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Acid-Catalyzed Domino Reactions of Tetraarylbut-2-yne-1,4-diols. Synthesis of Conjugated Indenes and Inden-2-ones

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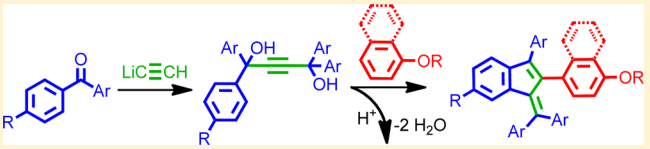
Supporting Information

ABSTRACT: The reaction of tetraarylbut-2-yne-1,4-diols with electron-rich aromatic compounds at room temperature, under *p*-TsOH catalysis, affords substituted polycyclic aromatic indene derivatives through a domino reaction involving the formation of a cationic allenylium intermediate. This species can undergo a series of competitive intramolecular cascade reactions, leading to a conjugated inden-2-one. This simple method allows the efficient synthesis of substituted indenes and inden-2-ones, in two steps, from aromatic ketones.



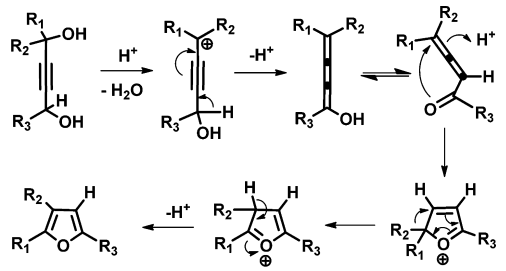
INTRODUCTION

Domino reactions are a powerful tool for the elegant construction of complex molecules from simple substrates with high atom economy. In this type of reaction, multiple C−C or C−X bonds are formed within the same reaction vessel, often involving different reactive processes, leading to the efficient synthesis of intricate molecules. Propargylic alcohols are versatile molecules that have been used with success in the domino synthesis of several cyclic compounds, including furans,[1] pyrroles,[1,2] tetrahydroquinolines,[3] oxazoles,[4] indenes,[5] pyrimidines,[6] and naphthopyrans.[7]

The reaction of diarylpropynols with naphthols, in acid medium, produces an ether intermediate which, through a series of consecutive intramolecular reactions (Claisen rearrangement, enolization, 1,5-hydrogen shift, and electrocyclization) leads to the in situ formation of naphthopyrans and the loss of one molecule of water.[8] These molecules exhibit important photochromic properties at room temperature and have been applied with great commercial success to the production of ophthalmic photochromic lenses.[9,10]

Curiously, the chemistry of the parent but-2-yne-1,4-diols has been much less explored, even though they show high reactivity in acidic medium and can be easily prepared from ketones.[11,12] Some but-2-yne-1,4-diols have been successfully converted to substituted furans[13] via a one-pot cascade reaction, involving the intramolecular electrophilic cyclization of the allenylium intermediate (Scheme 1), while 4-aminobut-2-yn-1-ols were efficiently transformed into dihydropyrroles, in high yields, by treatment with iodine at room temperature.[14] We have found that tetraarylbut-2-yne-1,4-diols can be easily transformed into indenes and inden-2-ones via a series of acid-catalyzed domino reactions.

Scheme 1. Acid-Catalyzed One-Pot Synthesis of Furans from Trisubstituted But-2-yne-1,4-diols



RESULTS AND DISCUSSION

Recently, we have shown that the acid-catalyzed reaction of tetraaryl-but-2-yne-1,4-diols with 2-naphthol, at room temperature, leads to the in situ formation of photochromic 1-vinylidenenaphtho[1,2-*b*]furans through a four-step domino reaction involving ether formation, Claisen rearrangement, enolization, and dehydration (Scheme 2).[15] Surprisingly, the substitution of 2-naphthol by the isomeric 1-naphthol, under the same reaction conditions, leads to a completely different set of cationic domino reactions which end in the formation of a conjugated indene.

1,1,4,4-Tetraarylbut-2-yne-1,4-diols **1** and **2** were easily prepared, in good yields (56−81%), by the reaction of lithium acetylide with an excess of benzophenones at room temperature (Scheme 3). The addition of a catalytic amount of *p*-TsOH to a solution of diol **1** (Ar = Ph) and 1-naphthol, in $CHCl_3$ at room temperature, leads to the rapid formation of an orange solution, from which the yellow dye **3** was easily isolated in

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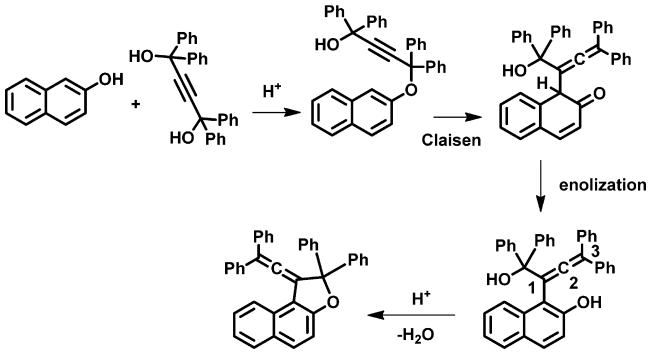
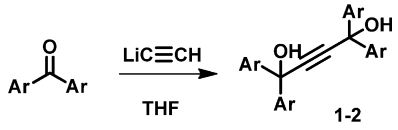
Scheme 2. Acid-Catalyzed One-Pot Synthesis of 1-Vinylidenenaphthofurans from Tetraarylbut-2-yne-1,4-diols

