Tetrahedron 69 (2013) 129–136

Contents lists available at SciVerse ScienceDirect

Tetrahedron

journal homepage: www.elsevier.com/locate/tet

Synthesis of benzo[*g*]chrysenes

Meng-Yang Chang *, Ming-Hao Wu

Department of Medicinal and Applied Chemistry, Kaohsiung Medical University, No. 100, Shih-Chuan 1st Road, Kaohsiung 807, Taiwan

ARTICLE INFO

Article history:
Received 22 August 2012
Received in revised form 11 October 2012
Accepted 18 October 2012
Available online 25 October 2012

Keywords:
Benzo[*g*]chrysenes
Claisen rearrangement
Grignard addition
Cyclodehydration
Photolytic Scholl oxidative annulation

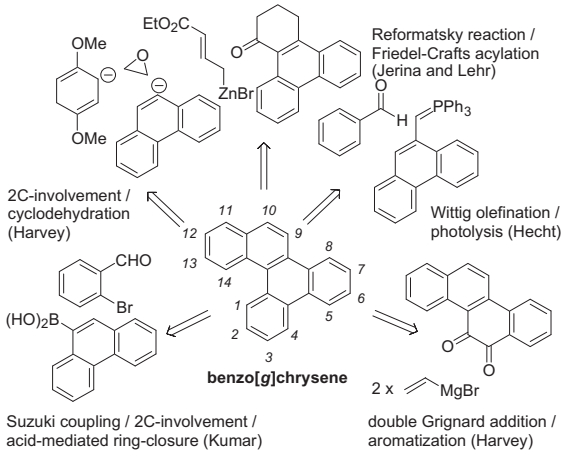
ABSTRACT

A facile synthetic route toward diversified benzo[*g*]chrysenes **2** starting with commercially available isovanillin (**1a**) or 3-hydroxybenzaldehyde (**1b**) in modest total yields is described via the transformations of Claisen rearrangement of **3**, Grignard addition of **4**, DBU-promoted cyclodehydration of **5**, and photolytic Scholl oxidative annulation of **6**. Skeleton **3** is prepared via O-allylation of **1** with *trans*-cinnamyl bromide.

1. Introduction

The skeleton of benzo[*g*]chrysene (BgC) consists of one pentacyclic aromatic hydrocarbon (PAH).[1,2] It is produced by the combustion of fossil fuels and organic materials, and has been employed as a substrate in investigations of the mechanisms underlying the carcinogenicity of PAHs.[3] Despite the importance of BgC as a cancer carcinogen, it is not readily yielded through synthesis. Common synthetic routes for making the skeleton of BgC include the double Grignard addition and aromatization (Harvey),[4] Wittig olefination and photolysis (Hecht),[5] Reformatsky reaction and Friedel–Crafts acylation (Lehr),[6] Suzuki cross-coupling reaction and acid-mediated ring-closure (Kumar),[7] and other approaches,[8] as shown in Scheme 1.

Since palladium complex mediated Suzuki–Miyaura cross-coupling of an organoboron compound with a broad range of polyhalogenated substituents is useful for stereospecific carbon–carbon bond formation, most of the related literature on synthetic PAHs is focused on cross-coupling annulation. There have been extensive studies on the process for preparing functionalized PAHs, such as dibenzochrysenes,[9] benzo[*a*]pyrenes,[10] and other structures.[11] However, as yet, there have been very few efficient syntheses of BgC skeletons bearing appropriate functional groups of different position. In continuation of our investigation with the application of **1a** and **1b**,[12] a novel synthetic sequence of A→D→E→B→C approach (from one benzene ring to five fused benzene rings) is employed to construct **2** with 12,13-dimethoxy groups, via a series of simple and efficient functional group transformations of Claisen rearrangement, Grignard addition, base-promoted cyclodehydration and photolytic Scholl annulation (Scheme 2).



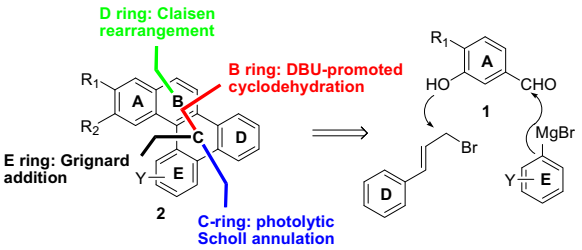
Scheme 1. Synthetic routes of benzo[*g*]chrysene (BgC).

2. Results and discussion

The starting materials, compounds **4a**–**e**, with the 2-cinnamyl group, were acquired from commercially available isovanillin (**1a**) and 3-hydroxybenzaldehyde (**1b**) with an *A-ring* motif, in moderate

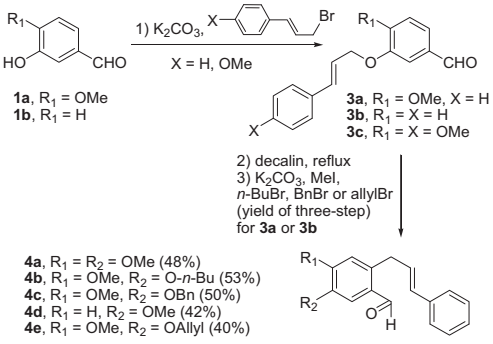
* Corresponding author. Tel.: +886 7 3121101x2220; fax: +886 7 3125339; e-mail addresses: mychang@kmu.edu.tw, mychang624@yahoo.com.tw (M.-Y. Chang).

0040-4020/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.tet.2012.10.054



Scheme 2. Retrosynthetic route of **2** from **1a**,**b**.

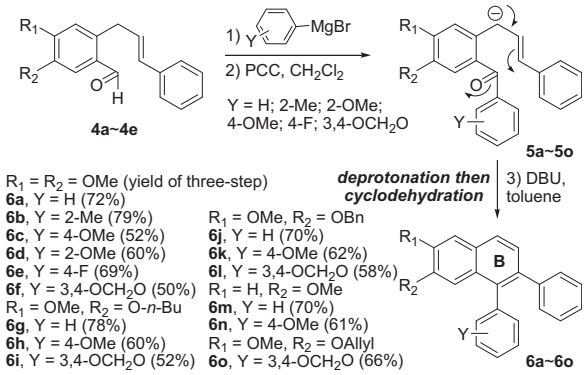
overall three-step yields according to the reported procedures in the standard sequence of O-allylation, Claisen rearrangement and O-alkylation as shown in Scheme 3.[12]



Scheme 3. Three-step synthesis of **4**.

O-Allylation of two phenols, **1a** or **1b**, with *trans*-cinnamyl bromide (*D ring*, X=H, OMe) afforded ether product **3a**, **3b** or **3c** in the presence of K_2CO_3 in THF at reflux for 8 h. To change the reaction solvent from THF to acetone, the allylation reaction of **1a** or **1b** provided a similar yield of cinnamyl ether product. However, chalcone was isolated as the major product during the aldol condensation of **1b**. Under the general double Claisen rearrangement condition (in refluxing decalin, 8 h) and O-alkylation condition (in refluxing THF, 8 h), **4a**–**e** were provided as the sole isomers from **1a**,**b**, with the acceptable yields of three-steps via O-allylation, Claisen rearrangement, and O-alkylation. Furthermore, Wittig olefination of **4a** with $Ph_3P{=}CHCO_2Et$ produced (*E*,*E*)-isomer **4f**. The structure of **4f** was determined by single-crystal X-ray crystallography. The stereochemistry of **4a**–**e** could also be demonstrated to be the *E*-configuration.[13] By controlling the heating time of cinnamyl ether, a product with one rearrangement and its double-rearranged isomer were isolated in different ratios under the abovementioned boiling conditions. Unfortunately, attempts at successfully completing the Claisen rearrangement of **3c** were unsuccessful. Furthermore, **6** was provided in moderate yields from three-steps of the Grignard methylation of **4a**–**e** with six arylmagnesium bromides (*E-ring*, Y=H; 2-Me; 2-OMe; 4-OMe; 4-F; 3,4-OCH_2O) and oxidation of the resulting alcohols with PCC, followed by DBU-promoted intramolecular cyclodehydration of **5** (see Scheme 4).

