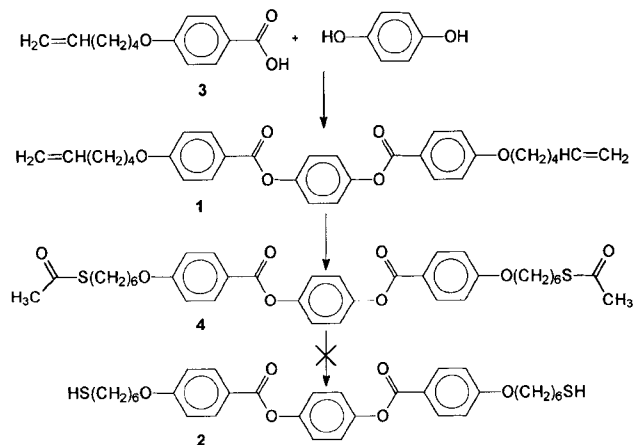


## Results and Discussion

### 1. Synthesis and Properties of 1, 2, and 11a

In order to obtain high-molecular weight materials in polymerization experiments, an exact stoichiometric olefin-thiol ratio is needed, as outlined in the introduction. One way of realizing this is by mixing a liquid-crystalline diolefin with a liquid-crystalline di-thiol. We synthesized both compounds as derivatives of the mesogenic group which had previously successfully been used with acrylates<sup>[1]</sup>, epoxides<sup>[13]</sup>, and vinyl ethers<sup>[16]</sup> (see Scheme 2). Di-olefin **1** was prepared through esterification of hydroquinone with 4-(5-hexenyloxy)benzoic acid (**3**) with the aid of dicyclohexylcarbodiimide and dimethylaminopyridine. To enable the introduction of the sulphur atoms ultimately resulting in the formation of di-thiol **2**, di-olefin **1** was made to react with thioacetic acid in a radical process initiated by azo-isobutyronitrile to form di-thio acetate **4**<sup>[16]</sup>. Attempts to form the desired di-thiol **2** by removing the acetyl groups of **4** failed. In order to remove these acetyl groups, the basic or acidic conditions needed (4-toluenesulphonic acid in ethanol, potassium hydroxide or ammonia in ethanol) were too strong and partially decomposed the mesogenic group, resulting in materials which could not be purified.

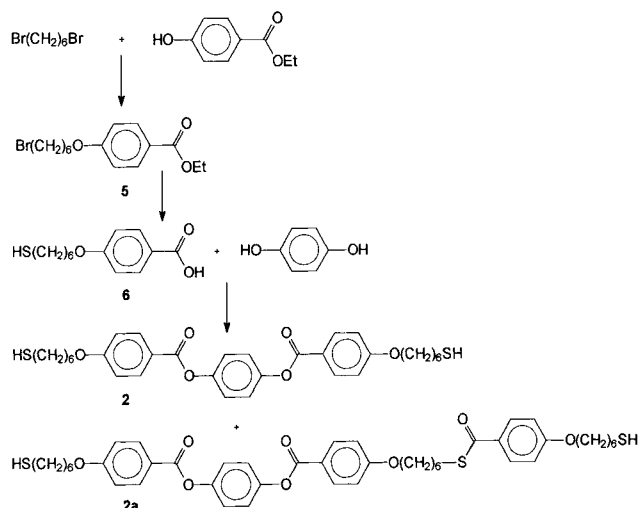
Scheme 2. Synthesis of 1,4-di-[4-(5-hexenyloxy)benzoyloxy]benzene (**1**) and attempted synthesis of 1,4-di-[4-(6-mercaptohexyloxy)benzoyloxy]benzene (**2**)



Scheme 3 shows an alternative way of obtaining di-thiol **2**. Use was made of 4-(6-mercaptohexyloxy)benzoic acid (**6**), which was prepared by reaction of ethyl 4-(6-bromohexyloxy)benzoate (**5**) with thiourea, followed by hydrolysis. Esterification of hydroquinone with acid **6** in the same way as described for the synthesis of di-olefin **1** resulted in the formation of di-thiol **2** contaminated with appreciable amounts of di-thiol **2a**. In this compound part of the mercapto groups had reacted with acid **6**. This by-product could easily be detected and quantified from the <sup>1</sup>H-NMR spectrum. The methylene group next to the thiocarboxy moiety appeared as a triplet at  $\delta = 3.1$  and the aromatic protons appeared as two doublets at  $\delta = 7.9$  and  $6.9$ . In order to suppress the formation of **2a**, the esterification reaction was carried out at 0°C using an excess of hydroquinone. 6% of **2a** was, however, formed which could not

be separated by means of crystallization. Separation by column chromatography (silica/dichloromethane) was not possible either. In attempts to purify **2** by column chromatography small amounts of disulphide were formed. The disulphide was detected by  $^1\text{H-NMR}$  in the form of a triplet at  $\delta = 2.65$ . Apparently, oxidation of **2** in dichloromethane solution is catalyzed by silica. The presence of **2a**, in principle, implies no problems in the polymerization reaction as it is also a dithiol. This should be taken into account when the stoichiometric mixtures of **1** and **2** are prepared for the polymerization experiments.

Scheme 3. Synthesis of 1,4-di-[4-(6-mercaptohexyloxy)benzoyloxy]benzene (**2**)

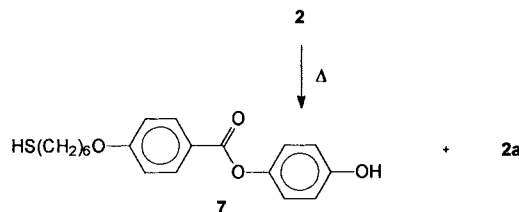


One way of avoiding the formation of **2a** is by making use of a protected form of acid **6**. For this purpose the mercapto group was protected as a tetrahydropyranyl sulphonyl ether and as *O*-methyl thiocarbonate, by reaction of **6** with dihydropyran and methyl chloroformate, respectively. In both cases we encountered the same problems as in the deprotection of thioacetate **4**. The basic or acidic conditions used to remove these groups resulted in decomposition of the mesogenic group, forming worthless materials.