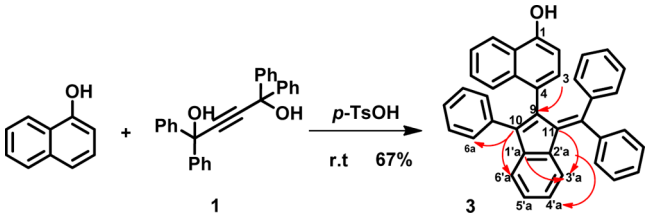


Scheme 3. Synthesis of 1,1,4,4-Tetraarylbut-2-yne-1,4-diols 1 (Ar = Ph) and 2 (Ar = *p*-MeOPh)



good yield after recrystallization (Scheme 4). This compound displays a strong and broad band in the UV−vis spectrum, centered at 372 nm (ε = 1.1 × 10^4 L mol^{-1} cm^{-1}), with a significant absorption above 400 nm; therefore, dilute solutions of **3** exhibit an intense yellow coloration.

Scheme 4. Synthesis of 1*H*-Indene Dye 3[a]



[a]Red arrows are related to long-range $^1H-^{13}C$ scalar couplings.

The structure of the polycyclic aromatic compound **3** was unambiguously established using 2D NMR experiments. In particular, $^1H-^1H$ scalar correlations among $H_{3'a}$ (6.54 ppm), $H_{4'a}$ (6.94 ppm), $H_{5'a}$ (7.21 ppm), and $H_{6'a}$ (7.39 ppm) were observed, which suggested the formation of an extra ring that gives rise to these four nonequivalent aromatic protons. Furthermore, a 2D HMBC experiment showed several $^1H-^{13}C$ long-range couplings that evidenced the five quaternary carbons of the indene part (Figure 1): correlations among the protons $H_{6'a}$ and H_{6a} (both at 7.15 ppm) and carbon C_{10} (144.1 ppm); correlation between the proton H_3 (6.88 ppm) and the carbon C_9 (137.3 ppm); correlations among the protons $H_{6'a}$ and $H_{4'a}$ and the carbon $C_{2'a}$ (137.6 ppm); correlations among the protons $H_{3'a}$ and $H_{5'a}$ and the carbon $C_{1'a}$ (143.0 ppm); correlation between the proton $H_{3'a}$ and the carbon C_{11} (139.0 ppm). Moreover, the scalar correlation between proton H_3 and carbon C_9 proves the naphthol group addition, resulting in bond formation between carbons C_4 and C_9. The phenolic OH signal was not observed in $CDCl_3$, probably due to a fast exchange, but the ^1H NMR spectrum recorded in DMSO showed its signal at 9.36 ppm.

The formation of dye **3** can be explained by a series of cascade reactions involving the elimination of two molecules of water, the generation of allenic intermediates, and two aromatic Friedel−Crafts type reactions (Scheme 5). The resonance-stabilized allenylium carbocation **A** is initially formed by dehydration of diol **1** and then attacked by 1-naphthol at one of the triple-bond carbons, which has some electrophilic character, leading to the formation of the allenic intermediate **B**. Then, under the present acidic conditions, this species loses a second molecule of water to afford the species **C**, which performs an intramolecular Nazarov electrocyclization[16,17] with formation of the five-membered ring **D**, which then provides the highly conjugated 1*H*-indene **3**.[18−20]

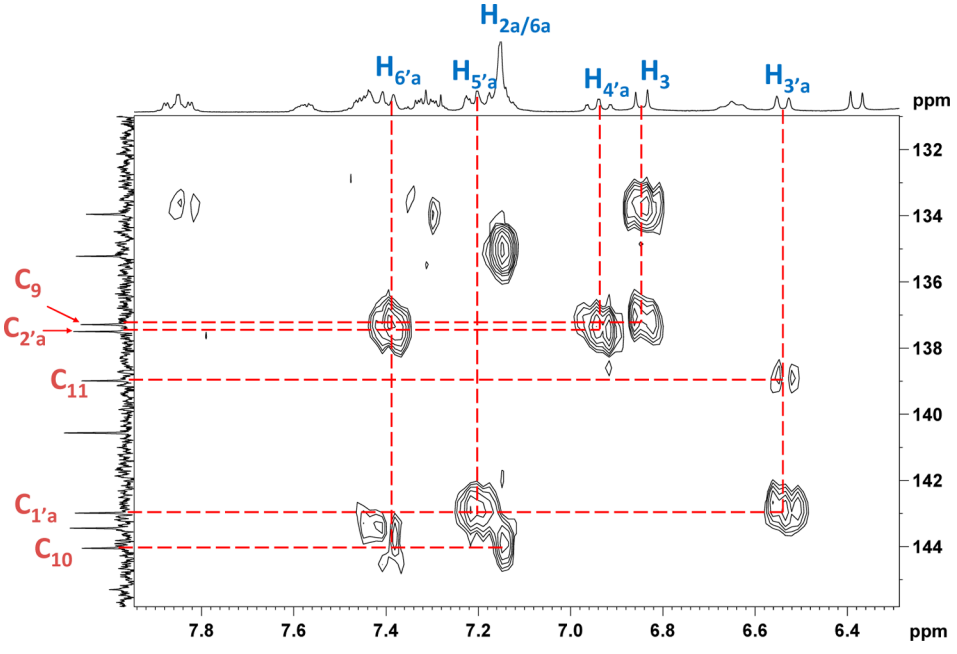


Figure 1. $^1H-^{13}C$ NMR HMBC of **3** in $CDCl_3$.