In the isolation of pure **5c**,**d**, **5f**, **5h**,**i**, **5k**,**l** and **5n**,**o** (Y=electron-donating oxygenated group), we found that some unknown by-products were slowly generated during the purification procedure. Because **5c**,**d**, **5f**, **5h**,**i**, **5k**,**5l**, and **5n**,**o** could not be separated as pure products by column chromatography; crude **5** was further reacted with DBU to construct the *B-ring* of **6** in toluene at reflux for 1 h. According to the literature method,[14] the useful transformation from benzoyl benzene **5** to naphthalene **6** required simultaneous high-pressure irradiation (400 W mercury lamp) in *t*-BuOK-promoted cyclodehydration. In our case, the



Scheme 4. Three-step synthesis of **6** (B-ring).

cyclodehydration reaction of skeleton **5** with DBU produced a better homogeneous reaction reactivity and experimental operation than the reported protocol in the synthesis of skeleton **6**. How is the cyclodehydration reaction of skeleton **5** produced? Skeleton **6** with a 1,2-diaryl group should first be generated as a conjugated carbanion from the deprotonation of the resulting **5** with benzoyl and the 2-cinnamyl group. After the subsequent intramolecular ring-closure and dehydration, the carbon framework of naphthalene is produced. By monitoring the reaction with TLC, brilliant blue colored naphthalene **6** with 1,2-diaryl group was easily observed in TLC plates after short wavelength UV irradiation. The three-step synthetic process for the formation of the naphthalene skeleton can be monitored by TLC until the reaction is completed. The formation of the cycloadduct **6** was confirmed through spectral analysis. For example, the ^1H NMR spectrum of **6a** exhibited two singlets at δ 7.25 and 7.01 for the protons of the A ring. The protons of the B ring appeared as two doublets at δ 7.79 and 7.47 (d, J=8.4 Hz). The structure of **6a** was confirmed by HRMS, which showed a peak at m/z 341.1550 [M^++1]. Furthermore, the skeleton of **6a** was determined by single-crystal X-ray crystallography.[13] Structure **6a** was shown in Fig. 1. Next, Scholl oxidation of **6** was further studied for contracting the *C-ring* of **2**. Scholl oxidation generates a new carbon–carbon bond between two functionalized aryl vertices.[9i,15,16]

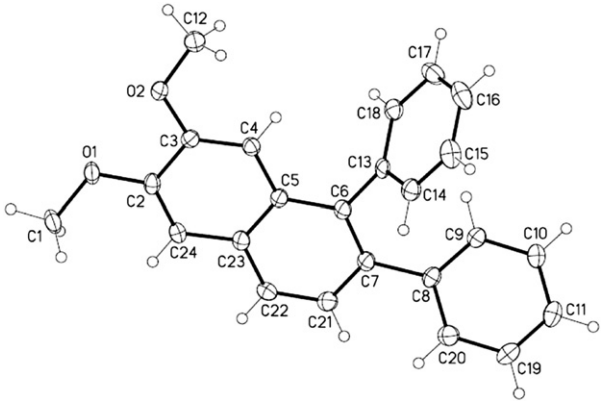
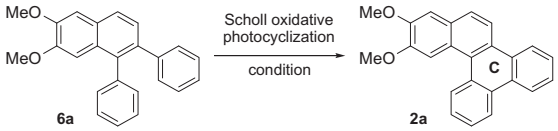


Fig. 1. X-ray structure of **6a**.

A number of processes are available for the Scholl reaction of *o*-terphenyl. The following combination of Lewis acid (or oxidant) and reaction solvent has been reported in the literature: $FeCl_3$ in CH_2Cl_2,[16a] $MoCl_5$ in CH_2Cl_2,[16b] $CuCl_2/AlCl_3$ in CS_2,[16c] $Tl(O_2CCF_3)_3$ in CF_3CO_2H,[16d] $PhI(O_2CCF_3)/BF_3{\cdot}OEt_2$ in CH_2Cl_2,[16e] MsOH/DDQ in CH_2Cl_2,[9i] and I_2/photolysis in benzene.[16f] These concise methodologies might result in high yields and present trace impurities or

byproducts. Of these methods, the photolytic Scholl oxidative annulation provides a more convenient operation and higher yields, as shown in Table 1. After screening seven Scholl conditions, we found that a metal-mediated coupling reaction of model substrate **6a** provided a lower yield (entries 1–3). Adjusting the DDQ as the oxidant, the isolated yields were not noticeably enhanced (entry 4), and **6a** was recovered in 48% yield.

Table 1
Synthesis of **2a** (C-ring)

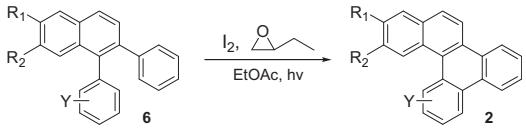


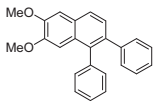
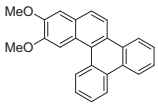
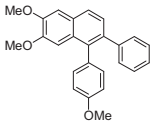
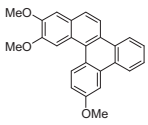
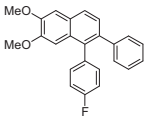
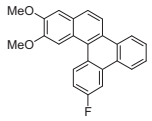
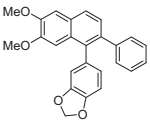
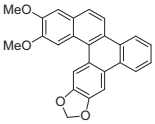
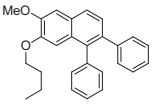
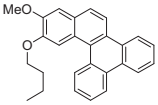
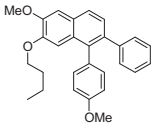
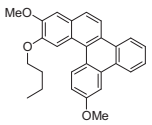
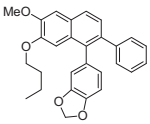
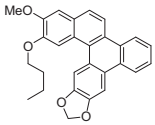
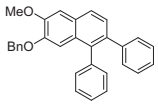
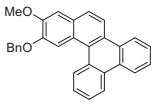
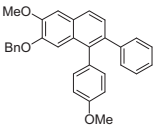
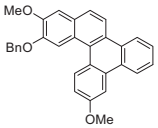
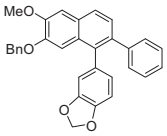
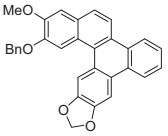
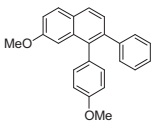
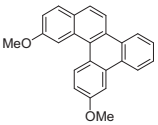
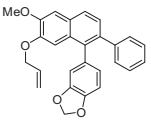
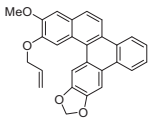
Entry	Reagents (equiv), solvent (mL), time (h)	Yield[a,b]
1	$FeCl_3$ (2), CH_2Cl_2 (10), 1	21%
2	$MoCl_5$ (2), CH_2Cl_2 (10), 1	27%
3	$CuCl_2$ (2), CH_2Cl_2 (10), 1	38%
4	MsOH (2), DDQ (2), CH_2Cl_2 (10), 1	48%
5	I_2 (1), benzene (15), 40	59%[c]
6	I_2 (1), EtOAc (15), 40	60%[c]
7	I_2 (1), 1,2-epoxybutane (10), EtOAc (15), 40	71%[c]
8	I_2 (2), 1,2-epoxybutane (30), EtOAc (15), 80	80%[c]

[a] The reactions were run on a 0.2 mmol scale with **6a** at rt.
[b] The product **2a** was >95% pure as determined by ^{1}H NMR analysis.
[c] The photolytic reaction was irradiated with 2540 Å.

When photolytic irradiation (2540 Å) was employed to the Scholl condition in benzene, the afforded yield of **2a** was improved to 59%, and **6a** was recovered in 30% yield (entry 5). When the 10 equiv of 1,2-epoxybutane was added, and the solvent was changed from benzene to EtOAc, **2a** was obtained in 71% yield and 10% of **6a** was recovered. When the equivalent of the reagent was increased and the reaction time extended, the acceptable 80% yield of **2a** was produced, and **6a** was isolated in nearly 6% yield. From the above results, we believe that the optimal reaction condition of photolytic Scholl oxidative annulation of **6** for preparing **2** should be iodine (2.0 equiv) and 1,2-epoxybutane (30.0 equiv) in EtOAc (15 mL) at rt for 80 h. Furthermore, twelve **2a**, **2c**, **2e**–**l**, and **2n**,**o** were obtained as a single isomer with the 20–80% yield via the above experimental condition (see Table 2). However, **6b** with the

Table 2
Photolytic Scholl annulation of **2**



Entry	Reactants **6**	Products **2**/yield[a–c] (%)
1	 **6a**	 **2a** / 80
2	 **6c**	 **2c** / 62
3	 **6e**	 **2e** / 40
4	 **6f**	 **2f** / 66
5	 **6g**	 **2g** / 75
6	 **6h**	 **2h** / 58
7	 **6i**	 **2i** / 55
8	 **6j**	 **2j** / 70
9	 **6k**	 **2k** / 62
10	 **6l**	 **2l** / 59
11	 **6n**	 **2n** / 20
12	 **6o**	 **2o** / 60

[a] For the best one-pot reaction conditions: the reactions were run on a 0.2 mmol scale with skeleton **6** at rt.
[b] The skeleton **2** were >95% pure as determined by ^{1}H NMR analysis.
[c] The photolytic reaction was irradiated with 2540 Å.

2-methoxy group (Y=OMe), or **6d** with the methyl group (Y=Me), could not be converted to **2b** or **2d** under photolytic annulation due to the steric hindrance of the Y group on the 2-position of the E ring. Only the starting material, **6b** or **6d**, was recovered. From the distribution of product yields, we found that the yield of **2e** with electron-withdrawing groups (Y=F) had a 40% yield. **6e** was recovered with a 39% yield. For the formed yield of **2c**, **2f**, **2h**,**i**, **2k**,**l** or **2o** with different electron-donating oxygenated groups, the better yield was produced by **2f**. When no substituent was at the E ring

(Y=H), **2a**, **2g** or **2j** provided the best yield under the photolytic Scholl oxidative annulation conditions. However, when R_1 was hydrogen, **6m** was recovered, and no **2m** was isolated. Only 20% yield of **2n** was obtained under the reaction condition. We believe that the methoxy group on the C-12 position affected the Scholl reaction. The structures of **2f**, **2i**, and **2k** were determined using single-crystal X-ray analysis.[13] Structures **2f**, **2i**, and **2k** were shown in Figs. 2–4.