Table 1 shows the temperatures of the phase transitions of **1** and **2**. These substances exhibit melting points of  $100^\circ\text{C}$  or higher. This implies that polymerization experiments have to be performed at elevated temperatures. When compound **2** was heated for about 5 minutes at  $200^\circ\text{C}$ , just above its clearing point, it remained isotropic upon cooling.  $^1\text{H-NMR}$  investigation of a sample showed that at these temperatures the mercapto group reacted with the aromatic ester moiety of the mesogenic group. This transesterification process is shown in Scheme 4. The signals typical of **2a** were observed and also those of an aromatic system which can be assigned to compound **7**. (The four doublets of the aromatic system of **7** were observed at the same positions of those of the similar compound **10a** (see scheme 5, whose synthesis will be described below). At  $120^\circ\text{C}$ , the temperature at which most of the polymerization experiments were carried out, this reaction was not observed,

even after heating for more than 2 hours, much longer than the duration of a polymerization experiment.

Scheme 4. Disproportionation of 1,4-di-[4-(6-mercaptohexyloxy)benzoyloxy]benzene (**2**) at  $200^\circ\text{C}$



Another way of achieving an exact stoichiometry for the olefin and mercapto groups is by using compound **11a**, which contains one olefinic group and one mercapto group. The synthesis of this compound is shown in Scheme 5. Hydroquinone has to be subsequently esterified by 4-(5-hexenyloxy)benzoic acid (**3**) and 4-(6-mercaptohexyloxy)benzoic acid (**6**). Monoprotected hydroquinone **8a** was used in order to avoid laborious purification methods. This compound can be easily prepared and purified and has proved very useful in the preparation of asymmetric liquid-crystalline diacrylates<sup>[5][21]</sup> and epoxides<sup>[13]</sup>. Thus, after the esterification of **8a** with **3** and deprotection of intermediate **9a**, phenolic compound **10a** was obtained. This compound was in turn esterified with **6**. Both esterification reactions were carried out with the aid of dicyclohexylcarbodiimide and dimethylaminopyridine. In these cases too, an excess of **10a** was used to suppress thioester formation. Nevertheless, about 3% of a compound similar to **2a** was formed. Fortunately, this has no effect on the olefin–thiol ratio. Therefore this compound is more preferable than the mixture of **1** and **2**. Compound **11a** was found to have a melting point of  $104^\circ\text{C}$  (see Table 1), which means that the polymerization had to be carried out well above  $100^\circ\text{C}$ .

Table 1. Phase transitions of liquid crystals **1**, **2**, **11a**, **11b**, and **14**

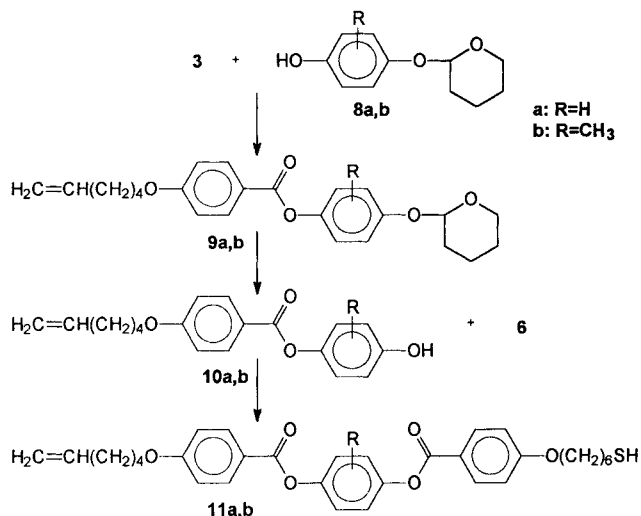
	<i>n</i>	R <sup>1</sup>	R <sup>2</sup>	R <sup>3</sup>	phase transitions/ $^\circ\text{C}$
<b>1</b>	1	H <sub>2</sub> C=CH	HC=CH <sub>2</sub>	H	Cr–129–N–204–I
<b>2</b> <sup>[a]</sup>	1	HS(CH <sub>2</sub> ) <sub>2</sub>	(CH <sub>2</sub> ) <sub>2</sub> SH	H	Cr–100–N–194–I
<b>11a</b> <sup>[a]</sup>	1	H <sub>2</sub> C=CH	(CH <sub>2</sub> ) <sub>2</sub> SH	H	Cr–104–N–208–I
<b>11b</b> <sup>[a]</sup>	1	H <sub>2</sub> C=CH	(CH <sub>2</sub> ) <sub>2</sub> SH	CH <sub>3</sub>	Cr–82–N–161–I
<b>14</b> <sup>[a]</sup>	0	HS(CH <sub>2</sub> ) <sub>2</sub>	HC=CH <sub>2</sub>	H	Cr–43–N–80–I

<sup>[a]</sup> All these compounds are contaminated with small amounts of a thio-ester byproduct, see text.

## 2. Photopolymerization of **1**, **2**, and **11a**

To study the polymerization behaviour of **11a**, a mixture containing 1% of the photoinitiator 2,2-dimethoxy-2-phenylacetophenone was prepared. Irradiating of this mixture in a DSC apparatus at  $120^\circ\text{C}$  and  $130^\circ\text{C}$  after melting resulted in the graphs shown in Figure 2. The presence of two peaks is explained by the subsequent occurrence of a reaction ex-

Scheme 5. Synthesis of 4-[4-(5-hexenyloxy)benzoyloxy]-1-[4-(6-mercaptohexyloxy)benzoyloxy]benzene (**11a**) and 4-[4-(5-hexenyloxy)benzoyloxy]-1-[4-(6-mercaptohexyloxy)benzoyloxy]methylbenzene (**11b**)