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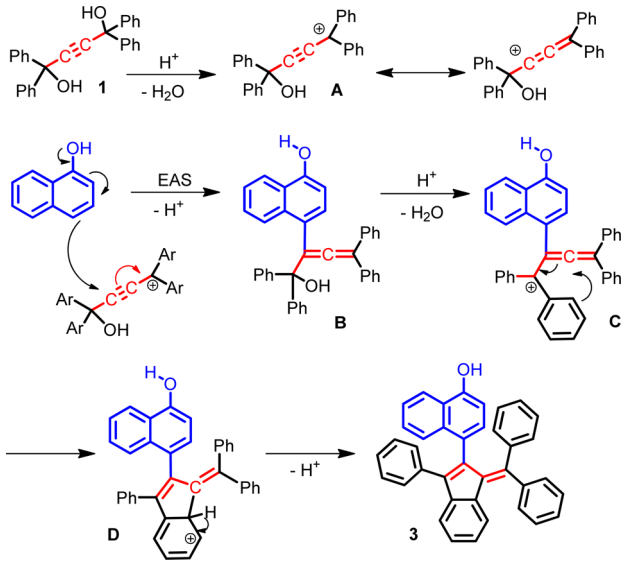
Scheme 5. Proposed Mechanism for the Formation of 1*H*-Indene Dye 3 from Tetraphenylbut-2-yne-1,4-diol 1 and 1-Naphthol



Under the same conditions the reaction of diol **2**, bearing four *p*-methoxy substituents, with 1-naphthol gave the corresponding 1*H*-indene dye **4a**. However, the reaction of **2** with phenol and 1-methoxynaphthalene, at room temperature, gave a mixture of two distinct dyes which were isolated by chromatography: the expected 1*H*-indenes **4b**,**c** and the second yellow dye **5**. With anisole, only the dye **5** was formed and isolated in a rather low yield (15%) (Scheme 6 and Table 1). The steric constraints of 1*H*-indenes **4a**−**c** dictate that the phenol, naphthol, or 1-methoxynaphthalene rings cannot be coplanar with the rest of the molecule and therefore they all exhibit similar λ_{max} values (389−396 nm). This evidence is confirmed by the fact that the λ_{max} values of phenolic dyes **4a**,**b** do not change upon addition of base (NBu_4OH). Similar 1-diarylmethylene-indenes have been prepared by palladium-catalyzed arylation of butadiynes[21] and acetylenes,[22] by acid-catalyzed intramolecular rearrangement of dimethylenecyclopropanes,[23] or by palladium-catalyzed intramolecular cyclization of 2-alkenylphenylacetylenes[24] and 1,2-dialkynylbenzenes.[25] However, all of these methods involve not easily accessible starting materials. These polycyclic compounds, also called benzofulvenes, are important precursors in polymer synthesis.[26−30]

The spectroscopic data of compound **5** pointed to a structure quite different from that of indenes **4a**−**c**. This dye shows an absorption band in the IR spectrum at 1715 cm^{-1} associated with a C=O bond, which was confirmed by the presence of a

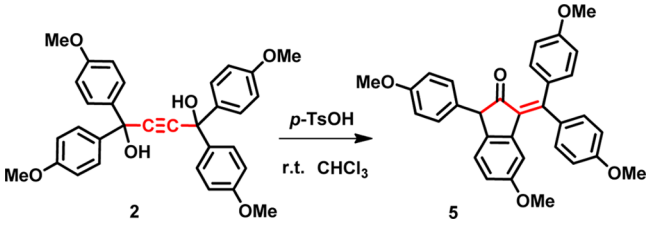
Table 1. Reactions of Tetraarylbut-2-yne-1,4-diol 2 with Different Aromatic Compounds

	product (yield, %)	
starting aromatic compd		
1-naphthol	**4a** (56)	
phenol	**4b** (23)	**5** (17)
1-methoxynaphthalene	**4c** (20)	**5** (20)
anisole		**5** (15)

signal at 203 ppm in the ^{13}C NMR spectrum, and exhibits an unexpected singlet in the ^{1}H NMR spectrum at 4.52 ppm. The 3-diphenylmethylene-1*H*-inden-2(3*H*)-one structure of this dye was unambiguously established using 2D NMR experiments: $^{1}H-^{1}H$ scalar couplings were measured in 2D-COSY experiments from the doublet signal of $H_{3'a}$ (6.29 ppm, ^{4}J = 2.5 Hz) up to $H_{6'a}$ (7.09 ppm) through $H_{5'a}$ (6.78 ppm). Dipolar contacts were evidenced among the singlet signal (H_{10}) at 4.51 ppm and the aromatic protons $H_{6'a}$ and $H_{2a/6a}$ at 7.09 ppm. $^{1}H-^{13}C$ long-range scalar correlations were measured between H_{10} (4.51 ppm) and the carbonyl function C_9 at 203 ppm. Finally, the benzhydrylidene part of the compound was highlighted by two $^{1}H-^{13}C$ long-range correlations among the protons $H_{2'/6'}$ (7.17 ppm) and $H_{2''/6''}$ (7.28 ppm) and the carbon C_{12} at 151.5 ppm.

