



# Reaction of azulene with 1,2-bis[4-(dimethylamino)phenyl]-1,2-ethanediol in a mixed solvent of methanol and acetonitrile in the presence of hydrochloric acid: a facile one-pot synthesis and properties of new triarylethylenes possessing an azulene-1-yl group

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## ARTICLE INFO

### Article history:

Received 8 March 2011

Received in revised form 7 May 2011

Accepted 9 May 2011

Available online 14 May 2011

### Keywords:

Azulene

Conjugated  $\pi$ -electron systems

Guaiazulene

One-pot syntheses

Properties

Triarylethylenes

Tetraarylethylenes

Tetraarylethanes

X-ray crystal structures

## ABSTRACT

Reaction of azulene (**1**) with 1,2-bis[4-(dimethylamino)phenyl]-1,2-ethanediol (**2**) in a mixed solvent of methanol and acetonitrile in the presence of 36% hydrochloric acid at 60 °C for 3 h gives 2-(azulene-1-yl)-1,1-bis[4-(dimethylamino)phenyl]ethylene (**3**) (8% yield), 1-(azulene-1-yl)-(*E*)-1,2-bis[4-(dimethylamino)phenyl]ethylene (**4**) (28% yield), and 1,3-bis[2,2-bis[4-(dimethylamino)phenyl]ethenyl]azulene (**5**) (9% yield). Besides the above products, this reaction affords 1,1-di(azulene-1-yl)-2,2-bis[4-(dimethylamino)phenyl]ethane (**6**) (15% yield), a *meso* form (1*R*,2*S*)-1,2-di(azulene-1-yl)-1,2-bis[4-(dimethylamino)phenyl]ethane (**7**) (6% yield), and the two enantiomeric forms (1*R*,2*R*)- and (1*S*,2*S*)-1,2-di(azulene-1-yl)-1,2-bis[4-(dimethylamino)phenyl]ethanes (**8**) (6% yield). Furthermore, addition reaction of **3** with **1** under the same reaction conditions as the above provides **6**, in 46% yield, which upon oxidation with DDQ (=2,3-dichloro-5,6-dicyano-1,4-benzoquinone) in dichloromethane at 25 °C for 24 h yields 1,1-di(azulene-1-yl)-2,2-bis[4-(dimethylamino)phenyl]ethylene (**9**) in 48% yield. Interestingly, reaction of 1,1-bis[4-(dimethylamino)phenyl]-2-(3-guaiazulenyl)ethylene (**11**) with **1** in a mixed solvent of methanol and acetonitrile in the presence of 36% hydrochloric acid at 60 °C for 3 h gives guaiazulene (**10**) and **3**, owing to the replacement of a guaiazulene-3-yl group by an azulene-1-yl group, in 91 and 46% yields together with **5** (19% yield) and **6** (13% yield). Similarly, reactions of 2-(3-guaiazulenyl)-1,1-bis(4-methoxyphenyl)ethylene (**12**) and 1,1-bis[4-[2-(dimethylamino)ethoxy]phenyl]-2-(3-guaiazulenyl)ethylene (**13**) with **1** under the same reaction conditions as the above provide **10**, 2-(azulene-1-yl)-1,1-bis(4-methoxyphenyl)ethylene (**16**), and 1,3-bis[2,2-bis(4-methoxyphenyl)ethenyl]azulene (**17**) (93, 34, and 19% yields) from **12** and **10** and 2-(azulene-1-yl)-1,1-bis[4-[2-(dimethylamino)ethoxy]phenyl]ethylene (**18**) (97 and 58% yields) from **13**.

