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Synthesis of Novel Thermally Reversible Photochromic Axially Chiral Spirooxazines

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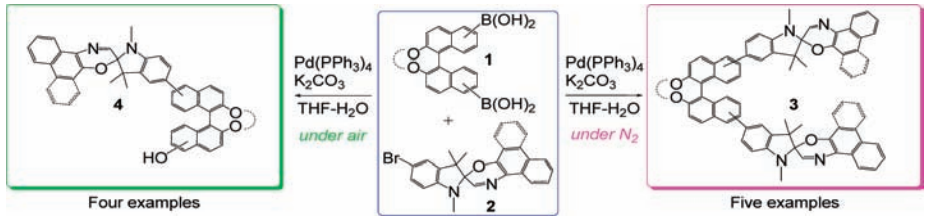
ABSTRACT



The Suzuki reactions of diboronic acid 1 and bromo-spirooxazine 2, under N_2 atmosphere and aerobic conditions, gave the dispirooxazine-substituted binaphthyl product 3 and the monospirooxazine-substituted binaphthyl derivative 4, respectively. The thermally reversible photochromic behavior of the target axially chiral spirooxazines 3 was investigated, and both the ring-opening process upon irradiation with 365 nm light and the thermally reverse ring-closing process were fast. These chiral spirooxazines were found to impart their chirality to an achiral liquid crystal host, at low doping levels, to form a self-organized photoresponsive helical superstructure.

Photochromic molecules that change color upon irradiation with UV light have attracted a great deal of interest because of their potential applications as smart light-driven molecular switches and devices. Among all the photochromic molecules, spirooxazines are a particularly interesting family due to their unique properties such as excellent photofatigue resistance, strong photocoloration, and fast thermal relaxation.[1] The colorless ring-closed spiro form of spirooxazine can be transformed into the colored ring-opened merocyanine form upon irradiation with UV light, whereas its reverse process occurs thermally in the dark or photochemically by irradiation with visible light. Since the physical and chemical properties of the two forms are dramatically different, the thermally reversible photochromic switching has been the basis for the intelligent materials with applications in three-dimensional optical memory, photochemical erasable memory, self-developing photography, actinometry, displays, filters, lenses of variable optical density, and photoswitchable sensors.[2]

It is also known that when a chiral molecule is doped in an achiral nematic liquid crystal (LC), its molecular chirality can be transferred to the nematic solvent to form a helical superstructure, i.e., chiral nematic phase, that can reflect light selectively according to Bragg's law. The ability of a chiral dopant to twist the nematic phase is defined as helical twisting power β according to the equation $\beta = (pc)^{-1}$, where p is the pitch length of the helical structure and c is the chiral dopant concentration. The isomerization of the spirooxazine upon irradiation with light can be used to control the helical

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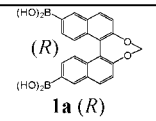
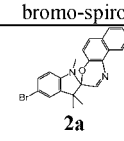
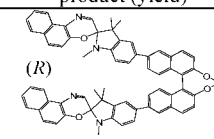
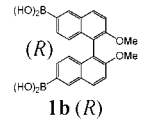
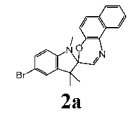
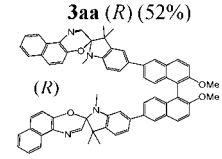
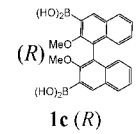
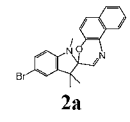
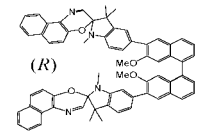
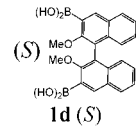
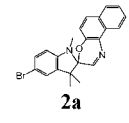
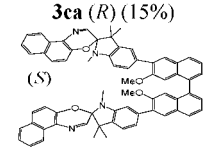
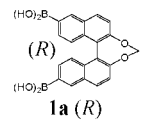
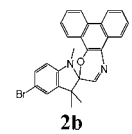
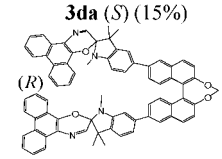
pitch and photochromic behavior, which would open the door to many applications.[3] However, to date, there have been only very few reports on chiral spirooxazines,[4] compared with numerous other chiral photoresponsive molecules such as chiral azobenzenes,[5] chiral dithienylethenes,[6] chiral spiropyrans,[7] and chiral fulgides.[8]