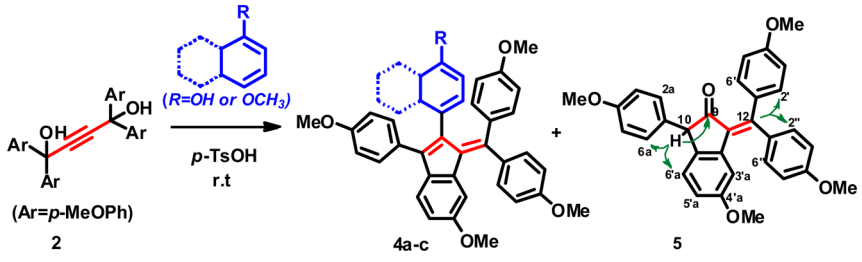
The inden-2-one dye **5** is probably formed by a competitive reaction in which the reactive allenylium carbocation, formed after dehydration of diol **2**, performs a set of intramolecular cascade reactions instead of being attacked by the aromatic compound present in the solution. In fact, treatment of diol **2** with *p*-TsOH for 24 h, at room temperature, affords directly the inden-2-one **5** (30%; Scheme 7); however, the diol **1**, with four phenyl groups, did not react under these conditions or under reflux, probably due to the lower reactivity of the unsubstituted phenyl rings.

Scheme 7. Synthesis of Inden-2-one 5 by Acid-Catalyzed Intramolecular Cyclization of Diol 2



We propose that, after acid-catalyzed dehydration of diol **2**, the carbocation **A** undergoes a rearrangement leading to the isomeric vinylic carbocation **D**, which then performs an

Scheme 6. Synthesis of Dyes 4a−c and 5 from Tetraarylbut-2-yne-1,4-diol 2



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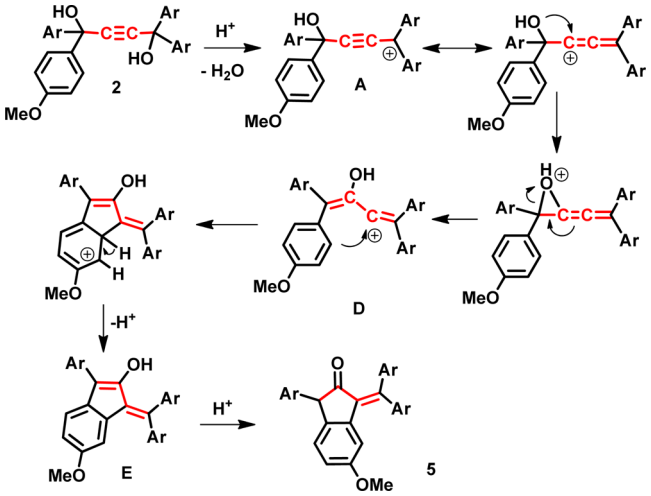
intramolecular electrophilic substitution to give the enol **E**. Finally, this compound, under the present acidic conditions, isomerizes to the inden-2-one **5** (Scheme 8).[16,17]

Scheme 8. Proposed Mechanism for the Formation of Inden-2-one 5 from But-2-yne-1,4-diol 2



While inden-1-ones are common compounds, 3-methylideneinden-2-ones are quite rare. A similar unsubstituted orange inden-2-one was previously prepared in two steps by $Co_2(CO)_8$-catalyzed deoxygenation of diphenylketene under a high pressure of CO at 120 °C for 40 h, followed by basic hydrolysis.[31] This compound exists preferentially in the ketonic form rather than in the enolic form (**E** in Scheme 8), and therefore it may be converted into substituted indenes by nucleophilic addition/elimination reactions.

CONCLUSION

In conclusion, under catalytic acidic conditions, tetraarylbut-2-yne-1,4-diols easily lose one water molecule, giving cationic allenylium intermediates that can react with electron-rich aromatic compounds to afford, through a domino reaction, substituted polycyclic aromatic indene derivatives. The allenylium intermediate derived from tetrakis(*p*-methoxyphenyl)but-2-yne-1,4-diol is very reactive and can perform a competitive intramolecular cascade reaction leading to an unusually colored inden-2-one. All of these complex transformations occur in a one-pot reaction at room temperature and constitute a simple synthesis of unusual polycyclic indenes and inden-2-ones.

EXPERIMENTAL SECTION

All reactions were monitored by thin-layer chromatography on aluminum plates coated with silica gel 60 (0.25 mm). NMR spectra were recorded at 298 K using 300, 400, or 500 MHz spectrometers. The new compounds were determined to be >95% pure by ^{1}H NMR spectroscopy. IR spectra were obtained using KBr pellets. Wavenumbers (λ_{max}) are reported in cm^{-1}. UV−vis spectra were recorded in $CHCl_3$. Melting points were determined in open capillary tubes and are uncorrected.