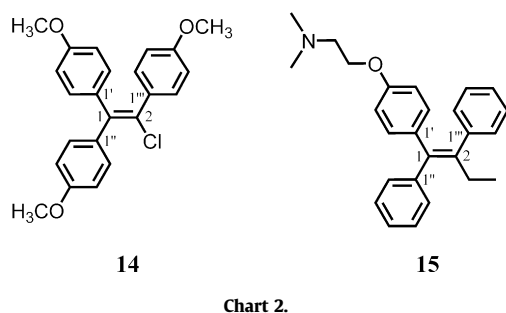
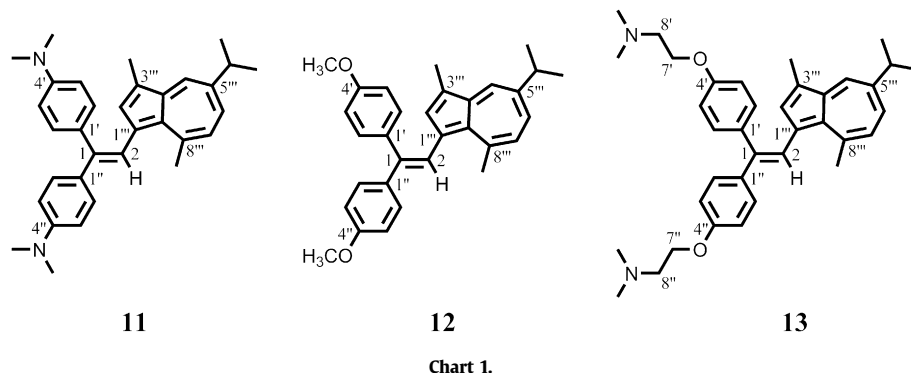
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## 1. Introduction

Parent azulene (**1**) and its derivatives have been studied to a considerable extent over the past 50 years and an extremely large number of the studies have been well documented and further naturally occurring guaiazulene<sup>1</sup> (**10**) (=7-isopropyl-1,4-dimethylazulene) has been widely used clinically as an anti-inflammatory and an anti-ulcer agent. However, none have really been used as other industrial materials. As a series of basic studies on creation and potential utility of novel functional materials with a guaiazulene-3-yl (=5-isopropyl-3,8-dimethylazulene-1-yl) (or another azulene-1-yl) group possessing a large dipole moment,<sup>2</sup> we

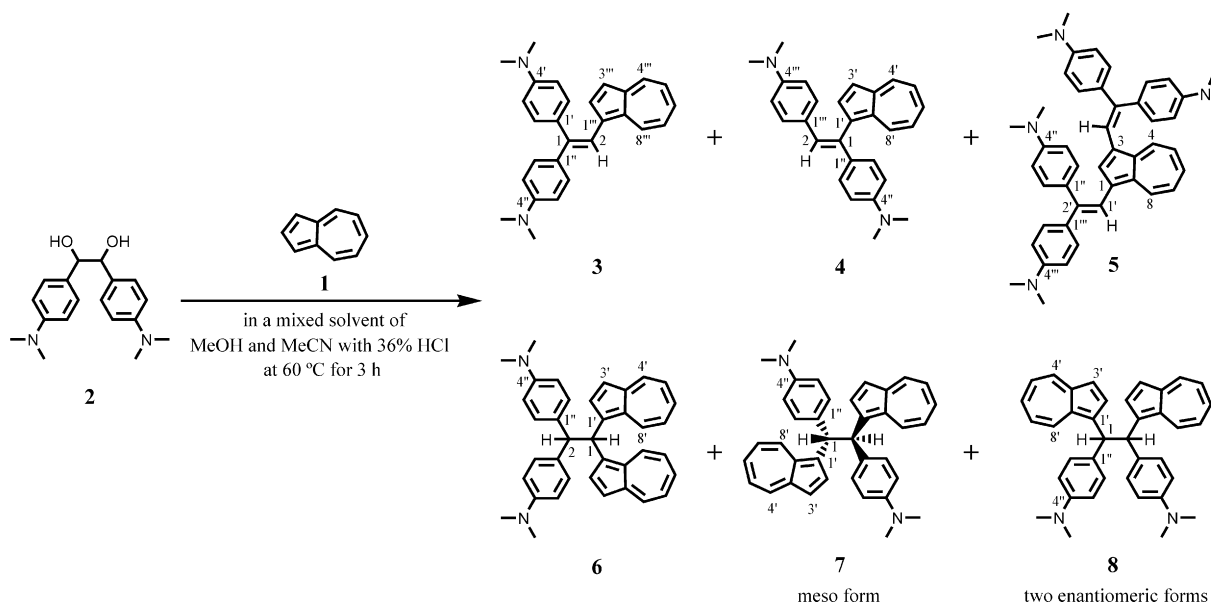
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have been working on facile preparation and crystal structures as well as spectroscopic, chemical, and electrochemical properties of new conjugated  $\pi$ -electron systems possessing a guaiazulene-3-yl<sup>3–25</sup> [or an azulene-1-yl<sup>10,17</sup> or a 3-(methoxycarbonyl)azulene-1-yl<sup>26</sup>] group. During the course of our basic and systematic investigations on azulenes, we discovered an efficient one-pot synthesis of the triarylethylenes **11**<sup>19</sup> and **12**<sup>10</sup> and a facile preparation of the triarylethylene **13**<sup>20</sup> previously (see Chart 1). Interestingly, the unique products **11** and **12**, possessing interesting molecular structures, serve as strong two-electron donors and one-electron acceptors and further the estrogenic activity of the chlorotrianisene analogue **12**<sup>10</sup> and the anti-estrogenic activity of the tamoxifen analogue **13**<sup>20</sup> are expected.<sup>27</sup> In relation to the triarylethylenes **11–13** with a guaiazulene-3-yl group, it is well known that chlorotrianisene [=2-chloro-1,1,2-tris(4-methoxyphenyl)ethylene]<sup>28</sup> (**14**) (see Chart 2) exhibits significant estrogenic activity,