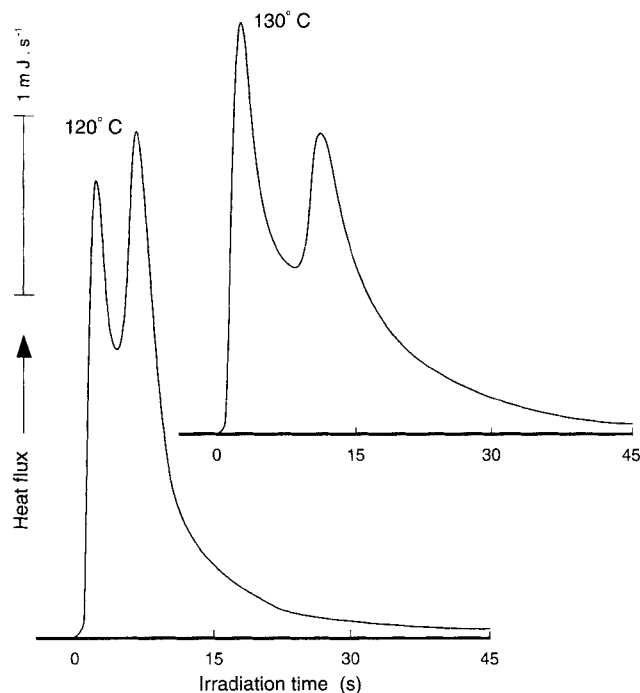


otherm and a crystallization exotherm. The first peak, attributable to the reaction exotherm, shows that the polymerization starts soon after the beginning of the irradiation. The second peak indicates crystallization of the reaction mixture, which will have an effect on the polymerization behaviour. At 130°C crystallization occurred at a later stage than at 120°C, which is understandable in terms of crystallization kinetics and thermodynamics. Owing to the crystallization, results of calculations of the degree of the conversion based on the integrated DSC curves would have been unreliable. For that reason we used  $^1\text{H-NMR}$  spectroscopy to obtain the conversion data. The new methylene groups of the sulphide bond were observed as a triplet at  $\delta = 2.60$ . The original mercapto hydrogen and olefinic signals were still observed. A conversion of about 70% of the reactive groups was deduced from the integral values of the samples taken at both polymerization temperatures. DSC analysis of the product obtained at 120°C showed that it melted between 160 and 175°C and became isotropic at about 260°C. Upon cooling, it crystallized around 140°C. In view of this crystallization temperature it is possible that the sample started to crystallize during polymerization. Crystallization is known to retard the polymerization reaction due to a reduced monomer mobility, which explains the relatively low conversion. These results were confirmed by size exclusion chromatography, which revealed an oligomeric material with a broad molecular weight distribution around 2000 and a relatively high monomer content.

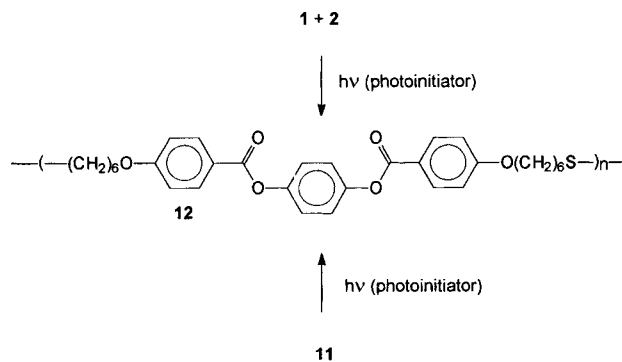
Similar results were obtained with mixtures of **1** and **2**. The method employed, though somewhat different than that used for **11a**, resulted in the formation of polymer **12** with the same chemical structure (see Scheme 6).

$^1\text{H-NMR}$  analysis of a 1% mixture of the photoinitiator in di-olefin **1** after irradiation, revealed no conversion of the double bonds. Therefore it can be concluded that homopolymerization of the olefinic bonds is not an important side reaction during the thiol-ene polymerization.

Figure 2. DSC trace of the photo-initiated polymerization of a **11a** containing 1% 2,2-dimethoxy-2-phenylacetophenone, at 120°C and 130°C



Scheme 6. Formation of poly{4-[4-(5-hexenyloxy)benzoyloxy]-1-[4-(6-mercaptohexyloxy)benzoyloxy]benzene} **12** from **1** and **2** or **11a** through photopolymerization



### 3. Synthesis and Properties of **11b**

Breaking the molecular symmetry by incorporating a methyl substituent in the central ring of three ring liquid crystals monomers, results in a decrease in the melting point and suppression of crystallization<sup>[2]</sup>. It was expected that this is also the case for the thiol-ene monomers and polymers. This would enable polymerization at lower temperatures with a higher degree of conversion. For that reason monomer **11b** was prepared. The synthesis was similar to that of **11a** (see Scheme 5), except that a mixture of products was obtained due to the fact that the starting compound **8b** was a mixture of the 2- and 3-methyl isomers. When **10b** was esterified with **6** in the same way as **10a**, product **11b** was found to be contaminated with appreciable amounts of the thioester byproduct. The 2-methyl isomer of **10b** was undoubtedly sterically hindered, which had a

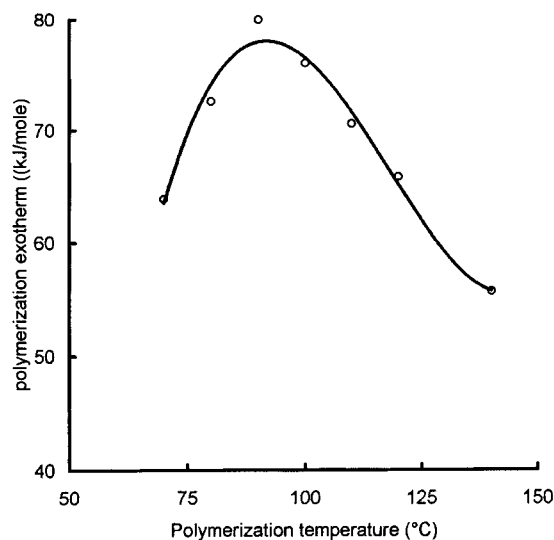
favourable effect on the thioesterification side reaction. The reaction with **6** was therefore carried out with 1.6 equivalents of **10b** instead of 1.2 equivalents. This resulted in less than 4% by-product.

