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SYNTHESIS AND PHOTOPHYSICAL PROPERTIES OF DIETHYNYLATED BIBENZOFURAN AND BENZODIFURAN DERIVATIVES

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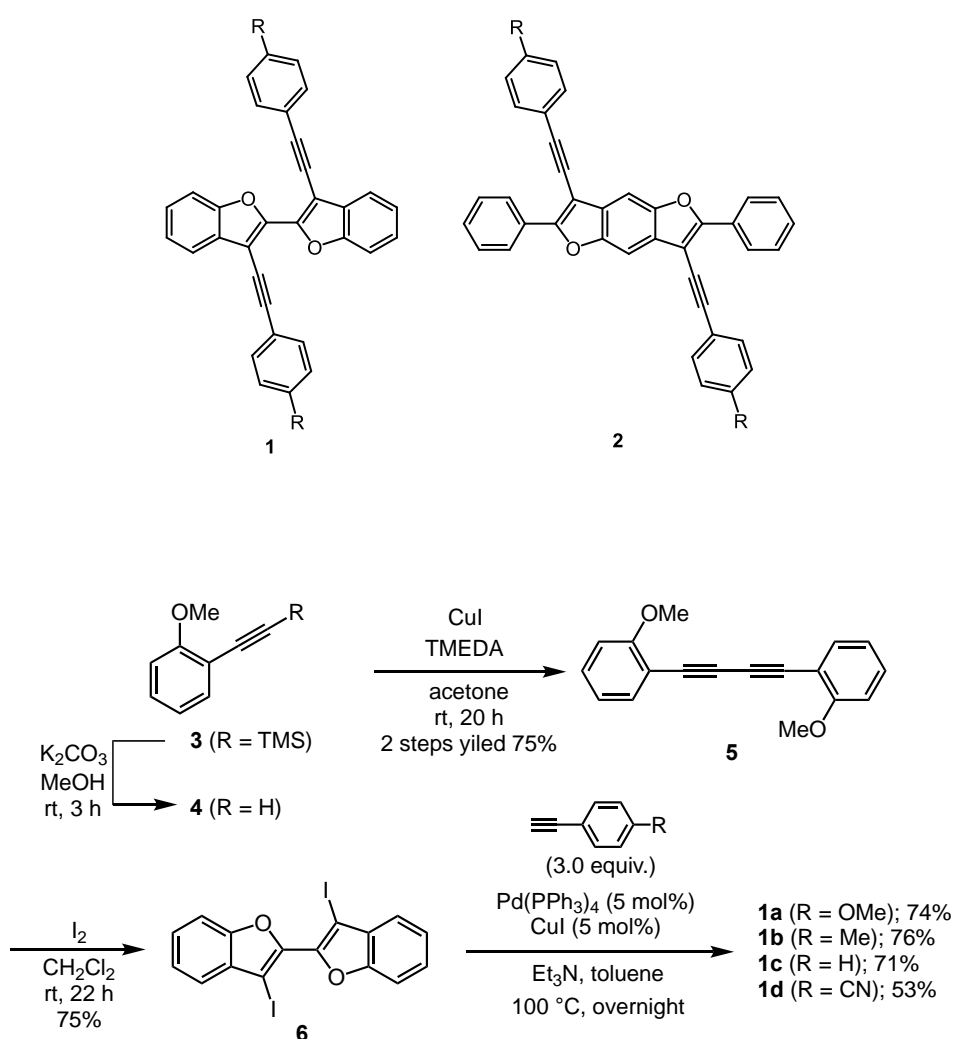
Abstract – The 3,3'-diethynyl-substituted 2,2'-bibenzofuran derivatives **1** and 3,7-diethynyl-substituted benzodifuran derivatives **2** were prepared from 1,4-bis(2-methoxyphenyl)-1,3-butadiyne and diethynyldimethoxybenzene by iodocyclization followed by Sonogashira coupling reaction, respectively.