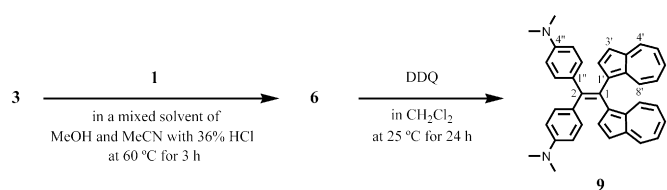


while tamoxifen {=1-[4-(2-dimethylaminoethoxy)phenyl]-(*E*)-1,2-diphenyl-1-butene} (15) (see Chart 2) exhibits significant anti-estrogenic activity, owing to the difference between the substituents of chlorotrianisene and those of tamoxifen. Furthermore, tamoxifen, which serves as a non-steroidal anti-estrogen,<sup>30</sup> has become a widely used drug for a first line endocrine therapy for all stages of breast cancer in pre- and postmenopausal women.<sup>32</sup> In addition to the above, chemistry and biochemistry of tamoxifen and its derivatives have been studied to a considerable extent over the past 30 years and syntheses, properties, and biological activities

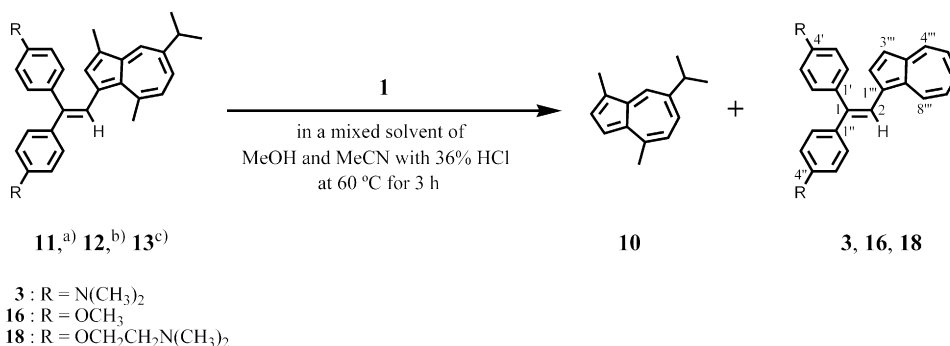
of those compounds have been reported.<sup>33–41</sup> Besides the above, numerous syntheses and properties of triaryl- (or tetraaryl-) substituted olefins have been documented.<sup>42–59</sup> Along with those studies on tri- and tetraarylethylenes, we have quite recently discovered the following three unique reactions (I)–(III); namely, (I) the reaction of **1** with **2** in a mixed solvent of methanol and acetonitrile in the presence of 36% hydrochloric acid at 60 °C for 3 h, giving new triarylethylenes **3–5** and new tetraarylethanes **6–8** simultaneously (see Scheme 1); (II) the addition reaction of **3** with **1** under the same reaction conditions as for (I), affording **6**, selectively, which upon oxidation with DDQ in dichloromethane at 25 °C for 24 h yields a new tetraarylethylene **9** selectively (see Scheme 2); and (III) the reactions of **11** (and **12** and **13**) with **1** under the same reaction conditions as for (I), providing **3** with **11** (and the previously reported chlorotrianisene analogue **16**<sup>10</sup> from **12** and a new tamoxifen analogue **18** from **13**), together with **10**, respectively, owing to the replacement of a 5-isopropyl-3,8-dimethylazulen-1-yl group by an azulen-1-yl group (see Scheme 3). We now wish to report spectroscopic properties, crystal structures, and electrochemical behavior of the products, with a view to comparative study, obtained from our discovered reactions of (I)–(III) and further a plausible reaction pathway for the formation of the triarylethylenes **3**, **16**, and **18** yielded from each reaction of (III).