The liquid-crystalline properties of **11b** are presented in Table 1. As expected, its melting and clearing points are lower than those of **11a**. Whereas **11a** started to crystallize below 90°C, **11b** could be supercooled to room temperature before it started to crystallize slowly.

#### 4. Photopolymerization of **11b**

Only one exothermic peak was obtained in the photopolymerization of **11b** at 90°C in a DSC apparatus in the same way as performed with **11a**. An exotherm of about 80 kJ/mole was measured, close to the theoretical value of 79 kJ/mol<sup>[17]</sup>. The <sup>1</sup>H-NMR spectrum of the photopolymerized product shows the absence of the original vinylic and mercapto protons. This means that the degree of conversion of **11b** is higher than that of **11a**. Size exclusion chromatography of the polymer revealed an average molecular weight (*M<sub>n</sub>*) of 14 · 10<sup>3</sup> and a broad molecular weight distribution (*M<sub>w</sub>/M<sub>n</sub>*) of 2.6. Figure 3 shows that lower reaction enthalpies were obtained at polymerization temperatures below and above 90°C. At higher temperatures, the polymerization takes place closer to the ceiling temperature<sup>[23]</sup> resulting in incomplete conversion. At lower temperatures crystallization probably occurs. The result at 90°C shows the superiority of **11b** over **11a**, which is probably attributable to suppression of crystallization of the polymer. DSC analysis of the photopolymerization product of **11b** at 90°C revealed a broad melting range between 130°C and 140°C and an isotropic transition at about 240°C. Upon cooling, crystallization started between 80°C and 60°C. The latter temperatures are lower than the polymerization temperature of 90°C, which explains the high degree of conversion, in spite of the fact that polymerization took place below the actual melting temperature.

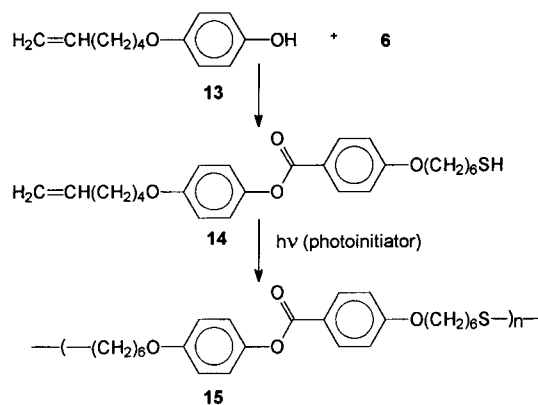
Figure 3. Polymerization exotherm as a function of the polymerization temperature measured by DSC of **11b**



#### 5. Synthesis and Properties of **14**

In order to carry out the polymerization at even lower temperatures, liquid crystal **14** containing a smaller mesogenic group was prepared. It was formed from acid **6** and 4-(5-hexenyloxy)phenol (**12**), (see Scheme 7) under the same esterification conditions as described above for the preparation of **11a**. The resultant compound was contaminated with about 10% thio-ester by-product, which was not removed. This monomer had a melting point of 43°C and a clearing point of 80°C (see table 1). It exhibited the nematic phase.

Scheme 7. Synthesis of 4-[4-(6-mercaptohexyloxy)benzoyloxy]-(5-hexenyloxy)benzene (**14**) and its photopolymerization to poly{4-[4-(6-mercaptohexyloxy)benzoyloxy]-(5-hexenyloxy)benzene} (**15**)



#### 6. Photopolymerization of **14**

After photopolymerization of **14** at 60°C, in the nematic phase, the <sup>1</sup>H-NMR spectra of the photopolymerized product **15** (see Scheme 7) revealed the absence of the original vinylic and mercapto protons. This means that the conversion for **14** is more complete than with **11a**. Only one exothermic peak was obtained in the DSC apparatus. Size exclusion chromatography revealed an average molecular weight of 8 · 10<sup>3</sup> which is somewhat lower than that obtained with **11b**. The molecular weight distribution was 2.7. Polymer **15** showed rather complex melting behaviour between 130 and 145°C after which it became liquid-crystalline. It became isotropic above 160°C. Upon cooling, the sample became liquid-crystalline again below 155°C and crystallization occurred at about 120°C. This crystallization did not seem to affect the polymerization at the relatively low temperature of 60°C; it probably sets in at a later stage. The morphology of the liquid-crystalline phase observed by polarizing microscopy points to a nematic phase. This is in agreement with the nematic phase observed for main-chain polymers containing the same mesogenic group connected by alkene spacers<sup>[18]</sup>.

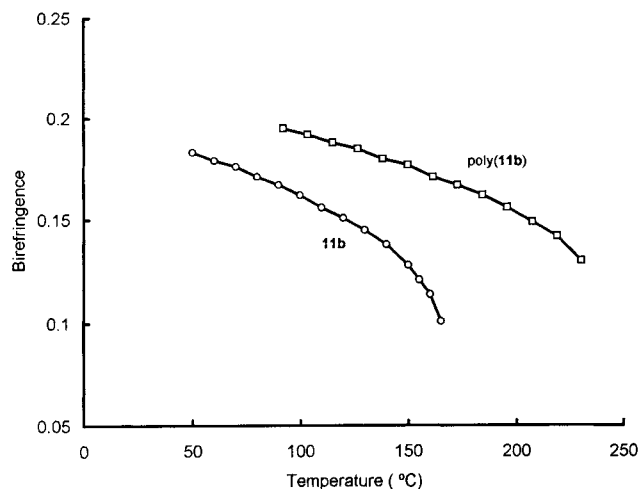
#### 7. Molecular Orientation and Optical Properties of the Monomers and Polymers