There are a lot of benzofuran derivatives as natural products and their derivatives show various pharmacological activities. Therefore, the synthetic methods and physical properties of benzofuran derivatives have been studied for many years.¹ Recently, the π -conjugated compounds with multiple furan rings have been applied in the field of organic functional materials, and the development of the efficient and convenient synthesis of their derivatives is of continuous interest.^{2,3} For example, the photophysical properties of benzodifuran derivatives are similar to those of anthracene and/or phenanthrene derivatives. Tsuji and Nakamura *et al.* have reported a convenient method for synthesis of benzodifuran derivatives substituted with various types of aryl groups by zinc-mediated cyclization of *o*-alkynyl phenols.^{2,4} They also have shown that their derivatives could be used as hole-transporting materials in organic light emitting devices. On the other hand, although Kynapcin-24, which are contained 3,3'-bibenzofuran framework, was shown to noncompetitively inhibit prolyl endopeptidase,⁵ the 2,2'-bibenzofuran derivatives have been synthesized in a few cases and have not been fully investigated for applications.⁶ As a few examples, the 3,3'-diaryl substituted 2,2'-bibenzofuran derivatives have been reported to apply to organic light emitting devices.⁷

A facile method for the synthesis of benzofurans by the reaction of 2-ethynylanisole derivatives with iodine has been reported by Larock.⁸ This is an excellent synthetic method that allows the construction of a benzofuran skeleton and the introduction of an iodine group at the 3-position of benzofuran. Although they have reported the synthesis of the diiodo derivatives of 2,2'-bibenzofuran^{8a} and benzodifuran,^{8b} there are

not many examples of synthesis of their π -extended compounds by using of the corresponding diiodo derivatives.^{9,10}

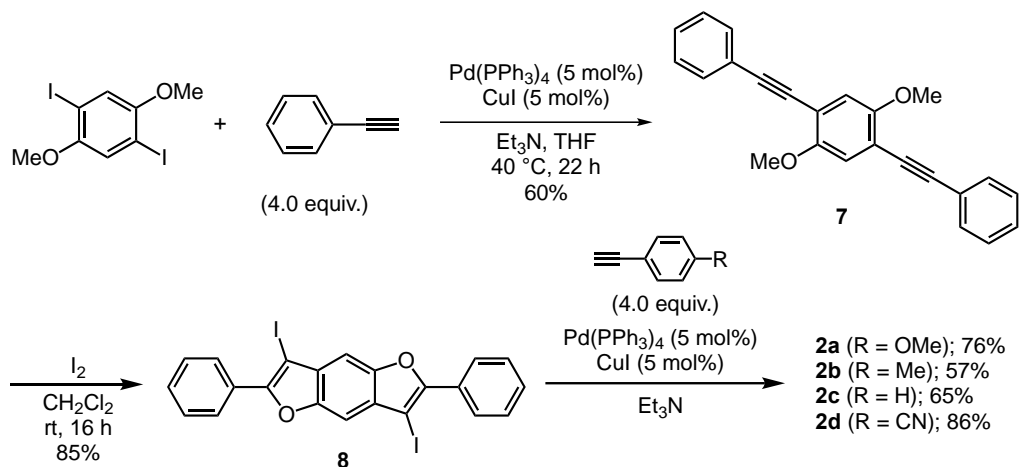
Extending the π -conjugated system of the framework is a useful approach to introduce additional useful properties. However, although there have been reports on the synthesis and properties of benzodifuran and 2,2'-bibenzofuran derivatives extended with the aryl group as described above, to our knowledge, there are no reports on the extension of the π -conjugated system of their derivatives with the ethynyl group. In this study, we planned to synthesize 3,3'-diethynyl-substituted 2,2'-bibenzofuran derivatives **1** and 3,7-diethynyl-substituted benzodifuran derivatives **2** using iodocyclization followed by Sonogashira coupling reaction.