**Scheme 1.** The reaction of **1** with **2** in a mixed solvent of methanol and acetonitrile with 36% HCl at 60 °C for 3 h, giving the three new triarylethylenes **3–5** and the four new tetraarylethanes **6–8** simultaneously.



**Scheme 2.** The reaction of **3** with **1** in a mixed solvent of methanol and acetonitrile with 36% HCl at 60 °C for 3 h yields the tetraarylethane **6**, selectively, which upon oxidation with DDQ in dichloromethane at 25 °C for 24 h provides a new tetraarylethylene **9** selectively.



**Scheme 3.** The reactions of **11–13** with **1** in a mixed solvent of methanol and acetonitrile with 36% HCl at 60 °C for 3 h. (a) Besides the products **10** and **3**, this reaction gave **5** and **6** (see Scheme 1) together with dark brown-colored polar resinous substances. (b) Besides the products **10** and **16**, this reaction gave the previously reported 1,3-bis[2,2-bis(4-methoxyphenyl)ethenyl]azulene (**17**) together with dark brown-colored polar resinous substances. (c) Besides the products **10** and **18**, this reaction gave dark brown-colored polar resinous substances.

## 2. Results and discussion

### 2.1. Reaction of **1** with **2**

In the previous papers, we reported that the reaction of **10** with 1,2-bis[4-(dimethylamino)phenyl]-1,2-ethanediol (**2**) in methanol in the presence of 36% hydrochloric acid at 60 °C for 3 h gave **11** (see Chart 1) in 81% yield,<sup>19</sup> and further that the reaction of **10** with 1,2-bis(4-methoxyphenyl)-1,2-ethanediol under the same reaction conditions as the above afforded **12** (see Chart 1) in 97% yield.<sup>10</sup> A reaction pathway for the formation of **11** and **12**, via pinacol rearrangement, was proposed.<sup>10,19</sup> For comparative purposes, the title reaction of **1** with **2** under the same reaction conditions as for the reaction of **10** with **2** was carried out carefully. As a result, the reaction provided no product, while this reaction in a mixed solvent of methanol<sup>60</sup> and acetonitrile<sup>60</sup> in the presence of 36% hydrochloric acid at 60 °C for 3 h yielded new triarylethylenes **3–5** and new tetraarylethanes **6–8**, simultaneously, as shown in Scheme 1 and Table 1. Thus, an apparent difference between the reaction behavior of guaiazulene (**10**) with **2**<sup>19</sup> and that of parent azulene (**1**) with **2** was appeared, owing to an influence of the difference between the dipole moment of **10** (1.574 D) and that of **1** (1.512 D).<sup>2</sup> Along with the above difference, the  $\pi$ -HOMO and  $\pi$ -LUMO energy levels, the calculated values of which correspond to the

**Table 1**  
The recovered starting material **1**/% and each yield/% of the products **3–8**<sup>a</sup>

Compound	<b>1</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>
Yield/%	19 <sup>b</sup>	8 <sup>c</sup>	28 <sup>c</sup>	9	15	6	6

<sup>a</sup> Besides the products **3–8**, this reaction gave dark brown-colored polar resinous substances.