The monomers were monolithically aligned in the nematic state between two glass substrates separated by 6 μm spacers and provided with a 200 nm rubbed polyimide coat-

ing. The monomer films were clear, colourless, and highly birefringent. Due to its poor conversion, monomer **11a** was not used for the optical measurements. Figure 4 shows the birefringence as a function of the temperature for monomer **11b**. At low temperatures, above the crystallization temperature, higher birefringences were measured than with the corresponding nematic diacrylates. This is explained by the existence of a broad mesophase and a better rod-like molecular conformation of the thiolene molecules due to the absence of the acrylate end-groups. Photopolymerization of the nematic monomer film of **11b** at 90°C caused the birefringence to increase considerably, as can be seen in Figure 5. In the same figure it can be observed that, unfortunately, the transmission had decreased considerably. Scattering due to domain formation is probably responsible for this effect. The macro alignment of the material may have been disturbed as a result of polymerization shrinkage, phase separation and crystallization with ongoing polymerization. The end value of the birefringence above 0.2 is much higher than the values obtained with the corresponding LC networks obtained from LC diacrylates<sup>[1]</sup>. As predicted in the introduction, the conformation of the LC main chain leads to higher order parameters in the polymer films and thus to higher birefringences. Figure 4 also shows the birefringence of a thin polymer film polymerized at 90°C as a function of the temperature. The plot only shows data measured between 90°C and the transition to the isotropic state at about 240°C. When the sample was cooled below 90°C it began to crystallize and it lost its transparency completely.

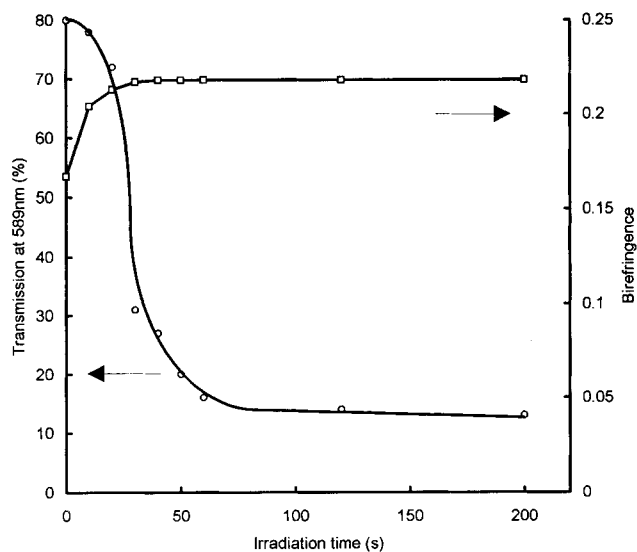
Monomer **14** formed a strongly scattering material upon polymerization and for that reason the birefringence could not be measured. Probably, in this type of experiments crystallization sets in earlier than measured by DSC. It was not investigated any further.

Figure 4. Birefringence values for monomer **11b** and the polymer formed after photopolymerization



Future studies will be carried out with this new type of compounds. These studies will focus on the effect of polymerization on the order in the liquid-crystalline state, the effect of molecular weight and crosslinking on the polymer

Figure 5. Change in birefringence (right) and transmission (left) during photopolymerization of monomer **11b** at 90°C



properties as ways for suppressing crystallization and suppressing other effects which cause a decrease in the transmission of the polymeric films.

## Conclusions

Liquid-crystalline monomers that can be used for so-called thiol-ene photopolymerization have been prepared successfully. Mesophase behaviour is observed at elevated temperatures. These molecules can be photopolymerized in the bulk if it is ensured that the structure of the monomers prevents crystallization during polymerization. In general, the polymers exhibit mesomorphic behaviour at high temperatures and are crystalline at ambient temperature. These polymers have a higher order than those obtained by photopolymerization of liquid crystalline diacrylates, and they hence have higher birefringence values.

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## Experimental Section

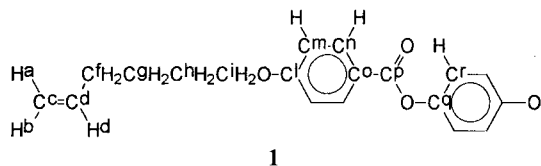
**General:** <sup>1</sup>H- and <sup>13</sup>C-NMR spectra were measured on a Bruker DPX 300 spectrometer, in CDCl<sub>3</sub> with TMS as internal standard. Chemical shifts are given in ppm, coupling constants *J* in Hz. The intermediate products exhibited <sup>1</sup>H-NMR spectra that are in accordance with their structures. – Phase transitions were measured on a Perkin Elmer DSC-7 apparatus. A Reichert microscope provided with a Mettler FP52 hot stage was used for texture measurements. – The photopolymerization experiments were performed identically to those with diacrylates as previously described<sup>[1]</sup>. – The birefringence, change of the birefringence, and transmission during polymerization were measured by UV-Vis spectroscopy between two crossed polarizers as described in ref.<sup>[1]</sup>.

The size exclusion chromatography experiments were performed in chloroform (0.2–0.5 mg/g). After filtration (Millex-LCR 0.5 μm filter), 25 μl of the solutions were injected on a GPC column (PL

gel-5  $\mu\text{m}$ -mixed-c column,  $300 \times 7.5 \text{ mm}^2$ , linear range 200 to  $3 \cdot 10^6$ , with guard column  $50 \times 7.5 \text{ mm}^2$ ) and eluted with chloroform at a flow of 1.0 ml/min. Detection occurs at 254 nm. The equipment is calibrated with a series of 16 narrow dispersed PS standards ( $M_w$ :  $580-3 \cdot 10^6$ ).

All solvents were obtained from Merck. All other chemicals were obtained from Acros Organics. The following chemicals were prepared according to literature procedures: 4-(5-hexenyloxy)benzoic acid (**3**)<sup>[13]</sup>, 4-(tetrahydropyran-2-yloxy)phenol (**8a**)<sup>[19]</sup>, and 4-(5-hexenyloxy)phenol (**13**)<sup>[13]</sup>.