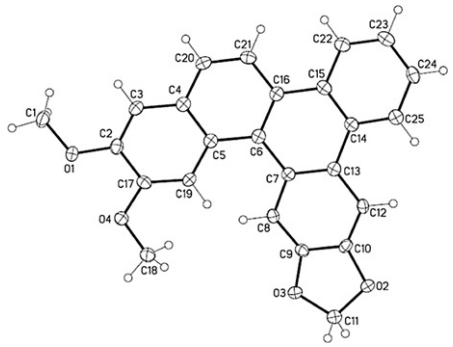


Fig. 2. X-ray structure of **2f**.

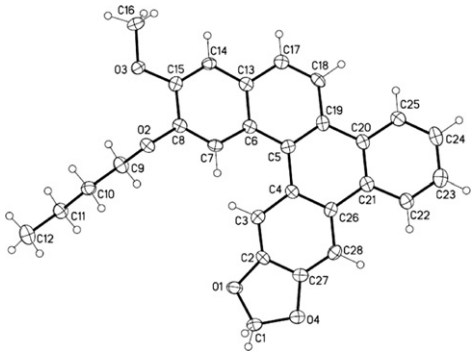


Fig. 3. X-ray structure of **2i**.

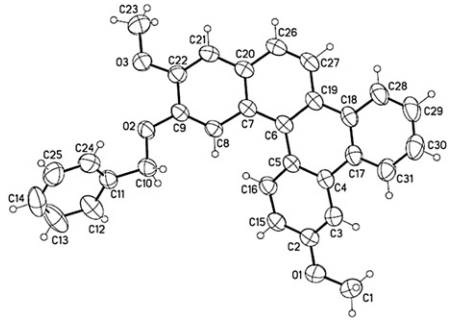


Fig. 4. X-ray structure of **2k**.

3. Conclusion

In summary, we have successfully presented a novel synthetic A→D→E→B→C ring formation through a sequence approach for the preparation of substituted benzo[*g*]chrysenes **2** via a series of simple and efficient functional group transformations of Claisen rearrangement, Grignard addition, base-promoted cyclodehydration, and photolytic Scholl annulation. This synthesis begins with simple starting materials and reagents, and provides a potential methodology for chemical biology research.

4. Experimental section

4.1. General

THF was distilled prior to use. All other reagents and solvents were obtained from commercial sources and used without further purification. Reactions were routinely carried out under an atmosphere of dry nitrogen with magnetic stirring. Products in organic solvents were dried with anhydrous magnesium sulfate before concentration in vacuo. Melting points were determined with a SMP3 melting apparatus. ^{1}H and ^{13}C NMR spectra were recorded on a Varian INOVA-400 spectrometer operating at 400 and at 100 MHz, respectively. Chemical shifts (δ) are reported in parts per million (ppm) and the coupling constants (J) are given in Hertz. High resolution mass spectra (HRMS) were measured with a mass spectrometer Finnigan/Thermo Quest MAT 95XL. X-ray crystal structures were obtained with an Enraf-Nonius FR-590 diffractometer (CAD4, Kappa CCD). Elemental analyses were carried out with Heraeus Vario III-NCSH, Heraeus CHN–OS-Rapid Analyzer or Elementar Vario EL III.

4.2. A representative synthetic procedure of skeleton 4 is as follows

K_2CO_3 (2.7 g, 20.0 mmol) was added to a stirred solution of isovanillin (**1a**, 1.52 g, 10.0 mmol) or 3-hydroxybenzaldehyde (**1b**, 1.22 g, 10.0 mmol) in THF (100 mL) at rt. The reaction mixture was stirred at rt for 10 min. *trans*-Cinnamyl bromide (2.4 g, 12.0 mmol) was added to the reaction mixture at rt. The reaction mixture was stirred at reflux for 8 h. The reaction was traced by TLC until **1a** or **1b** was consumed. The reaction mixture was cooled to rt, concentrated, and extracted with EtOAc (3×60 mL). The combined organic layers were washed with brine, dried, filtered, and evaporated to afford crude product under reduced pressure. Without further purification, decalin (8 mL) was added to a solution of skeleton **3**. The reaction mixture was stirred at reflux for 8 h. The reaction was traced by TLC until the resulting product was consumed. The reaction mixture was cooled to rt. Decalin was evaporated to afford crude product under reduced pressure. Without further purification, K_2CO_3 (550 mg, 4.0 mmol) was added to a solution of the resulting product in THF (100 mL) at rt. The reaction mixture was stirred at rt for 10 min. Methyl iodide (300 mg, 2.1 mmol), *n*-butyl bromide (290 mg, 2.1 mmol) or benzyl bromide (362 mg, 2.1 mmol) was added to the reaction mixture at rt. The reaction mixture was stirred at reflux for 8 h (the reaction was traced by TLC). The reaction mixture was cooled to rt, concentrated, and extracted with EtOAc (3×60 mL). The combined organic layers were washed with brine, dried, filtered, and evaporated to afford crude product under reduced pressure. Purification on silica gel (hexanes/EtOAc=8/1–4/1) afforded **4a**–**e**.

*4.2.1. 4,5-Dimethoxy-2-(3-phenylallyl)benzaldehyde (**4a**).* Compound **4a** is a known compound and the analytical data are consistent with those in the Ref. 12b,c.

*4.2.2. 5-Butoxy-4-methoxy-2-(3-phenylallyl)benzaldehyde (**4b**).* Yield=53% (1.72 g); colorless oil; HRMS (ESI, M^++1) calcd for $C_{21}H_{25}O_3$ 325.1804, found 325.1811; ^{1}H NMR (400 MHz, $CDCl_3$): δ 10.20 (s, 1H), 7.39 (s, 1H), 7.32–7.24 (m, 4H), 7.20–7.16 (m, 1H), 6.75 (s, 1H), 6.14–6.31 (m, 2H), 4.06 (t, J=6.4 Hz, 2H), 3.92 (s, 3H), 3.89 (d, J=4.8 Hz, 2H), 1.87–1.80 (m, 2H), 1.54–1.45 (m, 2H), 0.97 (t, J=7.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 189.98, 154.25, 147.41, 137.39, 137.01, 131.33, 128.88, 128.45 (2×), 127.25, 126.77, 126.07 (2×), 113.15, 112.73, 68.75, 56.06, 34.84, 31.03, 19.11, 13.78.

*4.2.3. 5-Benzyloxy-2-(3-phenylallyl)-4-methoxybenzaldehyde (**4c**).* Yield=50% (1.79 g); mp=103–105 °C (recrystallized from

hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{24}H_{23}O_3$ 359.1647, found 359.1450; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.48–7.45 (m, 1H), 7.46 (s, 1H), 7.40–7.20 (m, 10H), 6.79 (s, 1H), 6.39–6.36 (m, 2H), 5.19 (s, 2H), 3.95 (s, 3H), 3.92–3.90 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 189.97, 154.52, 147.02, 137.98, 137.05, 137.05, 136.46, 131.46, 128.80, 128.61 (2×), 128.52, 128.08, 127.52, 127.33 (2×), 126.14, 114.05, 113.36, 114.05, 113.36, 71.00, 56.15, 34.98.

*4.2.4. 5-Methoxy-2-(3-phenylallyl)benzaldehyde (**4d**).* Yield=42% (1.06 g); colorless oil; ^{1}H NMR (200 MHz, $CDCl_3$): δ 10.29 (s, 1H), 7.47 (s, 1H), 7.46–7.13 (m, 7H), 6.37–6.34 (m, 2H), 3.87 (s, 3H), 3.84 (d, J=4.8 Hz, 2H).

*4.2.5. 5-Allyloxy-4-methoxy-2-(3-phenylallyl)benzaldehyde (**4e**).* Yield=40% (1.23 g); colorless oil; HRMS (ESI, M^++1) calcd for $C_{20}H_{21}O_3$ 309.1491, found 309.1496; ^{1}H NMR (400 MHz, $CDCl_3$): δ 10.21 (s, 1H), 7.41 (s, 1H), 7.33–7.26 (m, 4H), 7.22–7.18 (m, 1H), 6.78 (s, 1H), 6.43–6.33 (m, 2H), 6.14–6.05 (m, 1H), 5.44 (dq, J=1.6, 17.2 Hz, 1H), 5.32 (dq, J=1.6, 10.8 Hz, 1H), 4.66 (dd, J=1.6, 5.2 Hz, 2H), 3.95 (s, 3H), 3.91 (d, J=4.4 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 189.95, 154.30, 146.82, 137.81, 137.04, 132.66, 131.46, 128.82, 128.52 (2×), 127.33, 126.78, 126.13 (2×), 118.53, 113.42, 113.23, 69.84, 56.12, 34.94.