Scheme 1. Synthesis of 3,3'-diethynyl-substituted 2,2'-bibenzofuran derivatives **1**

The synthesis of the 3,3'-diethynyl-substituted 2,2'-bibenzofuran derivatives **1** is shown in Scheme 1. First, **4** was prepared by the desilylation of **3** followed by the copper catalyzed homocoupling of **4** gave butadiyne **5** in the good yield. Next, under the previous synthetic condition by Larock,⁸ **6** was obtained by

iodocyclization of **5** using iodine. Finally, Sonogashira coupling of **6** and the aromatic terminal alkynes gave **1a-d** in moderate to good yields.



Scheme 2. Synthesis of 3,7-diethynyl-substituted benzodifuran derivatives **2**

Next, the 3,7-diethynyl-substituted benzodifuran derivatives **2** were prepared (Scheme 2). Diethynyldimethoxybenzene **7** was prepared by the Sonogashira reaction of 1,4-dimethoxybenzene and phenylacetylene, and then iodocyclization of **7** gave the diiodo benzodifuran **8**. Sonogashira reaction of **8** with the aromatic terminal alkynes afforded **2a-d** in good yields.

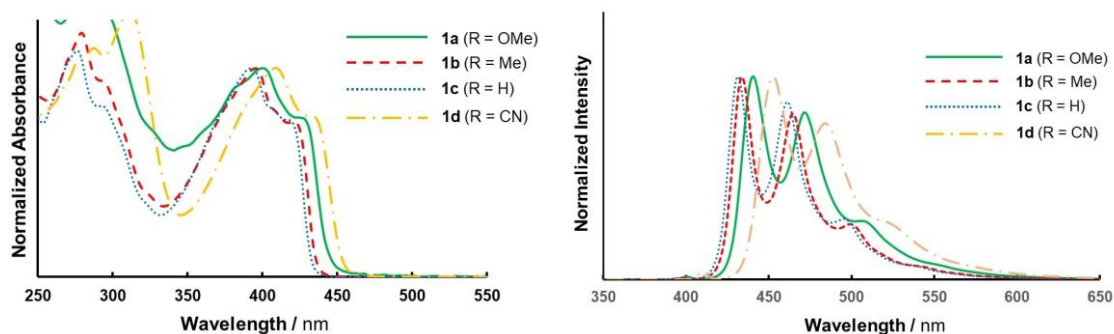


Figure 1. UV/vis (left) and FL (right) spectra of **1** in CH_2Cl_2

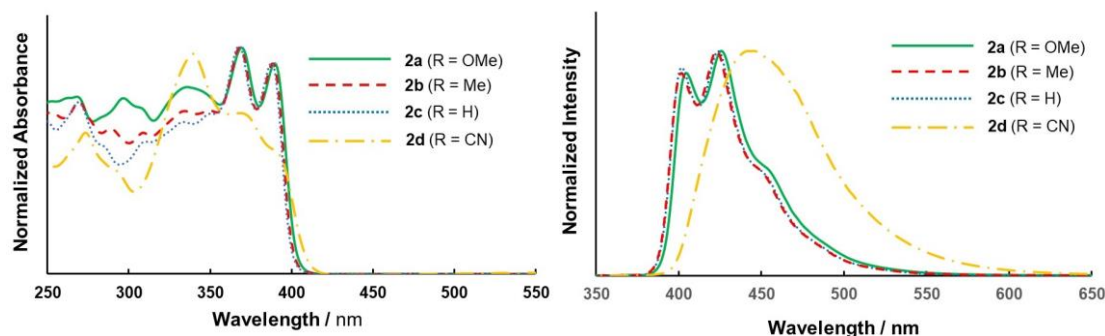


Figure 2. UV/vis (left) and FL (right) spectra of **2** in CH_2Cl_2

Table 1. Optical properties of **1** and **2**^a

Compd.	$\lambda_{\text{abs}} / \text{nm}$	$\lambda_{\text{em}} / \text{nm}$	Φ_{f}^b
1a	283, 399, 421(<i>sh</i>)	441, 472, 506	0.32
1b	279, 396, 421(<i>sh</i>)	434, 465, 500	0.48
1c	276, 393, 420(<i>sh</i>)	431, 461, 496	0.35
1d	312, 409, 432(<i>sh</i>)	453, 484, 522	0.74
2a	368, 389	404, 426, 450(<i>sh</i>)	0.35
2b	368, 388	402, 424, 451(<i>sh</i>)	0.35
2c	367, 387	402, 423, 450(<i>sh</i>)	0.44
2d	339, 368, 390	442	0.23