<sup>b</sup> The recovered starting material **1**.

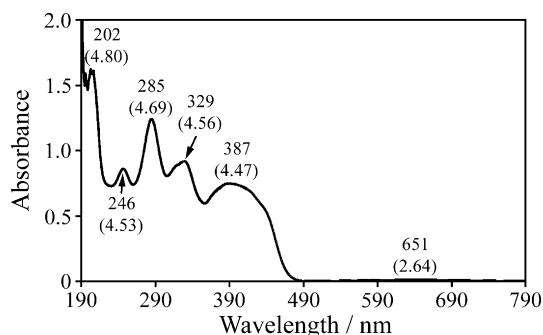
<sup>c</sup> A chromatographically inseparable mixture of the structural isomers **3** and **4** was obtained as a green powder (58 mg, 148  $\mu$ mol, 36% yield). Each yield of **3** and **4** was calculated from relative intensities of their <sup>1</sup>H NMR signals.

ionization potentials (for the  $\pi$ -HOMOs) and the electron affinities (for the  $\pi$ -LUMOs), and the atomic charges for the azulene rings **1** and **10** are shown in Ref. 61. The reaction mixture was carefully separated by silica gel column chromatography and each product thus obtained was recrystallized. The molecular structures of the products, i.e., the triarylethylenes **3–5** and the tetraarylethanes **6–8**, were established on the basis of spectroscopic data [UV–vis, IR, exact EI (or exact FAB) MS, and <sup>1</sup>H and <sup>13</sup>C NMR including NOE and 2D NMR (i.e., DQF COSY, HSQC, and HMBC)].

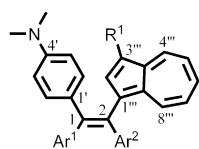
The structural isomers **3** and **4** were obtained as a chromatographically inseparable mixture (36% yield), while **3** could be

isolated, as stable single crystals, by recrystallization of the mixture. Each yield of **3** (8%) and **4** (28%) was calculated from relative intensities of the <sup>1</sup>H NMR signals of the mixture.

Compound **3** was obtained as dark green blocks. The spectroscopic properties of **3** are described as follows. The specific UV–vis absorption bands for azulene<sup>17</sup> were not observed. The UV–vis spectral pattern of **3** resembled that of **11**<sup>19</sup> (see Fig. 1), the longest absorption wavelength (nm, log  $\epsilon$ ) of which coincided with that of **11**. The IR spectrum showed specific bands resulting from the C–N, aromatic C=C, and C–H bonds. The molecular formula C<sub>28</sub>H<sub>28</sub>N<sub>2</sub> was determined by exact EIMS, the spectrum of which showed the M<sup>+</sup> ion peak. Similar to **11**, the <sup>1</sup>H NMR spectrum showed signals consistent with an azulene-1-yl group, signals consistent with a non-equivalent of two 4-(dimethylamino)phenyl groups, and a signal based on an ethylene unit (>C=CH–), all the signals of which were carefully assigned using NOE, DQF COSY, and computer-assisted simulation based on first-order analysis. A proton signal based on an ethylene unit (>C=CH–) of **1** ( $\delta$  7.66) showed an apparent up-field shift in comparison with that of **11**



**Fig. 1.** The UV–vis spectrum of **3** in acetonitrile. Concentration, **3**: 0.10 g L<sup>-1</sup> (255  $\mu$ mol L<sup>-1</sup>). Length of the cell: 0.1 cm. Log  $\epsilon$  values are given in parenthesis.