*4.2.6. 3-[4,5-Dimethoxy-2-(3-phenylallyl)phenyl]acrylic acid ethyl ester (**4f**).* Ph_3P=$CHCO_2Et$ (420 mg, 1.2 mmol) was added to **4a** (280 mg, 1.0 mmol) in CH_2Cl_2 (10 mL) at rt. The reaction mixture was stirred at reflux for 1 h. The solvent was concentrated under reduced pressure. The residue was extracted with EtOAc (3×30 mL). The combined organic layers were washed with brine, dried, filtered, and evaporated to afford crude product under reduced pressure. Purification on silica gel (hexanes/EtOAc=6/1–4/1) afforded **4f** (331 mg, 94%) as a colorless solid. Mp=116–117 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{22}H_{25}O_4$ 353.1753, found 353.1759; ^{1}H NMR (400 MHz): δ 7.99 (d, J=15.6 Hz, 1H), 7.34–7.27 (m, 4H), 7.21–7.18 (m, 1H), 7.10 (s, 1H), 6.74 (s, 1H), 6.34–6.26 (m, 3H), 4.25 (q, J=7.2 Hz, 2H), 3.91 (s, 3H), 3.90 (s, 3H), 3.65 (d, J=5.2 Hz, 2H), 1.33 (t, J=7.2 Hz, 3H); ^{13}C NMR (100 MHz): δ 167.18, 150.94, 147.82, 141.55, 137.26, 133.34, 131.25, 128.69, 128.47 (2×), 127.19, 126.15 (2×), 125.38, 117.15, 112.83, 108.82, 60.37, 55.94 (2×), 36.13, 14.33. Single-crystal X-ray diagram: crystal of compound **4f** was grown by slow diffusion of EtOAc into a solution of compound **4f** in CH_2Cl_2 to yield colorless prism. The compound crystallizes in the triclinic crystal system, space group P–1, a=8.8858 (6) Å, b=10.6870 (7) Å, c=11.4669 (7) Å, V=919.34 (10) Å^3, Z=2, D_{calcd}=1.273 g/cm^3, F(000)=376, 2θ range 2.08–26.43°, R indices (all data) R1=0.0511, wR2=0.1451.

4.3. A representative synthetic procedure of skeleton 6 is as follows

A solution of different Grignard reagent (1.0 M in THF, 1.5 mL, 1.5 mmol) was added to a stirred solution of the skeleton **4** (1.0 mmol) in THF (10 mL) at ice bath. The reaction mixture was stirred at rt for 5 h. Water (5 mL) was added to the reaction mixture and the mixture was filtered through a short plug of Celite. The filtrate was concentrated under reduced pressure. The residue was extracted with EtOAc (3×50 mL). The combined organic layers were washed with brine, dried, filtered, and evaporated to afford different crude product under reduced pressure. Without further purification, a solution of the resulting secondary alcohol in CH_2Cl_2 (10 mL) was added to a mixture of pyridinium chlorochromate (430 mg, 2.0 mmol) and Celite (500 mg) in CH_2Cl_2 (20 mL). After being stirred at rt for 3 h, the mixture was filtered through a short silica gel column. The filtrate was dried, filtered, and evaporated to yield crude compound. Without further purification, DBU (300 mg, 2.0 mmol) was added to a stirred solution of the resulting skeleton **5** in toluene (5 mL) at rt. The reaction mixture was stirred at reflux for 1 h. The reaction mixture was cooled to rt, concentrated, and extracted with EtOAc (3×30 mL). The combined organic layers were washed with brine, dried, filtered, and evaporated to afford crude products under reduced pressure. Purification on silica gel (hexanes/EtOAc=10/1–6/1) afforded skeleton **6**.

*4.3.1. 6,7-Dimethoxy-1,2-diphenylnaphthalene (**6a**).* Yield=72% (245 mg); mp=182–183 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{24}H_{21}O_2$ 341.1542, found 341.1550; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.79 (d, J=8.4 Hz, 1H), 7.47 (d, J=8.4 Hz, 1H), 7.35–7.13 (m, 11H), 7.01 (s, 1H), 4.05 (s, 3H), 3.76 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.46, 149.24, 142.21, 139.35, 136.80, 136.29, 131.21 (2×), 130.05 (2×), 128.67 (2×), 128.21 (2×), 127.83 (2×), 127.44 (2×), 126.64, 125.87, 106.20, 105.62, 55.82, 55.50. Single-crystal X-ray diagram: crystal of compound **6a** was grown by slow diffusion of EtOAc into a solution of compound **6a** in CH_2Cl_2 to yield colorless prisms. The compound crystallizes in the monoclinic crystal system, space group P 1 21/c 1, a=6.9648 (13) Å, b=27.326 (5) Å, c=9.7577 (17) Å, V=1782.8 (6) Å^3, Z=4, D_{calcd}=1.268 g/cm^3, F(000)=720, 2θ range 1.49–26.89°, R indices (all data) R1=0.0723, wR2=0.1350.

*4.3.2. 6,7-Dimethoxy-2-phenyl-1-o-tolylnaphthalene (**6b**).* Yield=79% (280 mg); mp=146–148 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{25}H_{23}O_2$ 355.1698, found 355.1703; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.79 (d, J=8.4 Hz, 1H), 7.47 (d, J=8.4 Hz, 1H), 7.24–7.13 (m, 10H), 6.71 (s, 1H), 4.04 (s, 3H), 3.71 (s, 3H), 1.91 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.58, 149.27, 142.10, 138.71, 136.92, 136.66, 135.58, 131.43, 129.73, 129.59 (2×), 128.55, 128.25, 128.11, 127.43 (2×), 127.22, 126.61, 126.04, 125.89, 125.27, 106.28, 105.34, 55.84, 55.53.

*4.3.3. 6,7-Dimethoxy-1-(4-methoxyphenyl)-2-phenylnaphthalene (**6c**).* Yield=52% (192 mg); colorless gum; HRMS (ESI, M^++1) calcd for $C_{25}H_{23}O_3$ 371.1647, found 371.1655; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.75 (d, J=8.4 Hz, 1H), 7.43 (d, J=8.4 Hz, 1H), 7.21–7.10 (m, 8H), 7.02 (s, 1H), 6.86–6.83 (m, 2H), 4.04 (s, 3H), 3.82 (s, 3H), 3.76 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.21, 149.45, 149.26, 142.45, 137.04, 135.98, 133.70, 132.30 (2×), 131.56, 130.17, 130.11 (2×), 127.55 (2×), 126.74, 125.83, 125.73, 113.34 (2×), 106.24, 105.71, 55.88, 55.62, 55.12; Anal. Calcd for $C_{25}H_{22}O_3$: C, 81.06; H, 5.99. Found: C, 81.45; H, 6.30.

*4.3.4. 6,7-Dimethoxy-1-(2-methoxyphenyl)-2-phenylnaphthalene (**6d**).* Yield=60% (222 mg); colorless gum; HRMS (ESI, M^++1) calcd for $C_{25}H_{23}O_3$ 371.1647, found 371.1651; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.77 (d, J=8.0 Hz, 1H), 7.45 (d, J=8.4 Hz, 1H), 7.30–7.25 (m, 2H), 7.19 (s, 1H), 7.18–7.11 (m, 4H), 7.08 (dd, J=1.6, 7.6 Hz, 1H), 6.91 (dt, J=1.2, 7.6 Hz, 1H), 6.86 (s, 1H), 6.85 (d, J=7.6 Hz, 1H), 4.03 (s, 3H), 3.73 (s, 3H), 3.52 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 157.44, 149.48, 149.23, 142.62, 137.52, 133.75, 132.60, 132.60, 130.20, 129.44 (2×), 128.70, 128.49, 127.27 (2×), 126.43, 125.98, 125.95, 120.31, 110.73, 106.33, 105.53, 55.87, 55.56, 55.23; Anal. Calcd for $C_{25}H_{22}O_3$: C, 81.06; H, 5.99. Found: C, 81.25; H, 6.32.

*4.3.5. 1-(4-Fluorophenyl)-6,7-dimethoxy-2-phenylnaphthalene (**6e**).* Yield=69% (246 mg); mp=66–68 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{24}H_{20}FO_2$ 359.1447, found 359.1452; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.78 (d, J=8.4 Hz, 1H), 7.44 (d, J=8.4 Hz, 1H), 7.22–7.11 (m, 8H), 7.04–6.99 (m, 2H), 6.93 (s, 1H), 4.04 (s, 3H), 3.77 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 161.65 (d, J=244.1 Hz), 149.63, 149.33, 142.05, 137.13, 135.29 (d, J=3.8 Hz), 135.15, 132.81, 132.72, 130.04 (2×), 128.71, 128.26, 127.60 (2×), 126.62, 126.08, 125.04, 115.02, 114.81, 106.31, 105.31, 55.87, 55.56.