^a Measured for 10^{-5} CH₂Cl₂ solution.

^b Absolute quantum yield was measured by using an integrating sphere.

The results of optical properties of **1-2** are shown in Figures 1, 2 and Table 1. The UV/vis spectra results of **1** are slightly red shifted compared to those of **2**. In both **1** and **2**, there was no significant difference in the UV absorption peaks due to the substituents. The structural optimization of **1** was performed by DFT calculations (see Figure S1 in SI). Their results show that the two benzofuran rings in **1** are planar and the HOMO and LUMO orbitals extend throughout the molecule. There is no clear difference in the HOMO-LUMO gap depending on the substituents, which is consistent with the experimental results. The calculation results of DFT of **2** were the same as those of **1**, the HOMO and LUMO orbitals extend throughout the molecule, and the HOMO-LUMO gap is almost the same regardless of the substituents (see Figure S2 in SI). The FL spectra of **1** in CH₂Cl₂ solution showed sharp peaks and a slight red shift when the electron-donating group was substituted. All compounds **1** had narrow Stokes shifts and moderate to high fluorescence quantum yields (32-74%).

Fluorescence measurements of **2** in CH₂Cl₂ solution showed that the spectra of **2c** (R = H), **2b** (R = Me), and **2a** (R = OMe) were sharp peaks due to their rigidity, and no significant difference in emission wavelength was observed. On the other hand, the spectrum of **2d** (R = CN) is broad and the red shift is observed compared to **2a-c**.

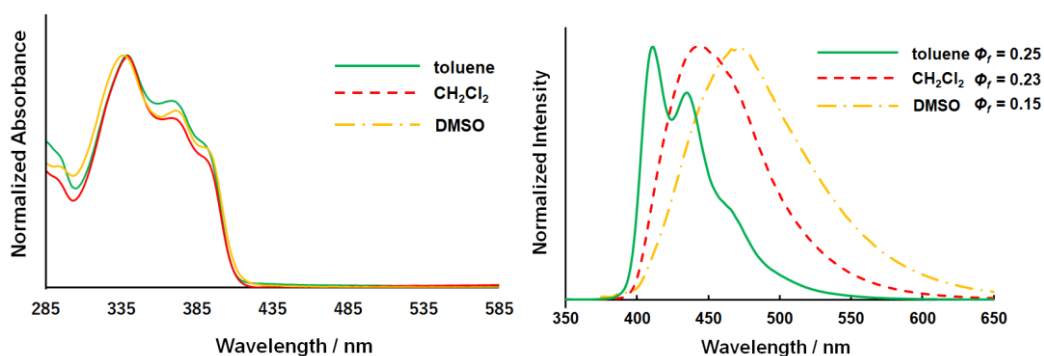


Figure 3. UV/vis (left) and FL (right) spectra of **2d** (R = CN) in various solvents

It seems that the spectrum of **2d** (R = CN) in CH₂Cl₂ shows the broad peak because the benzodifuran skeleton acts as a donor and the cyano phenyl group acts as an acceptor, leading to the intramolecular charge transfer. Therefore, the UV/vis and fluorescence spectra of **2d** was measured with various solvents (Figure 3).¹¹ There is no change in the UV/vis spectra, but the fluorescence spectra showed that the peak of **2d** in toluene having the lower polarity was observed a sharp peak at the shorter wavelength and as the polarity increased, the peaks of **2d** became broad and shifted to the longer wavelength. The difference in emission wavelength between toluene (411, 435 nm) and DMSO (472 nm) was 61 nm (3,144 cm⁻¹) and a relatively large fluorescent solvatochromism was observed.