**1,4-Di-[4-(5-hexenyloxy)benzoyloxy]benzene (1):** A mixture of 22 g of 4-(5-hexenyloxy)benzoic acid (**3**), 5.5 g of hydroquinone, 1.2 g of 4-*N,N*-dimethylaminopyridine and 150 ml of dichloromethane was cooled in an ice bath with magnetic stirring. 21 g of *N,N'*-dicyclohexylcarbodiimide was added and stirring was continued for one hour in the ice bath. After removing the ice bath, stirring was continued for 16 hours at room temperature. The crude product was obtained after elution of the mixture over a small silica column. 21.8 g of **1** (85%) was obtained as needles after crystallization from an ethanol-ethyl acetate (1:1) mixture. — <sup>1</sup>H NMR: 8.14 (d, 4 H,  $J = 8.6$ , H<sup>n</sup>), 7.26 (s, 4 H, H<sup>r</sup>), 6.97 (d, 4 H,  $J = 8.6$ , H<sup>m</sup>), 5.84 (m, 2 H,  $J_1 = 17.0$ ,  $J_2 = 10.2$ ,  $J_3 = 6.5$ , H<sup>d</sup>), 5.05 (d, 2 H,  $J = 17.0$ , H<sup>a</sup>), 4.98 (d, 2 H,  $J = 10.2$ , H<sup>b</sup>), 4.05 (t, 4 H,  $J = 6.5$ , H<sup>i</sup>), 2.15 (q, 4 H,  $J = 6.5$ , H<sup>f</sup>), 1.85 (m, 4 H,  $J_1 = 6.5$ ,  $J_2 = 7.0$ , H<sup>h</sup>), 1.60 (m, 4 H,  $J_1 = 6.5$ ,  $J_2 = 7.0$ , H<sup>g</sup>). — <sup>13</sup>C NMR: 164.8 (C<sup>p</sup>), 163.5 (C<sup>l</sup>), 148.4 (C<sup>q</sup>), 138.8 (C<sup>d</sup>), 132.3 (C<sup>n</sup>), 122.6 (C<sup>r</sup>), 121.5 (C<sup>o</sup>), 115.3 (C<sup>c</sup>), 114.3 (C<sup>m</sup>), 68.5 (C<sup>i</sup>), 33.8 (C<sup>f</sup>), 28.9 (C<sup>h</sup>), 25.7 (C<sup>g</sup>).



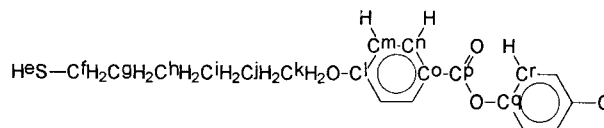
**1,4-Di-[(6-acetylthiohexyloxy)benzoyloxy]benzene (4):** A mixture of 5.1 g of 1,4-di-[4-(5-hexenyloxy)benzoyloxy]benzene (**1**), 2.5 ml of thioacetic acid, 20 mg of azoisobutyronitrile, and 25 ml of toluene was heated to 90°C. The reaction was followed by TLC (SiO<sub>2</sub> / 10% ethyl acetate in dichloroethane). Every two hours another 20 mg of azoisobutyronitrile was added until complete conversion of the starting product. 6 g of **4** (90%) was obtained as very fine needles after evaporation of the toluene and crystallization from 2-propanol. It exhibited the following phase transitions: Cr – 146°C – N – 156°C – I.

**Ethyl 4-(6-Bromohexyloxy)benzoate (5):** A mixture of 100 ml of 1,6-dibromohexane, 108 g of ethyl 4-hydroxybenzoate, 134 g of potassium carbonate, and 500 ml of 2-butanone was refluxed for 16 hours. After cooling and filtration, the 2-butanone was evaporated. The residue was dissolved in 400 ml of diethyl ether and extracted twice with 300 ml of a 10% sodium hydroxide solution. After extraction with 200 ml of a saturated sodium chloride solution and drying over magnesium sulphate, the diethyl ether was evaporated. To separate the product from the excess of 1,6-dibromohexane and the by-product, bis[ethyl 4-(1,6-hexylenedioxy)benzoate], the mixture was fractionated in a Kugelrohr apparatus. ( $T = 140^\circ\text{C}$ ,  $P = 0.03 \text{ mbar}$ ). 65.3 g of the product (31%) was obtained as a white solid.

**4-(6-Mercaptohexyloxy)benzoic Acid (6):** A mixture of 65.3 g of ethyl 4-(6-bromohexyloxy)benzoate (**5**), 22.8 g of thiourea and 40 ml of water was stirred for 2 hours at 110°C. After cooling 360 ml of a 10% sodium hydroxide solution was added. After refluxing for

2 hours, the hot solution was transferred to a beaker and with vigorously stirring a 2.5 N hydrochloric acid solution was added until pH = 1. The precipitated crude product was washed with 400 ml of water and dried at 60°C under vacuum. 38 g of the product (75%) was obtained after recrystallization from chloroform. Cr – 126 – N – 145 – I.

**1,4-Di-[4-(6-mercaptohexyloxy)benzoyloxy]benzene (2):** A mixture of 25.4 g of 4-(6-mercaptohexyloxy)benzoic acid (**6**), 5.7 g of hydroquinone, 1.2 g of 4-*N,N*-dimethylaminopyridine, and 150 ml of dichloromethane was cooled in an ice bath with magnetic stirring. 21 g of *N,N'*-dicyclohexylcarbodiimide was added and stirring was continued for 8 hours in the ice bath. After removing the ice bath, stirring was continued for 16 hours at room temperature. The crude product was obtained after elution of the mixture over a small silica column. 17.5g of **2** (60%) was obtained as a white powder after crystallization from ethyl acetate. It was contaminated with about 6% of the byproduct **2a**. — <sup>1</sup>H NMR: 8.14 (d, 4 H,  $J = 8.6$ , H<sup>n</sup>), 7.26 (s, 4 H, H<sup>r</sup>), 6.97 (d, 4 H,  $J = 8.6$ , H<sup>m</sup>), 4.05 (t, 4 H,  $J = 6.5$ , H<sup>k</sup>), 2.56 (q, 4 H,  $J = 7.5$ , H<sup>f</sup>), 1.9–1.4 (m, 16 H, H<sup>g</sup>, H<sup>h</sup>, H<sup>i</sup> and H<sup>j</sup>), 1.35 (t, 2 H,  $J = 7.5$ , H<sup>e</sup>). — <sup>13</sup>C NMR: 164.8 (C<sup>p</sup>), 163.5 (C<sup>l</sup>), 148.4 (C<sup>q</sup>), 132.3 (C<sup>n</sup>), 122.6 (C<sup>r</sup>), 121.5 (C<sup>o</sup>), 114.3 (C<sup>m</sup>), 68.5 (C<sup>k</sup>), 34.4 (C<sup>g</sup>), 29.6 (C<sup>j</sup>), 28.6 (C<sup>h</sup>), 26.1 (C<sup>i</sup>), 25.1 (C<sup>f</sup>).