To tailor chiral spirooxazines with satisfactory functionalities for the device performance, e.g., high helical twisting power and fast reversible thermal relaxation, here we reported the synthesis of novel axially chiral binaphthyl-based spirooxazines **3**. The Suzuki reaction was used to construct the target compound **3**. It is established that the 2,2′-bridged binaphthyl is a more powerful chiral building block compared to the corresponding unbridged one.[9] Thus, diboronic acid precursor **1a** was used to optimize the coupling reaction conditions. First, the intermediate **1a**[10] was prepared starting from (*R*)-binol with a slightly modified procedure according to the literature with a total yield of 5%. The synthesis of bromospirooxazine precursor **2a** and **2b** was commenced with the corresponding 1-(4-bromophenyl)hydrazine in four steps with a total yield of 40−50% (see Supporting Information).[11] With the intermediates in hand, the key Suzuki coupling reaction was then investigated. First, according to a standard Suzuki reaction condition,[12] under N_2 atmosphere, the treatment of **1a** with **2a** in a mixed solvent of THF and water at 70 °C, using K_2CO_3 as a base and 10 mol % of $Pd(PPh_3)_4$ as the catalyst, gave the dispirooxazine binaphthyl product **3aa** surprisingly in only a 5% yield, whereas most starting material **1a** was recovered. When using other solvents, such as THF, toluene, toluene/H_2O, benzene/H_2O, DMF/H_2O, or dioxane/H_2O, the yield of the reaction was still very low. We also used $Pd(OAc)_2$/L where the L is the (2-biphenyl)di-*tert*-butylphosphine as the catalyst.[13] Unfortunately, no target compound **3aa** was obtained. Fortunately, when we optimized the reaction conditions in which $Pd(PPh_3)_4$ was used as the catalyst and THF/H_2O were used as the sovlents, it was found that the reaction yield was dramatically increased if a larger amount of the catalyst was used. For example, a 52% yield for **3aa** was achieved when using 30 mol % of the $Pd(PPh_3)_4$ as the catalyst (Table 1, No. 1). On the basis of the optimized reaction conditions, the other target chiral spirooxazines **3** were readily prepared. The intermediates **1b**,[14] **1c**, and **1d**[15] were synthesized starting from (*R*)- or (*S*)-binol in 40−65% yield. The reactions of the diboronic acids **1b** and **1a** with the bromo-spirooxazine precursors **2a** and **2b** went smoothly in the presence of 30 mol % of $Pd(PPh_3)_4$ to give the target chiral spirooxazines **3ba** (40%, Table 1, No. 2) and **3ab** (50%, Table 1, No. 5), respectively. The reactions of **1c** and **1d** with **2a** gave the 3,3′-dispirooxazine-substituted products **3ca** and **3da**, respectively, with the yield of 15% (Table 1, No. 3 and 4). The low yield might result from the steric hindrance.

Interestingly, under aerobic conditions, the monospirooxazine-substituted binaphthyl derivative **4** was found to be

Table 1. Synthesis of the Dispirooxazine-Substituted Binaphthyl Derivative **3**[a]

no.	boronic acid	bromo-spiro	product (yield)[b]
1	 **1a** (*R*)	 **2a**	 **3aa** (*R*) (52%)
2	 **1b** (*R*)	 **2a**	 **3ba** (*R*) (40%)
3	 **1c** (*R*)	 **2a**	 **3ca** (*R*) (15%)
4	 **1d** (*S*)	 **2a**	 **3da** (*S*) (15%)
5	 **1a** (*R*)	 **2b**	 **3ab** (*R*) (50%)

[a] Reaction conditions: 0.5 equiv of diboronic acid (**1**), 1 equiv of aryl bromide (**2**), 0.3 equiv of $Pd(PPh_3)_4$, 10 equiv of K_2CO_3, THF−water (1/1, v/v), water (1 mL/mmol K_2CO_3), 70 °C, N_2, 12 h. [b] Isolated yield.

(4) (a) Hattori, H.; Uryu, T. *J. Polym. Sci., Part A: Polym. Chem.* **2000**, *38*, 887–894. (b) Hattori, H.; Uryu, T. *Liq. Cryst.* **2001**, *28*, 25–34. (c) Hattori, H.; Uryu, T. *Liq. Cryst.* **2001**, *28*, 1099–1104.

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(10) Park, J.-W.; Ediger, M. D.; Green, M. M. *J. Am. Chem. Soc.* **2001**, *123*, 49–56.

(11) Dürr, H.; Ma, Y.; Cortellaro, G. *Synthesis* **1994**, 294–298.

(12) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457–2483.

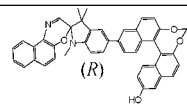
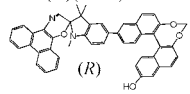
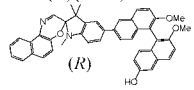
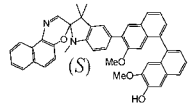
(13) Barder, T. E.; Walker, S. D.; Martinelli, J. R.; Buchwald, S. L. *J. Am. Chem. Soc.* **2005**, *127*, 4685–4696.