In conclusion, we synthesized the 3,3'-diethynyl-substituted 2,2'-bibenzofuran derivatives **1** and 3,7-diethynyl-substituted benzodifuran derivatives **2** by Sonogashira coupling reaction of the various aryl alkynes and corresponding diiodo derivatives, which were prepared by iodocyclization, in good yields. The UV spectra results for both **1** and **2** were found to be unaffected by the substituents and their FL spectra show the narrow Stokes shifts, reflecting the planarity and rigidity of them. It was also found that diethynyl-substituted benzodifuran derivative **2d** (R = CN) only exhibited large solvatochromic property.

EXPERIMENTAL

General: FT-IR spectra were recorded on a JASCO FT/IR-4100 instrument. ¹H-NMR spectra were recorded at 400 MHz and ¹³C-NMR spectra at 100 MHz on a JEOL AL400 or ECS400. Chemical shifts were reported in ppm relative to tetramethylsilane or residual solvent as the internal standard. Mass spectral analyses were performed on a JEOL JMS-700 spectrometer for EI and FAB ionization. Preparative HPLC separation was undertaken with a JAI LC-908 chromatograph using 600 mm x 20 mm JAIGEL-1H and 2H GPC columns with CHCl₃ as an eluent. All reagents were obtained from commercial suppliers and used without purification.

General Synthesis of **1**

A solution of **6** (1.0 equiv.), aromatic acetylene (3.0 equiv.), Pd(PPh₃)₄ (5 mol%), and CuI (5 mol%) in

degassed triethylamine and degassed toluene (1:1) was stirred at 100 °C (**1a**, **1b**, **1d**) or degassed triethylamine and degassed THF (1:1) was stirred at 40 °C (**1c**) for overnight under a nitrogen atmosphere. After cooling to room temperature, hexane was added to the reaction mixture and then the precipitation was washed with hexane, MeOH, and cooling CHCl₃. Further purification was carried out by recrystallization to give the corresponding diethynyl-bibenzofuran derivatives **1**.

3,3'-Bis((4-methoxyphenyl)ethynyl)-2,2'-bibenzofuran (**1a**): Yellow solid. mp 244-245 °C, ¹H-NMR (400 MHz, CDCl₃) δ 7.81 (d, *J* = 8.0 Hz, 2H), 7.57-7.50 (m, 6H), 7.40 (dd, *J* = 7.6 Hz, 2H), 7.35 (dd, *J* = 7.6 Hz, 2H), 6.89 (d, *J* = 9.2 Hz, 4H), 3.84 (s, 6H). ¹³C-NMR data could not be obtained due to quite low solubility. IR (KBr) 3434, 2925, 2207, 1604, 1496, 1438, 1289, 1246, 1173, 1153, 1140, 1026, 831, 741, 692 cm⁻¹. MS (APCI) *m/z* 494 (M⁺); HRMS (APCI): calcd for C₃₄H₂₂O₄: 494.1518 found 494.1514.

3,3'-Bis(*p*-tolylethynyl)-2,2'-bibenzofuran (**1b**): Yellow solid. mp 237-238 °C. ¹H-NMR (400 MHz, CDCl₃) δ 7.82 (d, *J* = 8.0 Hz, 2H), 7.59-7.53 (m, 6H), 7.42 (td, *J* = 7.6 Hz, 1.2 Hz, 2H), 7.36 (td, *J* = 7.6 Hz, 0.8 Hz, 2H), 7.18 (d, *J* = 8.0 Hz, 4H), 2.39 (s, 6H). ¹³C-NMR (400 MHz, CDCl₃) δ 148.0, 138.6, 132.3, 130.7, 129.9, 128.9, 128.4, 127.1, 124.5, 122.9, 121.8, 120.4, 110.7, 103.4, 98.2, 79.6, 21.0. IR (KBr) 2921, 2851, 2203, 1494, 1441, 1338, 1242, 1153, 1139, 875, 809, 740 cm⁻¹. MS (APCI) *m/z* 462 (M⁺); HRMS (APCI): calcd for C₃₄H₂₂O₂: 462.1620 found 462.1616.