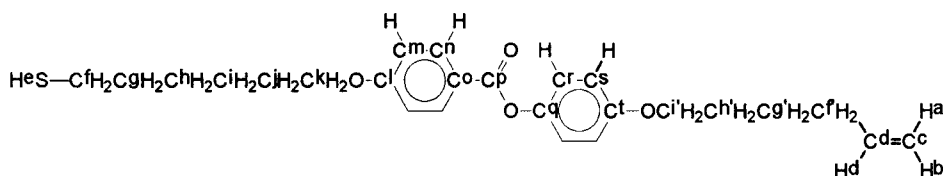
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**4-(Tetrahydropyran-2-yloxy)methylphenol, Mixture of the 2- and 3-Methyl Isomers (8b):** 90 ml of dihydropyran was added over a period of 30 minutes to a solution of 126 g of methylhydroquinone and 5 g of 4-toluenesulphonic acid in 1 l of diethyl ether. After stirring for another two hours, nitrogen was bubbled through and a deaerated solution of 45 g of sodium hydroxide in 500 ml of water was added. The aqueous layer obtained after separation, was acidified by purging with carbon dioxide. The crude product separated as a brown oil, which was extracted with 300 ml of carbon tetrachloride. After evaporation, the brown oil crystallized slowly. The solid was ground and washed twice with 300 ml of water. After drying over silica under vacuum, 59 g (28%) of **8b** was obtained as a light brown powder. It was an 1:1 mixture of the 3- and 2- methyl isomers as deduced from <sup>1</sup>H NMR; apart from a difference in the aromatic region, the acetalic C-H protons of the two isomers were observed separated at  $\delta = 3.30$  and 3.35.

**4-[4-(5-Hexenyloxy)benzoyloxy]phenol (10a):** A mixture of 22 g of 4-(5-hexenyloxy)benzoic acid (**3**), 19.4 g of 4-(tetrahydropyran-2-yloxy)phenol (**8a**), 1.2 g of 4-*N,N*-dimethylaminopyridine and 150 ml of dichloromethane was cooled in an ice bath with magnetic stirring. 21 g of *N,N'*-dicyclohexylcarbodiimide was added and stirring was continued for one hour in the ice bath. After removing the ice bath, stirring was continued for 16 hours at room temperature. Intermediate **9a** was obtained after filtration, evaporation of the dichloromethane and crystallization from ethanol. This product was mixed with 400 ml of ethanol and 4 g of pyridinium 4-toluenesulphonate. After stirring this mixture at 60°C for 2 hours, it was added dropwise to a mixture of 100 g of ice and 700 ml of water. The precipitated product was washed with 300 ml of water and dried over silica under vacuum. 26.0 g of **10a** (83%) was obtained as a white powder.

**4-[4-(5-Hexenyloxy)benzoyloxy]methylphenol, Mixture of the 2- and 3-Methyl Isomers (10b):** This reaction was performed in the



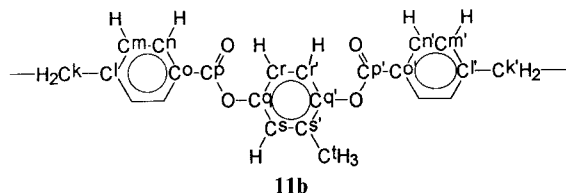


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same way as described for **10a**, starting with 20.8 g of **8b**. Intermediate **9b** was not recrystallized due to oil formation but washed twice with 150 ml of ethanol after it had crystallized slowly overnight. 18.0 g of **10b** (61%) was obtained as a light yellow powder.

**4-[4-(5-Hexenyloxy)benzoyloxy]-1-[4-(6-mercaptohexyloxy)benzoyloxy]benzene (11a)**: A mixture of 25.4 g of 4-(6-mercaptohexyloxy)benzoic acid (**6**), 34.3 g of 4-[4-(5-hexenyloxy)benzoyloxy]phenol (**10a**), 1.2 g of 4-*N,N*-dimethylaminopyridine, and 150 ml of dichloromethane was cooled in an ice bath with magnetic stirring. 21 g of *N,N'*-dicyclohexylcarbodiimide was added and stirring was continued for 8 hours in the ice bath. After removing the ice bath, stirring was continued for 16 hours at room temperature. The crude product was obtained after elution of the mixture over a small silica column. 34.9 g of **11a** (63%) was obtained as a white powder after crystallization from a 1:1 mixture of 2-propanol and ethyl acetate. It was contaminated with about 4% of a by-product as a result of thioesterification. Its NMR data are the same as those of a mixture of **1** and **2**.