*4.3.6. 1-(3,4-Methylenedioxyphenyl)-6,7-dimethoxy-2-phenylnaphthalene (**6f**).* Yield=50% (192 mg); colorless gum; HRMS

(ESI, M^++1) calcd for $C_{25}H_{21}O_4$ 385.1440, found 385.1449; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.75 (d, J=8.4 Hz, 1H), 7.42 (d, J=8.4 Hz, 1H), 7.24–7.14 (m, 6H), 7.03 (s, 1H), 6.77 (dd, J=0.8, 7.6 Hz, 1H), 6.69–6.66 (m, 2H), 5.99 (d, J=1.2 Hz, 1H), 5.95 (d, J=1.2 Hz, 1H), 4.04 (s, 3H), 3.80 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.53, 149.29, 147.25, 146.19, 142.30, 137.04, 135.79, 133.06, 129.95 (2×), 128.71, 128.49, 127.59 (2×), 126.69, 125.97, 125.87, 124.73, 111.67, 107.91, 106.25, 105.60, 100.84, 55.87, 55.68.

*4.3.7. 7-Butoxy-6-methoxy-1,2-diphenylnaphthalene (**6g**).* Yield=78% (297 mg); mp=127–128 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{27}H_{27}O_2$ 383.2011, found 383.2014; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.77 (d, J=8.4 Hz, 1H), 7.44 (d, J=8.4 Hz, 1H), 7.33–7.24 (m, 4H), 7.22–7.18 (m, 7H), 6.98 (s, 1H), 4.02 (s, 3H), 3.88 (t, J=6.8 Hz, 2H), 1.80–1.73 (m, 2H), 1.46–1.37 (m, 2H), 0.92 (t, J=7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.68, 148.95, 142.31, 139.45, 136.70, 136.23, 131.11 (2×), 130.11 (2×), 128.61, 128.29, 127.82 (2×), 127.47 (2×), 126.61, 126.54, 125.89, 125.85, 106.90, 106.38, 68.19, 55.91, 30.72, 19.12, 13.80.

*4.3.8. 7-Butoxy-6-methoxy-1-(4-methoxyphenyl)-2-phenylnaphthalene (**6h**).* Yield=60% (247 mg); colorless gum; HRMS (ESI, M^++1) calcd for $C_{28}H_{29}O_3$ 413.2117, found 413.2122; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.75 (d, J=8.4 Hz, 1H), 7.43 (d, J=8.4 Hz, 1H), 7.22–7.10 (m, 8H), 7.02 (s, 1H), 6.85 (d, J=8.8 Hz, 2H), 4.02 (s, 3H), 3.91 (t, J=6.8 Hz, 2H), 3.82 (s, 3H), 1.82–1.75 (m, 2H), 1.49–1.40 (m, 2H), 0.94 (t, J=7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.20, 149.65, 148.92, 142.50, 136.88, 135.85, 132.31 (2×), 131.65, 130.11 (2×), 128.65, 128.61, 127.52 (2×), 126.59, 125.79, 125.69, 113.30 (2×), 106.94, 106.39, 68.21, 55.90, 55.12, 30.78, 19.16, 13.83.

*4.3.9. 7-Butoxy-6-methoxy-1-(3,4-methylenedioxyphenyl)-2-phenylnaphthalene (**6i**).* Yield=52% (222 mg); colorless gum; HRMS (ESI, M^++1) calcd for $C_{28}H_{27}O_4$ 427.1909, found 427.1910; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.74 (d, J=8.4 Hz, 1H), 7.41 (d, J=8.4 Hz, 1H), 7.24–7.14 (m, 6H), 7.03 (s, 1H), 6.77 (d, J=7.6 Hz, 1H), 6.69–6.66 (m, 2H), 5.97 (d, J=1.2 Hz, 1H), 5.95 (d, J=1.2 Hz, 1H), 4.02 (s, 3H), 3.94 (t, J=6.8 Hz, 2H), 1.84–1.77 (m, 2H), 1.51–1.41 (m, 2H), 0.95 (t, J=7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.70, 148.99, 147.22, 146.16, 142.36, 136.89, 135.68, 133.16, 129.96 (2×), 128.61, 128.53, 127.59 (2×), 126.55, 125.94, 125.83, 124.74, 111.71, 107.88, 106.84, 106.39, 100.83, 68.27, 55.91, 30.78, 19.17, 13.82.

*4.3.10. 7-Benzyloxy-6-methoxy-1,2-diphenylnaphthalene (**6j**).* Yield=70% (290 mg); mp=134–135 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{30}H_{25}O_2$ 417.1855, found 417.1859; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.74 (d, J=8.4 Hz, 1H), 7.41 (d, J=8.4 Hz, 1H), 7.27–7.24 (m, 8H), 7.20 (s, 1H), 7.15–7.10 (m, 5H), 7.06–7.04 (m, 2H), 6.98 (s, 1H), 5.04 (s, 2H), 4.04 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.69, 148.15, 142.21, 139.30, 136.67, 136.56, 136.29, 131.20 (2×), 130.08 (2×), 128.72, 128.43 (2×), 128.08, 127.88 (2×), 127.68, 127.45 (2×), 127.43 (2×), 126.70, 126.48, 125.90, 125.81, 108.37, 106.43, 70.35, 55.93.

*4.3.11. 7-Benzyloxy-6-methoxy-1-(4-methoxyphenyl)-2-phenylnaphthalene (**6k**).* Yield=62% (277 mg); mp=144–145 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{31}H_{27}O_3$ 447.1960, found 447.1966; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.73 (d, J=8.4 Hz, 1H), 7.41 (d, J=8.4 Hz, 1H), 7.30–7.26 (m, 5H), 7.20 (s, 1H), 7.19–7.10 (m, 5H), 7.01 (s, 1H), 6.95 (d, J=8.8 Hz, 2H), 6.79 (d, J=8.8 Hz, 2H), 5.07 (s, 2H), 4.04 (s, 3H), 3.84 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.12, 149.66, 148.16, 142.41, 136.85 (2×), 136.65, 135.95, 132.22 (2×), 131.48, 130.92 (2×), 128.78, 128.42 (2×), 127.69, 127.52 (2×), 127.41 (2×), 126.77, 125.81, 125.64, 113.36 (2×), 108.44, 106.44, 70.42, 55.95, 55.15.

*4.3.12. 7-Benzyloxy-6-methoxy-1-(3,4-methylenedioxyphenyl)-2-phenylnaphthalene (**6l**).* Yield=58% (267 mg); mp=168–170 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{31}H_{25}O_4$ 461.1753, found 461.1750; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.74 (d, J=8.4 Hz, 1H), 7.40 (d, J=8.4 Hz, 1H), 7.33–7.14 (m, 11H), 7.04 (s, 1H), 6.73 (d, J=8.0 Hz, 1H), 6.56 (d, J=1.6 Hz, 1H), 6.52 (dd, J=1.6, 8.0 Hz, 1H), 6.03 (d, J=1.2 Hz, 1H), 5.97 (d, J=1.6 Hz, 1H), 5.12 (s, 2H), 4.05 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.70, 148.20, 147.13, 146.09, 142.24, 136.84, 136.61, 135.74, 132.97, 129.93 (2×), 128.72, 128.41 (2×), 128.33, 127.75, 127.57 (2×), 127.41 (2×), 126.70, 125.94, 125.78, 124.64, 111.65, 108.39, 107.94, 106.43, 100.80, 70.50, 55.91.

*4.3.13. 7-Methoxy-1,2-diphenylnaphthalene (**6m**).* Yield=70% (216 mg); mp=141–143 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{23}H_{19}O$ 311.1436, found 311.1440; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.83 (dd, J=8.4, 11.2 Hz, 2H), 7.43 (d, J=8.4 Hz, 1H), 7.31–7.11 (m, 11H), 6.97 (d, J=2.4 Hz, 1H), 3.69 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 157.89, 142.18, 139.21, 138.88, 136.51, 133.82, 131.33 (2×), 130.06 (2×), 129.38, 127.87, 127.52 (2×), 127.24, 127.15, 126.67, 126.11, 126.08, 118.05 (2×), 105.48, 55.09.

*4.3.14. 7-Methoxy-1-(4-methoxyphenyl)-2-phenylnaphthalene (**6n**).* Yield=61% (207 mg); mp=132–134 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{24}H_{21}O_2$ 341.1542, found 341.1546; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.83 (dd, J=7.6, 8.8 Hz, 2H), 7.48 (d, J=8.8 Hz, 1H), 7.43 (d, J=8.4 Hz, 1H), 7.22–7.09 (m, 6H), 7.02 (d, J=2.4 Hz, 1H), 6.96 (d, J=8.8 Hz, 1H), 6.84 (d, J=8.8 Hz, 2H), 3.82 (s, 3H), 3.72 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.25, 157.87, 142.38, 139.06, 134.19, 133.49, 132.36 (2×), 130.07 (2×), 129.38, 127.72, 127.58 (2×), 127.08, 126.12, 126.01, 118.03, 114.16, 113.37 (2×), 105.51, 55.34, 55.14.