3,3'-Bis(phenylethynyl)-2,2'-bibenzofuran (**1c**): Yellow solid. mp 234-235 °C. ¹H-NMR (400 MHz, CDCl₃) δ 7.83 (d, *J* = 7.2 Hz, 2H), 7.64 (dd, *J* = 7.2 Hz, 4H), 7.58 (d, *J* = 8.0 Hz, 2H), 7.43 (t, *J* = 6.8 Hz, 2H), 7.39-7.36 (m, 8H). ¹³C-NMR (400 MHz, CDCl₃) δ 154.5, 148.1, 131.6, 128.8, 128.5, 128.4, 126.4, 123.8, 123.4, 120.9, 111.6, 103.3, 98.0, 80.2. IR (KBr) 3443, 3057, 2207, 1483, 1473, 1442, 1337, 1240, 1153, 1140, 751, 741, 687 cm⁻¹. MS (APCI) *m/z* 434 (M⁺); HRMS (APCI): calcd for C₄₀H₂₆O₂: 434.1307. found 434.1307.

3,3'-Bis((4-cyanophenyl)ethynyl)-2,2'-bibenzofuran (**1d**): Yellow solid. mp >300 °C. ¹H-NMR (400 MHz, DMSO-*d*₆, 150 °C) δ 7.86 (d, *J* = 7.6 Hz, 2H), 7.81-7.76 (m, 8H), 7.72 (d, *J* = 8.4 Hz, 7.54 (dd, *J* = 7.6 Hz, 2H), 7.46 (dd, *J* = 7.6 Hz, 2H). ¹³C-NMR data could not be obtained due to quite low solubility. IR (KBr) 3441, 3057, 2210, 1636, 1602, 1489, 1442, 1339, 1242, 1156, 1144, 876, 835, 745 cm⁻¹. MS (APCI) *m/z* 484 (M⁺); HRMS (APCI): calcd for C₃₄H₁₆N₂O₂: 484.1212 found 484.1201.

General Synthesis of **2**

A solution of **8** (1.0 equiv.), aromatic acetylene (4.0 equiv.), Pd(PPh₃)₄ (6 mol%), and CuI (6 mol%) in degassed triethylamine and degassed THF (1:1) was stirred at 60 °C for overnight under a nitrogen atmosphere. After filtration of the reaction mixture, the resulting solid was washed with MeOH, hexane, and CHCl₃. The crude **2** was purified by reprecipitation (hexane and CHCl₃) to give the corresponding diethynyl-benzodifuran derivatives **2**. Further purification was carried out by recyclable preparative HPLC, if necessary.

3,7-Di-((4-methoxyphenyl)ethynyl)-2,6-diphenylbenzo[1,2-*b*:4,5-*b'*]difuran (**2a**): Yellow solid; mp 284-285 °C; ¹H-NMR (CDCl₃, 400 MHz) δ 8.36 (d, *J* = 8.0 Hz, 4H), 7.80 (s, 2H), 7.59 (d, *J* = 8.8 Hz, 4H), 7.51 (t, *J* = 8.4 Hz, 4H), 7.41 (t, *J* = 7.2 Hz, 2H), 6.95 (d, *J* = 8.8 Hz, 4H), 3.88 (s, 6H). ¹³C-NMR (CDCl₃, 400 MHz) δ 159.8, 156.7, 150.9, 133.0, 130.3, 129.1, 128.7, 126.0, 114.2, 101.52, 101.50, 99.8, 97.2, 55.4; IR (KBr) 3058, 3002, 2964, 2938, 2911, 2838, 2533, 2206, 2045, 1945, 1869, 1609, 1513, 1491, 1464, 1447, 1426, 1391, 1290, 1253, 1174, 1115, 1027, 888, 837, 766, 683, 533 cm⁻¹; MS (APCI) *m/z* 570 (M⁺); HRMS (APCI): calcd for C₄₀H₂₆O₄: 570.1831 found 570.1815.