**4-[4-(5-Hexenyloxy)benzoyloxy]-1-[4-(6-mercaptohexyloxy)benzoyloxy]methylbenzene, Mixture of the 2- and 3-Methyl Isomer (11b)**: This reaction was performed as described for the synthesis of **11a** with the exception that instead of 1.1 equivalent of **10a**, 1.6 equivalent of **10b** was used. **11b** was obtained in 48% yield as a white powder after crystallization from a 2:1 mixture of 2-propanol and ethyl acetate. It was also contaminated with about 3% of a by-product as a result of thioesterification. The NMR data which are different from those of **11a** are given below:  $^1\text{H}$  NMR: 8.16 (d, 4 H,  $J = 8.6$ ,  $\text{H}^{\text{n}}$ ), 8.14 (d, 4 H,  $J = 8.6$ ,  $\text{H}^{\text{n}}$ ), 7.17 (d, 1 H,  $J = 8.5$ ,  $\text{H}^{\text{r}}$ ), 7.13 (d, 1 H,  $J = 2.5$ ,  $\text{H}^{\text{s}}$ ), 7.08 (dd, 1 H,  $J_1 = 8.5$ ,  $J_2 = 2.5$ ,  $\text{H}^{\text{r}}$ ), 6.99 (d, 4 H,  $J = 8.6$ ,  $\text{H}^{\text{m}}$ ), 6.96 (d, 4 H,  $J = 8.6$ ,  $\text{H}^{\text{m}}$ ), 4.07 (t, 4 H,  $J = 6.5$ ,  $\text{H}^{\text{k}}$ ), 4.05 (t, 4 H,  $J = 6.5$ ,  $\text{H}^{\text{k}}$ ), 2.24 (s, 3 H,  $\text{H}^{\text{q}}$ ).  $^{13}\text{C}$  NMR: 164.9 ( $\text{C}^{\text{p}}$ ), 164.5 ( $\text{C}^{\text{p}}$ ), 163.5 ( $\text{C}^{\text{l}}$  and  $\text{C}^{\text{l}'}$ ), 148.4 ( $\text{C}^{\text{q}}$ ), 147.1 ( $\text{C}^{\text{q}'}$ ), 132.3 ( $\text{C}^{\text{o}}$  and  $\text{C}^{\text{o}'}$ ), 131.8 ( $\text{C}^{\text{s}}$ ), 124.1 ( $\text{C}^{\text{s}}$ ), 122.9 ( $\text{C}^{\text{r}}$ ), 121.4 and 121.6 ( $\text{C}^{\text{o}}$  and  $\text{C}^{\text{o}'}$ ), 120.0 ( $\text{C}^{\text{r}}$ ), 114.3 ( $\text{C}^{\text{m}}$  and  $\text{C}^{\text{m}'}$ ), 68.5 ( $\text{C}^{\text{k}}$  and  $\text{C}^{\text{k}'}$ ), 16.4 ( $\text{C}^{\text{q}}$ ).



**4-[4-(6-Mercaptohexyloxy)benzoyloxy](5-hexenyloxy)benzene (14)**: A mixture of 25.4 g of 4-(6-mercaptohexyloxy)benzoic acid (**6**), 21.1 g of 4-(5-hexenyloxy)phenol (**13**), 1.2 g of 4-*N,N*-dimethylaminopyridine, and 150 ml of dichloromethane was cooled in an ice bath with magnetic stirring. 21 g of *N,N'*-dicyclohexylcarbodiimide was added and stirring was continued for 8 hours in the ice

bath. After removing the ice bath, stirring was continued for 16 hours at room temperature. The crude product was obtained after elution of the mixture through a small silica column. 20.9 g of **14** (49%) was obtained as a white powder after crystallization from ethanol at 0°C. It was contaminated with about 10% by-product as a result of thioesterification.  $^1\text{H}$  NMR: 8.14 (d, 2 H,  $J = 8.6$ ,  $\text{H}^{\text{n}}$ ), 7.10 (d, 2 H,  $J = 8.5$ ,  $\text{H}^{\text{r}}$ ), 6.95 (d, 2 H,  $J = 8.6$ ,  $\text{H}^{\text{m}}$ ), 6.91 (d, 2 H,  $J = 8.6$ ,  $\text{H}^{\text{s}}$ ), 5.84 (m, 1 H,  $J_1 = 17.0$ ,  $J_2 = 10.2$ ,  $J_3 = 6.5$ ,  $\text{H}^{\text{d}}$ ), 5.05 (d, 1 H,  $J = 17.0$ ,  $\text{H}^{\text{a}}$ ), 4.98 (d, 1 H,  $J = 10.2$ ,  $\text{H}^{\text{b}}$ ), 4.04 (t, 2 H,  $J = 6.5$ ,  $\text{H}^{\text{k}}$ ), 3.97 (t, 2 H,  $J = 6.5$ ,  $\text{H}^{\text{l}}$ ), 2.55 (q, 2 H,  $J = 7.5$ ,  $\text{H}^{\text{f}}$ ), 2.13 (q, 2 H,  $J = 6.5$ ,  $\text{H}^{\text{f}'}$ ), 1.9–1.4 (m, 20 H,  $\text{H}^{\text{g}}$ ,  $\text{H}^{\text{h}}$ ,  $\text{H}^{\text{i}}$ ,  $\text{H}^{\text{j}}$  and  $\text{H}^{\text{j}'}$ ), 1.35 (t, 1 H,  $J = 7.5$ ,  $\text{H}^{\text{e}}$ ).  $^{13}\text{C}$  NMR: 165.3 ( $\text{C}^{\text{p}}$ ), 163.4 ( $\text{C}^{\text{l}}$ ), 156.8 ( $\text{C}^{\text{l}'}$ ), 144.4 ( $\text{C}^{\text{q}}$ ), 138.5 ( $\text{C}^{\text{d}}$ ), 132.2 ( $\text{C}^{\text{o}}$ ), 122.5 ( $\text{C}^{\text{r}}$ ), 121.8 ( $\text{C}^{\text{o}}$ ), 115.1 ( $\text{C}^{\text{s}}$ ), 114.8 ( $\text{C}^{\text{s}}$ ), 114.3 ( $\text{C}^{\text{m}}$ ), 68.1 + 68.2 ( $\text{C}^{\text{k}}$  +  $\text{C}^{\text{l}'}$ ), 34.9 ( $\text{C}^{\text{g}}$ ), 33.4 ( $\text{C}^{\text{f}'}$ ), 29.1 ( $\text{C}^{\text{h}}$ ), 28.7 ( $\text{C}^{\text{i}}$ ), 28.1 ( $\text{C}^{\text{b}}$ ), 25.5 ( $\text{C}^{\text{g}'}$ ), 25.3 ( $\text{C}^{\text{i}}$ ), 24.5 ( $\text{C}^{\text{f}}$ ).

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