*4.3.15. 7-Alloxy-6-methoxy-1-(3,4-methylenedioxyphenyl)-2-phenylnaphthalene (**6o**).* Yield=66% (271 mg); mp=156–157 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{27}H_{23}O_4$ 411.1596, found 411.1599; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.74 (d, J=8.4 Hz, 1H), 7.41 (d, J=8.0 Hz, 1H), 7.23–7.14 (m, 6H), 7.05 (s, 1H), 6.76 (d, J=8.0 Hz, 1H), 6.67 (d, J=1.2 Hz, 1H), 6.64 (dd, J=1.2, 8.0 Hz, 1H), 6.06–5.94 (m, 1H), 5.99 (d, J=1.2 Hz, 1H), 5.95 (d, J=1.2 Hz, 1H), 5.31–5.26 (m, 2H), 4.53 (d, J=5.6 Hz, 2H), 4.03 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.57, 148.36, 147.19, 146.17, 142.30, 136.95, 135.78, 133.10, 133.05, 129.97 (2×), 128.74, 128.40, 127.61 (2×), 126.74, 125.98, 125.85, 124.76, 118.62, 111.76, 107.91, 107.57, 106.40, 100.85, 69.58, 55.91.

4.4. A representative synthetic procedure of skeleton 2 is as follows

Skeleton **6** (0.2 mmol) and I_2 (100 mg, 0.4 mmol) was dissolved in EtOAc (15 mL) at rt. Then, 1,2-epoxybytane (440 mg, 6.0 mmol) was added to the reaction mixture and the reaction mixture was irradiated under a nitrogen atmosphere with a lamp (λ=2540 Å), using a Pyrex glass filter at rt for 80 h. The solvent was evaporated to afford crude product. Purification on silica gel (hexanes/EtOAc=4/1–2/1) afforded skeleton **2**.

*4.4.1. 12,13-Dimethoxybenzo[g]chrysene (**2a**).* Yield=80% (54 mg); mp=183–185 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{24}H_{19}O_2$ 339.1385, found 339.1388; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.96 (d, J=7.6 Hz, 1H), 8.73 (d, J=8.0 Hz, 2H), 8.69 (dd, J=2.0, 7.6 Hz, 1H), 8.63 (dd, J=2.0, 7.6 Hz, 1H), 8.50 (d, J=8.8 Hz, 1H), 8.40 (s, 1H), 7.89 (d, J=8.8 Hz, 1H), 7.72–7.60 (m, 3H), 7.33 (s, 1H), 4.09 (s, 3H), 4.06 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$):

δ 149.22, 149.00, 130.89, 130.09, 129.71, 129.55, 129.42, 128.34, 127.32, 127.18, 126.77, 126.52, 126.47, 126.45, 125.83, 125.42, 123.70, 123.48, 123.05, 119.18, 108.66, 107.18, 56.02, 55.91.

*4.4.2. 3,12,13-Trimethoxybenzo[g]chrysene (**2c**).* Yield=62% (47 mg); colorless gum; HRMS (ESI, M^++1) calcd for $C_{25}H_{21}O_3$ 369.1491, found 369.1496; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.87 (d, *J*=9.2 Hz, 1H), 8.62 (ddd, *J*=1.6, 5.6, 7.2 Hz, 2H), 8.48 (d, *J*=8.8 Hz, 1H), 8.33 (s, 1H), 8.12 (d, *J*=2.8 Hz, 1H), 7.83 (d, *J*=8.4 Hz, 1H), 7.69 (dt, *J*=1.6, 6.8 Hz, 1H), 7.66 (dt, *J*=1.6, 6.8 Hz, 1H), 7.31 (s, 1H), 7.25 (dd, *J*=2.8, 8.8 Hz, 1H), 4.09 (s, 3H), 4.07 (s, 3H), 4.06 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.19, 149.08, 149.97, 132.52, 130.45, 129.91, 129.47, 129.21, 127.42, 126.73, 126.57, 125.95, 125.52, 125.13, 123.92, 123.56, 123.10, 119.22, 114.48, 108.66, 107.17, 105.96, 56.01, 55.90, 55.50.

*4.4.3. 3-Fluoro-12,13-dimethoxybenzo[g]chrysene (**2e**).* Yield=40% (28 mg); mp=178–180 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{24}H_{18}FO_2$ 357.1291, found 357.1296; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.92 (dd, *J*=5.6, 9.2 Hz, 1H), 8.62 (dd, *J*=1.6, 8.0 Hz, 1H), 8.54 (dd, *J*=1.6, 8.0 Hz, 1H), 8.47 (d, *J*=9.2 Hz, 1H), 8.32 (dd, *J*=2.4, 10.8 Hz, 1H), 8.27 (s, 1H), 7.86 (d, *J*=8.4 Hz, 1H), 7.73–7.65 (m, 2H), 7.35 (ddd, *J*=2.8, 8.0, 9.2 Hz, 1H), 7.31 (s, 1H), 4.09 (s, 3H), 4.05 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 161.33 (d, *J*=244.9 Hz), 149.34, 149.10, 132.90 (d, *J*=8.3 Hz), 130.86, 130.46, 130.43, 130.37, 129.49, 128.78, 127.92, 126.85, 126.64, 126.30, 126.15, 123.56, 123.24, 119.14, 114.07 (d, *J*=22.7 Hz), 109.02 (d, *J*=22.0 Hz), 108.37, 107.23, 56.00, 55.19.

*4.4.4. 2,3-Methylenedioxy-12,13-dimethoxybenzo[g]chrysene (**2f**).* Yield=66% (50 mg); mp=220–222 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{25}H_{19}O_4$ 383.1283, found 383.1284; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.61–8.59 (m, 1H), 8.48–8.46 (m, 1H), 8.46 (d, *J*=8.8 Hz, 1H), 8.36 (s, 1H), 8.30 (s, 1H), 8.07 (s, 1H), 7.81 (d, *J*=8.8 Hz, 1H), 7.66–7.61 (m, 2H), 7.30 (s, 1H), 6.13 (s, 2H), 4.08 (s, 3H), 4.06 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 148.94, 148.91, 147.48 (2×), 147.19, 129.49, 129.37, 129.32, 127.02, 126.61, 126.48, 126.40, 125.71, 125.42, 125.17, 123.48, 122.85, 119.22, 108.43, 107.26, 106.78, 102.52, 101.45, 56.07, 55.90. Single-crystal X-ray diagram: crystal of compound **2f** was grown by slow diffusion of EtOAc into a solution of compound **2f** in CH_2Cl_2 to yield colorless prisms. The compound crystallizes in the orthorhombic crystal system, space group *P n a* 21, *a*=26.3820 (19) Å, *b*=3.7786 (3) Å, *c*=17.0118 (4) Å, *V*=1695.9 (2) Å^3, *Z*=4, D_{calcd}=1.498 g/cm^3, *F*(000)=800, 2θ range 1.95–26.41°, *R* indices (all data) *R*1=0.0316, *wR*2=0.0744.

*4.4.5. 13-Butoxy-12-methoxybenzo[g]chrysene (**2g**).* Yield=75% (53 mg); mp=120–122 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{27}H_{25}O_2$ 381.1855, found 381.1856; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.94 (dd, *J*=0.8, 8.0 Hz, 1H), 8.73 (dd, *J*=1.6, 7.2 Hz, 1H), 8.69 (dd, *J*=2.0, 7.2 Hz, 1H), 8.63 (dd, *J*=2.0, 7.2 Hz, 1H), 8.50 (d, *J*=8.8 Hz, 1H), 8.38 (s, 1H), 7.88 (d, *J*=8.8 Hz, 1H), 7.72–7.60 (m, 4H), 7.32 (s, 1H), 4.21 (t, *J*=6.8 Hz, 2H), 4.07 (s, 3H), 1.99–1.92 (m, 2H), 1.62–1.53 (m, 2H), 1.02 (t, *J*=7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.42, 148.75, 130.87, 130.12, 129.74, 129.55, 129.36, 128.79, 128.43, 127.30, 127.11, 126.73, 126.46, 126.43, 125.80, 125.44, 123.66, 123.48, 123.05, 119.04, 109.97, 107.34, 68.77, 55.95, 31.19, 19.30, 13.93.

*4.4.6. 13-Butoxy-3,12-dimethoxybenzo[g]chrysene (**2h**).* Yield=58% (48 mg); mp=116–118 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{28}H_{27}O_3$ 411.1960, found 411.1969; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.85 (d, *J*=9.2 Hz, 1H), 8.62 (ddd, *J*=1.6, 5.2, 7.2 Hz, 2H), 8.47 (d, *J*=9.2 Hz, 1H), 8.31 (s, 1H), 8.12 (d, *J*=2.8 Hz, 1H), 7.82 (d, *J*=8.4 Hz, 1H), 7.71–7.63 (m, 2H), 7.31 (s, 1H), 7.25 (dd, *J*=2.8, 9.2 Hz, 1H), 4.20 (t, *J*=6.8 Hz, 2H), 4.08 (s, 3H), 4.07 (s, 3H), 1.99–1.92 (m, 2H), 1.63–1.53 (m, 2H), 1.03 (t, *J*=7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.16, 149.42, 148.63, 132.48, 130.49, 130.01, 129.42, 129.19, 127.40, 126.67, 126.51, 125.89, 125.53, 125.15, 123.98, 123.56, 123.08, 119.09, 114.52, 110.04, 107.36, 105.87, 68.79, 55.93, 55.50, 31.21, 19.31, 13.94.