**3** : Ar<sup>1</sup> = 4-(CH<sub>3</sub>)<sub>2</sub>NC<sub>6</sub>H<sub>5</sub>, Ar<sup>2</sup> = R<sup>1</sup> = H

**4** : Ar<sup>1</sup> = R<sup>1</sup> = H, Ar<sup>2</sup> = 4-(CH<sub>3</sub>)<sub>2</sub>NC<sub>6</sub>H<sub>5</sub>

**5** : Ar<sup>1</sup> = 4-(CH<sub>3</sub>)<sub>2</sub>NC<sub>6</sub>H<sub>5</sub>, Ar<sup>2</sup> = H, R<sup>1</sup> = 1,1-bis[4-(CH<sub>3</sub>)<sub>2</sub>NC<sub>6</sub>H<sub>5</sub>]ethylen-2-yl unit

**9** : Ar<sup>1</sup> = 4-(CH<sub>3</sub>)<sub>2</sub>NC<sub>6</sub>H<sub>5</sub>, Ar<sup>2</sup> = azulene-1-yl group, R<sup>1</sup> = H

**Chart 3.** For comparative purposes on the <sup>1</sup>H and <sup>13</sup>C NMR chemical shifts ( $\delta$ ) of the products **3**, **4**, **5**, and **9** (see Tables 2 and 3), the numbering schemes of **4**, **5**, and **9** are changed as shown in Chart 3.

( $\delta$  7.81), owing to the difference between the substituents of the azulene-1-yl and guaiazulene-3-yl groups. The <sup>13</sup>C NMR spectrum exhibited 22 carbon signals assigned using HSQC and HMBC. Similar to the above <sup>1</sup>H NMR chemical shift, the C-2 carbon signal based on an ethylene unit ( $\text{>C}^1=\text{C}^2\text{H-}$ ) of **1** ( $\delta$  117.2) revealed an apparent up-field shift in comparison with that of **11** ( $\delta$  125.4), owing to the difference between the substituents of the azulene-1-yl and guaiazulene-3-yl groups. Thus, the spectroscopic data for **3** led to a similar molecular structure to **11**, via pinacol rearrangement, illustrated in Scheme 1, the crystal structure of which was described in Section 2.4. Besides the above, the selected <sup>1</sup>H and <sup>13</sup>C NMR chemical shifts of **3** (see Chart 3) compared with those of **4** (see Chart 3) are shown in Tables 2 and 3, whose results and discussion are described as follows.

From the <sup>1</sup>H and <sup>13</sup>C NMR spectral data of **4** (containing **3**), signals consistent with an azulene-1-yl group, signals consistent with a non-equivalent of the two 4-(dimethylamino)phenyl groups for the formation of the E form, and a signal based on an ethylene unit ( $-\text{CH}=\text{C}<$ ) were carefully assigned for the molecular structure **4**, without pinacol rearrangement, illustrated in Scheme 1. The <sup>1</sup>H NMR chemical shifts of **4** (see Chart 3), compared with those of **3** (see Chart 3), are as follows (see Table 2): namely, the H-1 proton signal of **4** showed an up-field shift in comparison with the H-2 proton signal of **3**. The H-2',6', H-3',5', (CH<sub>3</sub>)<sub>2</sub>N-4', and H-7''' proton signals of **4** revealed up-field shifts in comparison with those of **3**; however, the H-2''', H-3''', H-4''', and H-5''' proton signals of **4** showed down-field shifts in comparison with those of **3**. The H-6''' and H-8''' proton signals of **4** coincided with those of **3**. Besides the <sup>1</sup>H NMR signals, the <sup>13</sup>C NMR chemical shifts of **4**, compared with those of **3**, are as follows (see Table 3): namely, the C-1, C-1', C-2',6', and C-4' carbon signals of **4** showed up-field shifts in comparison with those of **3**; however, the C-2, C-2''', C-7''', and C-8''' carbon signals of **4** revealed down-field shifts in comparison with those of **3**. The C-3',5', (CH<sub>3</sub>)<sub>2</sub>N-4', C-3''', C-4''', C-5''', and C-6''' carbon signals of **4** coincided with those of **3**. The C-1''', C-3a''', and C-8a''' carbon signals of **4** could not be assigned, because those signals were included in other signals. Thus, an apparent difference between the <sup>1</sup>H and <sup>13</sup>C NMR signals of **3** and those of **4**, owing to the structural isomers of **3** and **4**, was observed.