Synthesis of Diols 1 and 2. A suspension of lithium acetylide−ethylenediamine complex (90%, 2.475 g, 26.9 mmol) and 1.5 equiv of benzophenone or 4,4′-dimethoxybenzophenone in dry THF (50 mL) was stirred at room temperature for 3 days. The mixture was then filtered and the solvent evaporated under reduced pressure. The residue was diluted with water (75 mL) and this solution extracted with AcOEt (3 × 40 mL). The organic phase was dried (Na_2SO_4) and the solvent slowly removed under reduced pressure. During the solvent evaporation, the ketone, a white solid, was removed by fractionation precipitation. The remaining oil was purified by chromatography (petroleum ether/ethyl acetate), affording the diols as white solids.

*1,1,4,4-Tetraphenylbut-2-yne-1,4-diol (**1**).* Yield: 3.80 g, 81%. Mp: 201.4−203.0 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.59 (d, J = 7.9 Hz, 8H), 7.39−7.23 (m, 12H), 2.86 (s, 2H, OH). EI-MS (TOF): m/z (%) 372 (32), 371 (11), 370 (14), 356 (28), 344 (22), 267 (22), 265 (27), 252 (11), 208 (10), 207 (14), 182 (64), 181 (10), 179 (13), 178 (17), 165 (19), 05 (100), 77 (50). HRMS: calcd for $C_{28}H_{20}O$ (M − H_2O) 372.1514, found 372.1503.

*1,1,4,4-Tetrakis(4-methoxyphenyl)but-2-yne-1,4-diol (**2**).* Yield: 1.42 g, 56%. Mp: 136.5−138.0 °C. ^{1}H NMR (400 MHz,$CDCl_3$): δ 7.48 (d, J = 8.7 Hz, 8H), 6.83 (d, J = 8.7 Hz, 8H), 3.77 (s, 12H, OCH_3), 2.80 (s, 2H, OH). EI-MS (TOF): m/z (%) 492 (11), 490 (10), 476 (23), 464 (14), 243 (10), 242 (81), 211 (33), 135 (100), 107 (15), 92 (19), 77 (19). HRMS: calcd for $C_{32}H_{28}O_5$ (M − H_2O) 492.1937, found 492.1936.

Synthesis of 4-(3-Phenyl-1-(diphenylmethylene)-1*H*-inden-2-yl)naphthalen-1-ol (3). A solution of 1-naphthol (250 mg; 1.73 mmol), diol **1** (1.1 equiv), and *p*-toluenesulfonic acid hydrate (catalytic) in $CHCl_3$ (15 mL) was stirred at room temperature for 2 h. Water (40 mL) was added to the deep orange solution, the organic layer was separated, and the aqueous phase was extracted with ethyl acetate (2 × 25 mL). The organic extracts were dried with anhydrous Na_2SO_4, and the solvent was removed under reduced pressure, leaving an orange oil which was crystallized from CH_2Cl_2 and petroleum ether to afford indene **3** (583 mg; 67%) as a yellow solid. UV−vis: λ_{max} 372 nm ($CHCl_3$, ε = 1.1 × 10^4). Mp: 241.2−242.0 °C. IR (KBr, cm^{-1}): 3438, 3059, 2359, 2337, 1630, 1587, 1436, 1336, 1272, 1218, 1179, 1043, 750, 700. ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.26 (broad, $H_{3'/4'/5'}$), 6.38 (d, J = 7.6 Hz, H_2), 6.54 (d, J = 7.8 Hz, $H_{3'a}$), 6.66 (broad, $H_{2'/6'}$), 6.84 (d, J= 7.6 Hz, H_3), 6.94 (t, J = 7.4 Hz, $H_{4'a}$), 7.15 (broad, $H_{2a\text{-}6a}$), 7.20 (t, J = 7.2 Hz, $H_{5'a}$), 7.31 (m, $H_{6/7}$), 7.39 (d, J = 7.2 Hz, $H_{6'a}$), 7.45 (m, $H_{6''}$), 7.57 (m, $H_{2''}$), 7.84 (d, J = 8.4 Hz, H_5), 7.87 (d, J = 8.3 Hz, H_8). ^{13}C NMR (75 MHz, $CDCl_3$): δ 107.9, 119.8, 121.0, 123.7, 123.8, 124.3, 125.0, 125.5, 125.8, 126.3, 126.6, 126.9, 127.7, 127.8, 128.4, 128.8, 129.2, 129.5, 130.1, 130.6, 134.0, 135.2, 137.3, 137.5, 139.0, 140.6, 143.0, 143.4, 144.0, 149.9. EI-MS (TOF): m/z (%) 498 (100), 422 (22), 421 (97), 420 (27), 344(8), 315 (5). HRMS: calcd for $C_{38}H_{26}O$ 498.1984, found 498.1983.

Synthesis of Indene Dyes 4a−c and Inden-2-one 5. A solution of the aromatic compound (0.35 mmol), diol **2** (1.1 equiv; 195 mg; 0.38 mmol) and *p*-toluenesulfonic acid hydrate (catalytic) in $CHCl_3$ (15 mL) was stirred at room temperature for 2 h. After water addition (30 mL) the organic phase was separated and the aqueous phase was extracted with diethyl ether (2 × 25 mL). The combined organic extracts were dried (Na_2SO_4), and the solvent was removed under reduced pressure. The residue was purified by crystallization (CH_2Cl_2/petroleum ether) (compound **4a**) or column chromatography (0−25% EtOAc/petroleum ether) (compounds **4b**,**c**, **5**) to afford one or two dyes.