*4.4.7. 13-Butoxy-2,3-methylenedioxy-12-methoxybenzo[g]chrysene (**2i**).* Yield=55% (47 mg); mp=164–166 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{28}H_{25}O_4$ 425.1753, found 425.1754; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.61–8.59 (m, 1H), 8.48–8.46 (m, 1H), 8.46 (d, *J*=8.8 Hz, 1H), 8.34 (s, 1H), 8.29 (s, 1H), 8.07 (s, 1H), 7.81 (d, *J*=8.8 Hz, 1H), 7.65–7.62 (m, 2H), 7.29 (s, 1H), 6.14 (s, 2H), 6.21 (t, *J*=6.8 Hz, 2H), 4.07 (s, 3H), 1.99–1.92 (m, 2H), 1.62–1.53 (m, 2H), 1.03 (t, *J*=7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.36, 148.49, 147.47, 147.20, 129.49, 129.41, 129.27, 126.98, 126.56 (2×), 126.45, 126.33, 125.72, 125.48, 125.21, 123.49, 122.84, 119.09, 109.82, 107.44, 106.89, 102.48, 101.45, 68.84, 55.94, 31.22, 19.30, 13.89. Single-crystal X-ray diagram: crystal of compound **2i** was grown by slow diffusion of EtOAc into a solution of compound **2i** in CH_2Cl_2 to yield colorless prisms. The compound crystallizes in the monoclinic crystal system, space group *P* 1 21/*c* 1, *a*=6.3608 (6) Å, *b*=27.461 (3) Å, *c*=23.465 (2) Å, *V*=4090.4 (7) Å^3, *Z*=8, D_{calcd}=1.379 g/cm^3, *F*(000)=1792, 2θ range 1.14–26.41°, *R* indices (all data) *R*1=0.1411, *wR*2=0.1410.

*4.4.8. 13-Benzyloxy-12-methoxybenzo[g]chrysene (**2j**).* Yield=70% (58 mg); colorless gum; HRMS (ESI, M^++1) calcd for $C_{30}H_{23}O_2$ 415.1698, found 415.1702; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.67 (dt, *J*=2.4, 8.8 Hz, 2H), 8.61 (d, *J*=8.8 Hz, 1H), 8.48 (d, *J*=8.8 Hz, 1H), 8.36 (d, *J*=8.0 Hz, 1H), 8.27 (s, 1H), 7.87 (d, *J*=8.8 Hz, 1H), 7.69–7.54 (m, 5H), 7.48–7.31 (m, 5H), 5.37 (s, 2H), 4.12 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.43, 147.85, 137.04, 130.72, 130.02, 129.58, 129.50, 128.76 (2×), 128.25, 128.14, 127.87, 127.25, 127.08, 126.95 (2×), 126.73, 126.39, 126.28, 126.11, 125.81, 125.18, 123.48, 123.45, 123.01, 119.28, 111.28, 107.47, 70.47, 55.97.

*4.4.9. 13-Benzyloxy-3,12-dimethoxybenzo[g]chrysene (**2k**).* Yield=62% (52 mg); HRMS (ESI, M^++1) calcd for $C_{31}H_{25}O_3$ 445.1804, found 445.1806; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.59 (dt, *J*=1.2, 8.8 Hz, 2H), 8.46 (d, *J*=8.8 Hz, 1H), 8.23 (d, *J*=9.2 Hz, 1H), 8.18 (s, 1H), 8.07 (d, *J*=2.4 Hz, 1H), 7.81 (d, *J*=8.8 Hz, 1H), 7.69–7.62 (m, 2H), 7.55 (d, *J*=7.2 Hz, 2H), 7.47 (t, *J*=7.2 Hz, 2H), 7.41–7.37 (m, 1H), 7.34 (s, 1H), 6.93 (dd, *J*=2.4, 8.8 Hz, 1H), 5.37 (s, 2H), 4.12 (s, 3H), 4.05 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 157.97, 149.39, 147.65, 137.12, 132.33, 130.37, 129.82, 129.63, 129.21, 128.77 (2×), 127.83, 127.35, 126.90 (2×), 126.63, 126.52, 125.85, 125.45, 124.86, 123.73, 123.83, 123.05, 119.33, 114.73, 111.32, 107.44, 105.76, 70.43, 55.97, 55.43. Single-crystal X-ray diagram: crystal of compound **2k** was grown by slow diffusion of EtOAc into a solution of compound **2k** in CH_2Cl_2 to yield colorless prisms. The compound crystallizes in the monoclinic crystal system, space group *P* 1 21/*n* 1, *a*=12.2066 (3) Å, *b*=8.1982 (2) Å, *c*=23.0377 (6) Å, *V*=2269.34 (10) Å^3, *Z*=4, D_{calcd}=1.301 g/cm^3, *F*(000)=936, 2θ range 1.80–26.39°, *R* indices (all data) *R*1=0.0573, *wR*2=0.1204.

*4.4.10. 13-Benzyloxy-2,3-methylenedioxy-12-methoxybenzo[g]chrysene (**2l**).* Yield=59% (54 mg); mp=178–180 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{31}H_{23}O_4$ 459.1596, found 459.1608; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.59–8.57 (m, 1H), 8.46–8.44 (m, 2H), 8.31 (s, 1H), 8.12 (s, 1H), 8.05 (s, 1H), 7.80 (d, *J*=8.8 Hz, 1H), 7.64–7.59 (m, 2H), 7.57–7.55 (m, 2H), 7.42–7.38 (m, 2H), 7.33–7.30 (m, 2H), 6.14 (s, 2H), 5.34 (s, 2H), 4.09 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.47, 147.97, 147.45, 147.16 (2×), 136.83, 129.61, 129.47, 129.33, 128.72 (2×), 128.03, 127.45 (2×), 126.95, 126.58, 126.43, 126.32, 125.70, 125.36, 125.06, 123.47, 122.82, 119.34, 111.13, 107.60, 106.89, 102.44, 101.39, 71.09, 55.94.

*4.4.11. 3,13-Dimethoxybenzo[g]chrysene (**2n**).* Yield=20% (13 mg); colorless gum; HRMS (ESI, M^++1) calcd for $C_{24}H_{19}O_2$ 339.1385,

found 339.1391; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.93 (d, J=9.2 Hz, 1H), 8.64 (dt, J=2.4, 7.6 Hz, 2H), 8.46 (d, J=9.2 Hz, 1H), 8.34 (d, J=2.0 Hz, 1H), 8.13 (d, J=2.4 Hz, 1H), 7.91 (t, J=8.8 Hz, 1H), 7.72–7.68 (m, 3H), 7.26 (dd, J=2.4, 8.8 Hz, 2H), 4.08 (s, 3H), 3.99 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.16, 157.95, 132.43, 132.38, 131.15, 130.85, 130.26, 130.04, 129.60, 129.55, 127.40, 126.92, 126.49, 123.98, 123.90, 123.11, 118.59, 116.94, 114.62, 114.22, 108.96, 105.87, 55.50 (2×).

*4.4.12. 13-Alloxy-2,3-methylenedioxy-12-methoxybenzo[g]chrysene (**2o**).* Yield=60% (49 mg); mp=134–136 °C (recrystallized from hexanes and EtOAc); HRMS (ESI, M^++1) calcd for $C_{27}H_{21}O_4$ 409.1440, found 409.1436; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.59–8.56 (m, 1H), 8.47–8.44 (m, 1H), 8.44 (d, J=8.8 Hz, 1H), 8.25 (s, 1H), 8.24 (s, 1H), 8.05 (s, 1H), 7.79 (d, J=8.8 Hz, 1H), 7.64–7.60 (m, 2H), 7.29 (s, 1H), 6.25–6.16 (m, 1H), 6.12 (s, 2H), 5.56 (dq, J=1.2, 17.2 Hz, 1H), 5.46 (dq, J=1.2, 10.4 Hz, 1H), 4.81 (dt, J=1.6, 5.6 Hz, 2H), 4.08 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.17, 147.72, 147.44, 147.16, 133.46 (2×), 129.48, 129.37, 129.33, 126.91, 126.55, 126.42, 126.33, 125.67, 125.32, 124.98, 123.46, 122.82, 119.24, 118.64, 110.38, 107.39, 107.09, 102.41, 101.42, 69.78, 55.89.

Acknowledgements

The authors would like to thank the National Science Council of the Republic of China for its financial support.

Supplementary data

Scanned photocopies of ^{1}H and ^{13}C NMR spectral data and crystallographic data of **4f**, **6a**, **2f**, **2i**, and **2k** (CIF) were supported. Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.tet.2012.10.054.