(14) Germaneau, R.; Chavignon, R.; Tranchier, J.-P.; Rose-Munch, F.; Rose, E.; Collot, M.; Duhayon, C. *Organometallics* **2007**, *26*, 6139–6149.

(15) Wipf, P.; Jung, J.-K. *J. Org. Chem.* **2000**, *65*, 6319–6337.

the main product. For instance, the reaction of **1a** with **2a** without the degassing process gave the compound **4aa** as the major product (39%) together with the compound **3aa** as the minor product (18%) (Table 2, No. 1). Similar results

Table 2. Synthesis of Compound **4**[a]

no.	acid **1**	spiro **2**	product **3** (yield)[b]	product **4** (yield)[b]
1	**1a**	**2a**	**3aa** (18%)	 **4aa** (*R*)(39%)
2	**1a**	**2b**	**3ab** (20%)	 **4ab** (*R*)(40%)
3	**1b**	**2a**	**3ba** (15%)	 **4ba** (*R*)(30%)
4	**1d**	**2a**	**3da** (6%)	 **4da** (*S*)(10%)

[a] Reaction conditions: 0.5 equiv of boronic acid (**1**), 1 equiv of aryl bromide (**2**), 0.3 equiv of $Pd(PPh_3)_4$, 10 equiv of K_2CO_3, THF−water (1/1, v/v), water (1 mL/mmol K_2CO_3), 70 °C, air, 12 h. [b] Isolated yield.

were obtained for the reactions of other diboronic acids with the bromo-spirooxazine (Table 2).

The formation of those spirooxazine binaphthyl derivatives **3** and **4** is straightforward. In the absence of oxygen, the reaction of the two boronic acid function groups with the bromo-spirooxazine under two consecutive Suzuki reaction processes (oxidative addition of the bromo-spirooxazine with palladium(0), transmetalation with the boronic acid, then reductive elimination of the diarylpalladium complex) gave the dispirooxazine-substituted binaphthyl derivatives **3**. On the other hand, in the presence of oxygen, the oxidation of the boronic acid to the hydroxyl (−OH) became a competitive reaction.[16] So, one of the boronic acid groups in the starting material underwent oxidation, while another boronic acid group reacted with the bromo-spirooxazine to give the monospirooxazine-substituted binaphthyl derivative **4**.

Noticeably, since all the reactions involving the binathphyl moieties were performed at a temperature below 100 °C, the loss of the enantiomeric excess of the products was negligible.[10,17] All the structures of those chiral spirooxazines are confirmed by ^1H, ^{13}C NMR, HR-MS, UV−vis, circular dichroism (CD), as well as elementary analysis (see Supporting Information).

All the axially chiral spirooxazines exhibited the expected thermally reversible photochromic behavior in both organic solvent and LC host. Both the ring-opening and the ring-closing processes are fast (less than 1 min), especially in the high polar solvents such as THF, DCM, MeOH, and acetonitrile at room temperature. The transmittance spectrometry was used to get the kinetics of the thermal relaxation.[4,18] For example, the transmittance changes of a solution of **3aa** in *n*-heptane were measured after reaching the photostationary state (PSS) by irradiation with 365 nm light (Figure 1a). As seen in the figure, the intensity of the

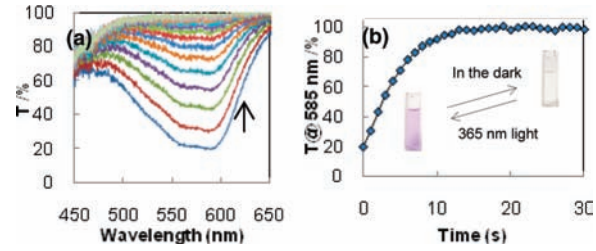


Figure 1. (a) Transmittance spectra changes of **3aa** at 25 °C in *n*-heptane (6×10^{-5} M) followed by 365 nm irradiation for 30 s to reach the PSS state in the dark (purple). The arrow indicates the spectra changing tendency, and the spectra were recorded every 1 s. (b) Thermal relaxation monitored at 585 nm (λ_{max} for the MC form in *n*-heptane) versus time. It takes about 15 s to thermally relax back to the initial state (colorless).