With 1-naphthol as the starting material, the red dye **4a** (120 mg; 56% yield) was obtained.

*4-(1-(Bis(4-methoxyphenyl)methylene)-6-methoxy-3-(4-methoxyphenyl)-1H-inden-2-yl)naphthalen-1-ol (**4a**).* UV−vis: λ_{max} = 395 nm ($CHCl_3$, ε = 1.3 × 10^4). Mp: 127.5−129.8 °C. IR (KBr, cm^{-1}): 3438, 2930, 2359, 1601, 1501, 1465, 1251, 1172, 1029, 836. ^{1}H NMR (500 MHz, T = 353 K, DMSO-d_6): δ 3.51 (s, OCH_3), 3.51 (s, OCH_3), 3.67 (s, OCH_3), 3.85 (s, OCH_3), 5.98 (broad, $H_{3'/5'}$), 6.10 (d, J = 2.2 Hz, $H_{3'a}$), 6.40 (broad, $H_{2'/6'}$), 6.47 (d, J = 7.8 Hz, H_2), 6.72 (d, J = 8.5 Hz, $H_{3a/5a}$), 6.74 (dd, J = 1.8 Hz and J = 8.3 Hz, $H_{5'a}$), 6.84 (d, J = 7.7 Hz, H_3), 7.05 (d, J = 8.6 Hz, $H_{2a/6a}$), 7.00−7.15 (broad, $H_{3''/5''/6''}$), 7.12 (d, J = 8.4 Hz, $H_{6'a}$), 7.22 (t, J = 7.9 Hz, H_7), 7.26 (t, J = 7.3 Hz, H_6), 7.40 (broad, $H_{2''}$), 7.66 (d, J = 8.3 Hz, H_5), 7.86 (d, J = 8.2 Hz, H_8), 9.37 (broad, OH). ^{13}C NMR (75 MHz, T = 353 K, DMSO-d_6): δ 55.41, 55.44, 55.47, 55.9, 107.9, 110.4, 112.0, 112.6, 113.9, 114.5, 114.8, 120.0, 122.0, 123.9, 124.5, 125.7, 125.9, 126.0, 127.9, 128.5,

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130.36, 130.45, 131.9, 132.5, 133.8, 135.6, 135.8, 136.1, 137.9, 139.5, 141.9, 149.1, 152.1, 157.6, 158.4, 158.8, 160.3. EI-MS (TOF): m/z (%) 618 (100), 511 (11), 367 (13), 339 (7). HRMS: calcd for $C_{42}H_{34}O_5$ 618.2406, found 618.2411.

With phenol as the starting material, two dyes were isolated: the yellow-orange solid **5** (17%, less polar) and the red solid **4b** (23%, more polar).

*4-(1-(Bis(4-methoxyphenyl)methylene)-6-methoxy-3-(4-methoxyphenyl)-1H-inden-2-yl)phenol (**4b**).* UV−vis: λ_{max} 389 nm ($CHCl_3$, ε = 1.7 × 10^4). Mp: 202.2−204.9 °C. IR (KBr, cm^{-1}): 3457, 3952, 2833, 1601, 1501, 1465, 1279, 1243, 1172, 1029, 836. ^{1}H NMR (300 MHz, DMSO-d_6): δ 3.45 (s, OCH_3), 3.61 (s, OCH_3), 3.74 (s, OCH_3), 3.85 (s, OCH_3), 5.88 (d, J = 1.8 Hz, $H_{3'a}$), 6.20 (d, J = 8.5 Hz, H_2), 6.43 (d, J = 9 Hz, $H_{3'}$), 6.54d, J = 8.5 Hz, H_3), 6.67 (dd, J = 1.8 Hz and J = 8.2 Hz, $H_{5'a}$), 6.72 (d, J = 8.8 Hz, $H_{2'}$), 6.85 (d, J = 8.8 Hz, H_{3a}), 7.02 (d, $H_{6'a}$), 7.05 (d, J = 8.3 Hz, H_{2a}), 7.08 (d, J = 8.5 Hz, $H_{3''}$), 7.25 (d, J =8.3 Hz, $H_{2''}$), 8.94 (s, OH). ^{13}C NMR (75 MHz, DMSO-d_6): δ 55.1, 55.4, 55.5, 55.8, 109.9, 111.8, 112.9, 113.9, 114.3, 114.7, 119.8, 127.4, 127.8, 131.1,132.0, 132.5, 133.7, 133.9, 135.9, 136.2, 136.7, 136.9, 139.5, 140.8, 148.8, 155.1, 157.6, 158.4, 159.4, 160.4. EI-MS (TOF): m/z (%) 568 (100), 553 (14), 460 (3), 417 (3), 284 (3). HRMS: calcd for $C_{38}H_{32}O_5$ 568.2250, found 568.2256.

With 1-methoxynaphthalene as the starting material, two dyes were isolated: the orange solid **4c** (20%) and the yellow-orange solid **5** (20%).