References and notes

1. (a) Harvey, R. G. *Polycyclic Aromatic Hydrocarbons*; Wiley-VCH: New York, NY, 1997; (b) Harvey, R. G. *Polycyclic Aromatic Hydrocarbons: Chemistry and Carcinogenicity*; Cambridge University: Cambridge, UK, 1991; (c) Bax, A.; Ferretti, J. A.; Nashed, N.; Jerina, D. M. *J. Org. Chem.* **1985**, *50*, 3029; (d) Jogenson, K. *Molecules* **2010**, *15*, 4334.
2. (a) Harvey, R. G. *Polycyclic Aromatic Hydrocarbons: Chemistry and Carcinogenesis*; Cambridge University: Cambridge, 1991; (b) Harvey, R. G.; Geacintov, N. E. *Acc. Chem. Res.* **1988**, *21*, 66.
3. For the reviews on PAHs, see: (a) Weil, T.; Vosch, T.; Hofkens, J.; Peneva, K.; Müllen, K. *Angew. Chem., Int. Ed.* **2010**, *49*, 9068; (b) Wu, J.; Pisula, W.; Müllen, K. *Chem. Rev.* **2007**, *107*, 718; (c) Anthony, J. E. *Chem. Rev.* **2006**, *106*, 5028; (d) Karitzky, A. R.; Li, J.; Xie, L. *Tetrahedron* **1999**, *55*, 8263.
4. (a) Sukumaran, K. B.; Harvey, R. G. *J. Org. Chem.* **1981**, *46*, 2740; (b) Tang, X.-Q.; Harvey, R. G. *Tetrahedron Lett.* **1995**, *36*, 6037; (c) Zhang, J.-T.; Harvey, R. G. *Tetrahedron* **1999**, *55*, 625; (d) Kiselyov, A. S.; Lee, H.; Harvey, R. G. *J. Org. Chem.* **1995**, *60*, 6123 and cited references therein; (e) Wu, A.; Xu, D.; Lu, D.; Penning, T. M.; Blair, I. A.; Harvey, R. G. *Tetrahedron* **2012**, *68*, 7217.
5. (a) Krzeminski, J.; Lin, J.-M.; Amin, S.; Hecht, S. S. *Chem. Res. Toxicol.* **1994**, *7*, 125; (b) Luch, A.; Glatt, H.; Platt, K. L.; Oesch, F.; Seidal, A. *Carcinogenesis* **1994**, *15*, 2507; (c) Sayer, J. M.; Yagi, H.; Croisy-Delcey, M.; Jerina, D. M. *J. Am. Chem. Soc.* **1981**, *103*, 4970.
6. (a) Bushman, D. R.; Grossman, S. J.; Jerina, D. M.; Lehr, R. E. *J. Org. Chem.* **1989**, *54*, 3533; (b) Utermoehlen, C. M.; Singh, M.; Lehr, R. E. *J. Org. Chem.* **1987**, *52*, 5574.
7. (a) Kumar, S. *J. Org. Chem.* **1997**, *62*, 8535; (b) Kumar, S. *Synthesis* **2001**, 841.
8. Laali, K. K.; Okazaki, T. *J. Org. Chem.* **2001**, *66*, 780.
9. (a) Shimizu, M.; Nagao, I.; Tomioka, Y.; Hiyama, T. *Angew. Chem., Int. Ed.* **2008**, *47*, 8096; (b) Shimizu, M.; Nagao, I.; Kadowaki, T.; Hiyama, T. *Tetrahedron* **2011**, *67*, 8014; (c) Navale, T. S.; Zhai, L.; Lindeman, S. V.; Rathore, R. *Chem. Commun.* **2009**, 2857; (d) Yamaguchi, S.; Swager, T. M. *J. Am. Chem. Soc.* **2001**, *123*, 12087; (e) Li, C.-W.; Wang, C.-I.; Liao, H.-Y.; Chaudhuri, R.; Liu, R.-S. *J. Org. Chem.* **2007**, *72*, 9203; (f) Sharma, A. K.; Kumar, S.; Amin, S. *J. Org. Chem.* **2004**, *69*, 3979; (g) Chaudhuri, R.; Hsu, M.-Y.; Li, C.-W.; Wang, C.-I.; Chen, C.-J.; Lai, C.-K.; Chen, L.-Y.; Liu, S.-H.; Wu, C.-C.; Liu, R.-S. *Org. Lett.* **2008**, *10*, 3053; (h) Schultz, A.; Laschat, S.; Diele, S.; Nimtz, M. *Eur. J. Org. Chem.* **2003**, 2829; (i) Navale, T. S.; Thakur, K.; Rathore, R. *Org. Lett.* **2011**, *13*, 1634.
10. (a) Harvey, R. G.; Lim, K.; Dai, Q. *J. Org. Chem.* **2004**, *69*, 1372; (b) Schlude, H. *Chem. Ber.* **1971**, *104*, 3995; (c) Johnson, W. S. *Org. React.* **1944**, *2*, 114; (d) Zhang, F.-J.; Cortez, C.; Harvey, R. G. *J. Org. Chem.* **2000**, *65*, 3952.
11. (a) Wang, Z.; Dotz, F.; Enkelmann, V.; Mullen, K. *Angew. Chem., Int. Ed.* **2005**, *44*, 1247; (b) Yue, W.; Lv, A.; Gao, J.; Jiang, W.; Hao, L.; Li, C.; Li, Y.; Polander, L. E.; Barlow, S.; Hu, W.; Di Motta, S.; Negri, F.; Marder, S. R.; Wang, Z. *J. Am. Chem. Soc.* **2012**, *134*, 5770; (c) Chen, T.-A.; Liu, R.-S. *Org. Lett.* **2011**, *13*, 4644; (d) Chen, J.-D.; Lu, H.-Y.; Chen, C.-F. *Chem.—Eur. J.* **2010**, *16*, 11843.
12. (a) Chang, M.-Y.; Lee, N.-C. *Synlett* **2012**, 867; (b) Chang, M.-Y.; Wu, M.-H.; Lee, N.-C.; Lee, M.-F. *Tetrahedron Lett.* **2012**, *53*, 2125; (c) Chang, M.-Y.; Wu, M.-H. *Tetrahedron Lett.* **2012**, *53*, 3173; (d) Chang, M.-Y.; Wu, M.-H.; Lee, T.-W. *Tetrahedron* **2012**, *68*, 6224; (e) Chang, M.-Y.; Wu, M.-H.; Chen, Y.-L. *Tetrahedron Lett.* **2012**, *53*, 4156; (f) Chang, M.-Y.; Tai, H.-Y.; Chen, Y.-L.; Hsu, R.-T. *Tetrahedron* **2012**, *68*, 7941; (g) Chang, M.-Y.; Wu, M.-H.; Tai, H.-Y. *Org. Lett.* **2012**, *14*, 3936; (h) Chang, M.-Y.; Wu, M.-H. *Tetrahedron* **2012**, *68*, 9616; (i) Chang, M.-Y.; Chan, C.-K.; Lin, S.-Y.; Hsu, R.-T. *Tetrahedron* **2012**, *68*, 10272.
13. CCDC 894231 (**4f**), 892761 (**6a**), 892794 (**2f**), 896140 (**2i**), and 896671 (**2k**) contain the supplementary crystallographic data for this paper. This data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK; fax: 44-1223-336033; e-mail: deposit@ccdc.cam.ac.uk).
14. (a) De Koning, C. B.; Michael, J. P.; Rousseau, A. L. *Tetrahedron Lett.* **1997**, *38*, 893; (b) De Koning, C. B.; Michael, J. P.; Rousseau, A. L. *J. Chem. Soc., Perkin Trans. 1* **2000**, 787; (c) De Koning, C. B.; Manzini, S. S.; Michael, J. P.; Mmutlane, E. M.; Tshabidi, T. R.; Van Otterlo, W. A. L. *Tetrahedron* **2005**, *61*, 555; (d) Sibi, M. P.; Dankwardt, J. W.; Snieckus, V. *J. Org. Chem.* **1986**, *51*, 271; (e) Pearson, D. E.; Buehler, C. A. *Chem. Rev.* **1974**, *74*, 45; (f) Rao, B. B.; Wei, J.-R.; Lin, C.-H. *Org. Lett.* **2012**, *14*, 3640.
15. (a) Berresheim, A. J.; Muller, M.; Muller, K. *Chem. Rev.* **1999**, *99*, 1747; (b) Kumar, S. *Liq. Cryst.* **2005**, *32*, 1089.
16. (a) Boden, N.; Bushby, R. J.; Headdock, G.; Lozman, O. R.; Wood, A. *Liq. Cryst.* **2001**, *28*, 139; (b) King, B. T.; Kroulik, J.; Robertson, C. R.; Rempala, P.; Hilton, C. L.; Korinek, J. D.; Gortari, L. M. *J. Org. Chem.* **2007**, *72*, 2279; (c) Simpson, C. D.; Mattersteig, G.; Martin, K.; Gherghel, L.; Bauer, R. E.; Rader, H. J.; Mullen, K. *J. Am. Chem. Soc.* **2004**, *126*, 3139; (d) McKillop, A.; Turrell, A. G.; Young, D. W.; Taylor, E. C. *J. Am. Chem. Soc.* **1980**, *102*, 6504; (e) Churruca, F.; SanMartin, R.; Carril, M.; Urtiaga, M. K.; Solans, X.; Tellitu, I.; Dominguez, E. *J. Org. Chem.* **2005**, *70*, 3178; (f) Zhang, X.; Jiang, X.; Zhang, K.; Mao, L.; Luo, J.; Chi, C.; Chan, H. S. O.; Wu, J. *J. Org. Chem.* **2010**, *75*, 8069.