peak around 585 nm [λ_{max} for the merocyanine (MC) form] was gradually decreasing by the observation of gradual increase of the transmittance due to the color-bleaching. By using these data, the thermal relaxation at 585 nm versus time is reproduced in Figure 1b. As seen in Figure 1b, the thermal relaxation process of **3aa** in *n*-heptane is fast. It takes less than 20 s to be thermally back to the initial state. After the transmittance was transferred into the absorbance by using the equation $A = -\ln(T)$, where A is the absorbance and T is the transmittance, the resultant smooth curve is well fitted by the monoexponential equation ($A = B\exp(-kt) + C$) with a rate constant of 0.24 s^{-1} (see Supporting Information). Representative thermal relaxation rate constants of the spirooxazine-substituted binaphthyl compounds and the starting bromo-spirooxazines measured in *n*-heptane and dichloromethane are summarized in the Table 3. As seen in Table 3, the thermal back reaction of spirooxazines upon irradiation with UV light is greatly dependent on the medium polarity. For example, the thermal back time of **3aa** in CH_2Cl_2 is 2 s, whereas it is 15 s in *n*-heptane. Also, it clearly shows that the steric and electronic effects dramatically influence the rates of the ring-closing reaction. The steric repulsion

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Table 3. Thermal Relaxation Rate Constants and Time for the Spirooxazines (25 °C)

	k^a/s^{-1}		time^b/s	
compd	in *n*-heptane	in CH_2Cl_2	in *n*-heptane	in CH_2Cl_2
2a	0.20	0.87	27	5
2b	0.04	0.18	96	22
3aa	0.24	2.11	15	2
3ab	0.05	0.39	76	6
3ba	0.27	1.74	10	3
3ca	0.42	1.69	11	3

[a] The data were obtained by transmittance spectra measurement fitting by using the monoexponential equation [$A = B \exp(-kt) + C$]. [b] The thermally back to the initial state in the dark after reaching the PSS by the irradiation with 365 nm light.

Table 4. Helical Twisting Powers (β) of the Chiral Spirooxazines as Dopants in E7 for the Initial State and the Photostationary State (PSS) upon Irradiation with 365 nm Light and the Stationary State (SS) after Thermal Relaxation[a]

	β_M (μm^{-1})		
dopant	initial state	$PSS_{365\ nm}$	$SS_{thermal\ relaxation}$
3aa	87	94	87
3ab	64	84	64
3ba	60	48	60
3ca	47	41	47

[a] $\beta = 1/(p \cdot c \cdot ee)$, where p is the pitch of the cholecteric phase, c is the molar fraction of the dopant in E7, and ee is the enantionmeric excess. Here the ee is considered as 1.

favoring formation of the spiropyran form has been reported.[19] Electronic effects are usually interpreted in terms of their influence upon the extent of charge separation in the MC form.[20] The spirophenanthoxazines with three fused benzene rings are expected to be more efficient to stabilize the MC form, compared to those spironaphthoxazines which only have two fused benzene rings. Thus, in these environments, spirophenanthoxazine **3ab** caused rate constant (k) to decrease about 5-fold, compared to the compound **3aa**.

As expected, doping the chiral spirooxazine **3** in an achiral LC host can induce the chiral nematic (N*) phase with a characteristic oily streak texture (see Supporting Information). Their helical twisting powers (β) were measured in a wedge cell by pitch determination. Some typical results are given in the Table 4. The bridged chiral spirooxazines exhibited higher helical twisting power than the corresponding unbridged ones. Interestingly, as for compounds **3aa** and **3ab**, which possess two spirooxazine units in the bridged binaphthyl moiety, the helical twisting power became larger upon the irradiation with UV light (365 nm), while for other chiral spirooxazines, the helical twisting power became smaller under the same condition. This is probably because of the more rodlike structure in the MC form for the compounds **3aa** and **3ab**, compared to that for others. The fact that the dihedral angle between the two naphthalene moieties of the bridged compound is smaller than that in the corresponding unbridged compounds might be one of the reasons for the formation of the more rodlike structure in the MC form. It is worth mentioning that, among those chiral dispirooxazines, the bridged binaphthylene derivative **3aa** exhibited the largest helical twisting power in E7.

In conclusion, a series of spirooxazines containing an axially chiral binaphthalene moiety, for the first of their kind, were synthesized and characterized. The Suzuki coupling reactions under N_2 atmosphere and aerobic conditions gave the dispirooxazine-substituted binaphthyl product and the monospirooxazine-substituted binaphthyl derivative, respectively. Both the ring-opening process upon irradiation with UV light and the thermally reversible ring-closing process were fast. The thermal relaxation rate is strongly influenced by the medium polarity as well as the structure of the spirooxazine. Furthermore, these axially chiral spirooxazines were found to impart their chirality to an achiral LC host, at low doping levels, to form a self-organized optically tunable helical superstructure. This bifunctional system is promising for future application because the system exhibits excellent thermally reversible photochromic behavior and chiral induction capability in liquid crystal hosts.

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Supporting Information Available: Details of the synthesis, characterization data, copies of ^1H and ^{13}C NMR spectra, measurement of the thermal relaxation rate, and measurement of HTP. This material is available free of charge via the Internet at http://pubs.acs.org.

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