3,7-Di-(*p*-tolylethynyl)-2,6-diphenylbenzo[1,2-*b*:4,5-*b'*]difuran(**2b**): Yellow green solid. mp >300 °C. ¹H-NMR (CDCl₃, 400 MHz) δ 8.37 (d, *J* = 8.4 Hz, 4H), 7.81 (s, 2H), 7.56 (d, *J* = 8.4 Hz, 4H), 7.52 (t, *J* = 8.0 Hz, 4H), 7.42 (tt, *J* = 7.6 Hz, 1.6 Hz, 2H), 7.24 (d, *J* = 8.8 Hz, 4H), 2.42 (s, 6H). ¹³C-NMR (CDCl₃, 400 MHz) δ 150.9, 138.7, 131.4, 129.3, 129.2, 129.1, 128.72, 128.69, 126.00, 125.98, 120.3, 101.5, 99.7, 97.4, 21.6, IR (KBr) 3053, 3027, 2919, 2861, 2209, 1888, 1685, 1600, 1562, 1513, 1492, 1427, 1395, 1360, 1251, 1152, 1113, 1095, 810, 767, 687, 505 cm⁻¹; MS (APCI) *m/z* 538 (M⁺); HRMS (APCI): calcd for C₄₀H₂₆O₂: 538.1933. found 538.1914.

3,7-Di-(phenylethynyl)-2,6-diphenylbenzo[1,2-*b*:4,5-*b'*]difuran (**2c**): Yellow green solid. mp 296-297 °C. ¹H-NMR (CDCl₃, 400 MHz) δ 8.36 (d, *J* = 7.6 Hz, 4H), 7.80 (s, 2H), 7.66 (d, *J* = 7.2 Hz, 4H), 7.52 (t, *J* = 7.2 Hz, 4H), 7.43-7.42 (m, 8H). ¹³C-NMR (CDCl₃, 400 MHz) δ 150.9, 131.6, 130.16, 130.15, 129.3, 128.73, 128.72, 128.5, 126.0, 123.3, 101.5, 99.6, 99.5, 97.2, 81.0. IR (KBr) 3055, 3031, 2208, 1950, 1879, 1801, 1750, 1671, 1600, 1584, 1567, 1482, 1426, 1391, 1247, 1153, 1114, 1069, 839, 764, 688 cm⁻¹. MS (APCI) *m/z* 510 (M⁺); HRMS (APCI): calcd for C₃₈H₂₂O₂: 510.1620 found 510.1616.

3,7-Di-((4-cyanophenyl)ethynyl)-2,6-diphenylbenzo[1,2-*b*:4,5-*b'*]difuran (**2d**): Yellow solid. mp >300 °C. ¹H-NMR (DMSO-*d*₆, 400 MHz, 150 °C) δ 8.28 (d, *J* = 8.0 Hz, 2H), 8.02-7.95 (m, 1H), 7.88-7.87 (m, 2H), 7.79-7.74 (m, 1H), 7.66-7.51 (m, 4H). ¹³C-NMR data could not be obtained due to quite low solubility. IR (KBr) 3448, 2991, 2924, 2378, 2342, 2222, 2206, 1655, 1636, 1228, 1092, 957, 809 cm⁻¹; MS (APCI) *m/z* 560 (M⁺); HRMS (APCI): calcd for C₄₀H₂₀N₂O₂: 560.1525 found 560.1495.

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 - Although FL spectrum of **1d** (R=CN) was also measured in various solvents, no fluorescent solvatochromism was observed.