*1-(1-(Bis(4-methoxyphenyl)methylene)-6-methoxy-3-(4-methoxyphenyl)-1H-inden-2-yl)-4-methoxynaphthalene (**4c**).* UV−vis: λ_{max} 396 nm ($CHCl_3$, ε = 1.5 × 10^4). Mp: 239.7−241.8 °C. IR (KBr, cm^{-1}): 3438, 3002, 2959, 2930, 2830, 2366, 1601, 1501, 1458, 1251, 1172, 1086, 1029, 822, 767. ^{1}H NMR (300 MHz, $CDCl_3$): δ 3.53 (s, OCH_3), 3.56 (s, OCH_3), 3.72 (s, OCH_3), 3.88 (s, 2 × OCH_3), 5.76 (broad, $H_{3'/5'}$), 6.11 (broad, $H_{2'/6'}$), 6.31 (d, J = 2.1 Hz, $H_{3'a}$), 6.42 (d, J = 7.9 Hz, H_2), 6.69 (d, J = 8.8 Hz, $H_{3a/5a}$), 6.76 (dd, J = 2.3 Hz and J = 8.3 Hz, $H_{5'a}$), 6.89 (d, J = 7.9 Hz, H_3), 6.96 (m, $H_{3''/5''}$), 7.11 (d, $H_{6'a}$), 7.11 (d, J = 8.6 Hz, $H_{2a/6a}$), 7.15 (dd, 2.5 Hz and J = 8.7 Hz, $H_{6''}$), 7.29 (m, $H_{6/7}$), 7.51 (dd, J 2 Hz and J = 8.2 Hz, $H_{2''}$), 7.81 (m, H_5), 7.96 (m, H_8). ^{13}C NMR (75 MHz, $CDCl_3$): δ 54.98, 55.02, 55.18, 55.34, 55.41, 103.6, 109.6, 111.2, 112.4, 113.2, 113.8, 114.2, 120.1, 121.3, 124.3, 125.2, 125.6, 126.2, 126.2, 127.9, 128.2, 129.8, 130.4, 132.0, 132.7, 133.5, 133.8, 135.8, 136.3, 138.1, 138.4, 139.5, 148.9, 154.0, 157.7, 158.2, 158.6, 160.1. EI-MS (TOF): m/z (%) 632 (100), 311 (7), 255 (6), 243 (8) 237 (16), 236 (27), 152 (5). HRMS: calcd for $C_{43}H_{36}O_5$ 632.2563, found 632.2562.

Starting from anisole only the yellow/orange solid **5** was isolated.

*3-(Bis(4-methoxyphenyl)methylene)-5-methoxy-1-(4-methoxyphenyl)-1H-inden-2(3H)-one (**5**).* UV−vis: λ_{max} 394 nm ($CHCl_3$, ε = 1.2 × 10^4). Mp: 90.7−92.7 °C. IR (KBr, cm^{-1}): 3438, 2952, 2830, 1715, 1601, 1572, 1501, 1479, 1295, 1251, 1172, 1029, 829. ^{1}H NMR (300 MHz, $CDCl_3$): δ 3.51 (s, OCH_3), 3.80 (s, OCH_3), 3.81 (s, OCH_3), 3.88 (s, OCH_3), 4.52 (s, H_{10}), 6.29 (d, J = 2.7 Hz, $H_{3'a}$), 6.78 (dd, J = 2.5 Hz and J = 8.2 Hz, $H_{5'a}$), 6.81 (d, J = 8.9 Hz, $H_{3'/5'}$), 6.86 (d, J = 8.7 Hz, $H_{3a/5a}$), 6.97 (d, J = 8.9 Hz, $H_{3''/5''}$), 7.09 (d, J = 8.5 Hz, $H_{2a/6a}$ and $H_{6'a}$), 7.17 (d, J = 8.9 Hz, $H_{2'/6'}$), 7.28 (d, J = 8.7 Hz, $H_{2''/6''}$). ^{13}C NMR (75 MHz, $CDCl_3$): δ 55.9, 55.22, 55.28, 55.4, 56.8, 107.5, 112.8, 114.0, 114.1, 115.7, 126.6, 129.5, 129.9, 131.7, 131.9, 132.4, 133.0, 133.6, 133.9, 142.4, 151.6, 158.4, 158.7, 160.5, 160.7, 203.0. EI-MS (TOF): m/z (%) 492 (100), 464 (34), 449 (22), 434 (10), 433 (27), 357 (26), 341 (11), 254 (15), 239 (13), 226 (35), 211 (20). HRMS: calcd for $C_{32}H_{28}O_5$ 492.1937, found 492.1932.

Direct Synthesis of Inden-2-one 5 from Diol 2. To a solution of diol **2** (100 mg; 0.19 mmol) in $CHCl_3$ (10 mL) was added *p*-TsOH (catalytic). The mixture was stirred at room temperature for 1 day. Then, water (50 mL) was added and the organic phase was separated. The aqueous phase was extracted with $CHCl_3$ (3 × 25 mL), and the organic phases were dried with Na_2SO_4 and concentrated under reduced pressure. The residue was purified by crystallization (CH_2Cl_2/petroleum ether) to give **5** as yellow-orange crystals (29 mg; 30%).

■ ASSOCIATED CONTENT

Supporting Information

One- and two-dimensional NMR spectra of all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Nishibayashi, Y.; Yoshikawa, M.; Inada, Y.; Milton, M. D.; Hidai, M.; Uemura, S. *Angew. Chem., Int. Ed.* **2003**, *42*, 2681.

(2) Liu, X. T.; Huang, L.; Zheng, F. J.; Zhan, Z. P. *Adv. Synth. Catal.* **2008**, *350*, 2778.

(3) Ye, Y. Y.; Zhao, L. B.; Zhao, S. C.; Yang, F.; Liu, X. Y.; Liang, Y. M. *Chem. Asian J.* **2012**, *7*, 2014.

(4) Pan, Y. M.; Zheng, F. J.; Lin, H. X.; Zhan, Z. P. *J. Org. Chem.* **2009**, *74*, 3148.

(5) Zhu, Y. X.; Yin, G. W.; Hong, D.; Lu, P.; Wang, Y. G. *Org. Lett.* **2011**, *13*, 1024.

(6) Lin, M.; Chen, Q. Z.; Zhu, Y.; Chen, X. L.; Cai, J. J.; Pan, Y. M.; Zhan, Z. P. *Synlett* **2011**, 1179.

(7) Gabbutt, C. D.; Heron, B. M.; Instone, A. C.; Horton, P. N.; Hursthouse, M. B. *Tetrahedron* **2005**, *61*, 463.

(8) Zsindely, J.; Schmid, H. *Helv Chim. Acta* **1968**, *51*, 1510.

(9) Corns, S. N.; Partington, S. M.; Towns, A. D. *Color. Technol.* **2009**, *125*, 249.

(10) Coelho, P. J.; Silva, C. J. R.; Sousa, C.; Moreira, S. *J. Mater. Chem. C* **2013**, *1*, 5387.

(11) Sundar, J. K.; Kumar, K. M.; Vijayakumar, V.; Suresh, J.; Natarajan, S.; Lakshman, P. L. N. *Acta Crystallogr., Sect. E: Struct. Rep. Online* **2010**, *66*, O679.

(12) Sekikawa, A.; Sugi, H.; Tahara, K.; Toda, F. US Patent 4780317, 1988.

(13) Mothe, S. R.; Lauw, S. J. L.; Kothandaraman, P.; Chan, P. W. H. *J. Org. Chem.* **2012**, *77*, 6937.

(14) Ji, K. G.; Zhu, H. T.; Yang, F.; Shaukat, A.; Xia, X. F.; Yang, Y. F.; Liu, X. Y.; Liang, Y. M. *J. Org. Chem.* **2010**, *75*, 5670.

(15) Sousa, C. M.; Berthet, J.; Delbaere, S.; Coelho, P. J. *J. Org. Chem.* **2013**, *78*, 6956.

(16) Spencer, W. T.; Levin, M. D.; Frontier, A. J. *Org. Lett.* **2011**, *13*, 414.

(17) Spencer, W. T.; Vaidya, T.; Frontier, A. J. *Eur. J. Org. Chem.* **2013**, 3621.

(18) Langer, P.; Doring, M.; Seyferth, D.; Gorls, H. *Chem. Eur. J.* **2001**, *7*, 573.

(19) Lu, J. M.; Shi, M. *Chem. Eur. J.* **2009**, *15*, 6065.

(20) Cordier, P.; Aubert, C.; Malacria, M.; Lacote, E.; Gandon, V. *Angew. Chem., Int. Ed.* **2009**, *48*, 8757.

(21) Dyker, G.; Borowski, S.; Henkel, G.; Kellner, A.; Dix, I.; Jones, P. G. *Tetrahedron Lett.* **2000**, *41*, 8259.

(22) Pfeffer, M.; Sutter, J. P.; Rotteveel, M. A.; Decian, A.; Fischer, J. *Tetrahedron* **1992**, *48*, 2427.

(23) Lu, B. L.; Shi, M. *Eur. J. Org. Chem.* **2011**, 243.
(24) Ye, S. Q.; Gao, K.; Zhou, H. B.; Yang, X. D.; Wu, J. *Chem. Commun.* **2009**, 5406.
(25) Lee, C. Y.; Wu, M. J. *Eur. J. Org. Chem.* **2007**, 3463.
(26) Nakano, T.; Takewaki, K.; Yade, T.; Okamoto, Y. *J. Am. Chem. Soc.* **2001**, *123*, 9182.
(27) Cappelli, A.; Mohr, G. L.; Anzini, M.; Vomero, S.; Donati, A.; Casolaro, M.; Mendichi, R.; Giorgi, G.; Makovec, F. *J. Org. Chem.* **2003**, *68*, 9473.
(28) Kosaka, Y.; Kitazawa, K.; Inomata, S.; Ishizone, T. *ACS Macro Lett.* **2013**, *2*, 164.
(29) Cappelli, A.; Paolino, M.; Grisci, G.; Giuliani, G.; Donati, A.; Mendichi, R.; Boccia, A. C.; Botta, C.; Mroz, W.; Samperi, F.; Scamporrino, A.; Giorgi, G.; Vomero, S. *J. Mater. Chem.* **2012**, *22*, 9611.
(30) Cappelli, A.; Galeazzi, S.; Giuliani, G.; Anzini, M.; Donati, A.; Zetta, L.; Mendichi, R.; Aggravi, M.; Giorgi, G.; Paccagnini, E.; Vomero, S. *Macromolecules* **2007**, *40*, 3005.
(31) Hong, P.; Sonogash, K.; Hagihara, N. *Tetrahedron Lett.* **1971**, 1105.