**Table 2**  
The selected <sup>1</sup>H NMR chemical shifts ( $\delta$ ) of **3**, **4**<sup>a</sup>, **5**<sup>a</sup>, and **9**<sup>a</sup> in benzene-*d*<sub>6</sub>

Proton	<b>3</b>	<b>4</b> <sup>a</sup>	<b>5</b> <sup>a</sup>	<b>9</b> <sup>a</sup>
H-1	—	7.45	—	—
H-2	7.66	—	7.45	—
H-2',6'	7.49	7.00	7.32	7.38
H-3',5'	6.62	6.22	6.51	6.31
(CH <sub>3</sub> ) <sub>2</sub> N-4'	2.52	2.32	2.55	2.34
H-2'''	7.78	8.05	7.76	7.98
H-3'''	7.08	7.45	—	7.22
H-4'''	7.71	8.02	8.16	7.80
H-5'''	6.60	6.72	6.55	6.54
H-6'''	7.09	7.05	7.02	6.88
H-7'''	6.68	6.59	6.52	6.44
H-8'''	8.33	8.38	8.16	8.27

<sup>a</sup> For comparative purposes, the numbering schemes of **4**, **5**, and **9** are changed as shown in Chart 3.

Compound **5** (9% yield) was obtained as a dark yellowish-brown paste. The spectroscopic properties of **5** are described as follows. The UV–vis spectral pattern of **5** resembled that of **3** (see Fig. 2), indicating the formation of the molecule with an extended  $\pi$ -electron system in comparison with the starting material **1**. The IR spectrum showed specific bands resulting from the C–N, aromatic C=C, and C–H bonds. The molecular formula C<sub>46</sub>H<sub>48</sub>N<sub>4</sub> was determined by exact FABMS, the spectrum of which showed the [M+H]<sup>+</sup> ion peak. Similar to **3**, the <sup>1</sup>H and <sup>13</sup>C NMR spectra showed signals consistent with an azulene ring possessing two substituents at the C-1 and C-3 positions and signals based on an equivalent of the two 2,2-bis[4-(dimethylamino)phenyl]ethenyl substituents, all the signals of which were carefully assigned using similar techniques to **3**. Besides the above, the selected <sup>1</sup>H and <sup>13</sup>C NMR signals of **5** (see Chart 3) compared with those of **3** (see Chart 3) are shown in Tables 2 and 3. As the results, an apparent difference between the <sup>1</sup>H and <sup>13</sup>C NMR signals of **5** and those of **3**, owing to the azulene possessing two substituents at the C-1 and C-3 positions and the azulene possessing a substituent at the C-1 position, was appeared. Thus, the spectroscopic data for **5** led to the molecular structure, via pinacol rearrangement generated by the reaction of **3** with **2**, illustrated in Scheme 1.

The tetraarylethane **6** (15% yield) (see Scheme 1) was obtained as dark blue blocks, while the *meso* form **7** (6% yield) (see Scheme 1) and the two enantiomeric forms **8** (6% yield) (see Scheme 1) were obtained as dark blue needles, respectively. The IR spectra of **6**–**8** showed specific bands resulting from the C–N, aromatic C=C, and C–H bonds, respectively. The molecular formulas (C<sub>38</sub>H<sub>36</sub>N<sub>2</sub> each) for **6**–**8** were determined by exact FABMS, each spectrum of which showed the [M+H]<sup>+</sup> ion peak. The <sup>1</sup>H NMR spectra for the structural isomers **6**–**8**, along with the <sup>13</sup>C NMR spectra for **6** and **7**, showed signals consistent with an equivalent of the two azulene-1-yl groups, signals consistent with an equivalent of the two 4-(dimethylamino)phenyl groups, and a signal (or signals) based on

**Table 3**  
The selected <sup>13</sup>C NMR chemical shifts ( $\delta$ ) of **3**, **4**<sup>a</sup>, **5**<sup>a</sup>, and **9**<sup>a</sup> in benzene-*d*<sub>6</sub>

Carbon	<b>3</b>	<b>4</b> <sup>a</sup>	<b>5</b> <sup>a</sup>	<b>9</b> <sup>a</sup>
C-1	141.3	127.8	141.7	<sup>b</sup>
C-2	117.2	133.7	117.2	144.0
C-1'	130.5	127.9	130.3	133.9
C-2',6'	132.1	130.3	131.7	132.9
C-3',5'	113.0	112.7	113.3	112.0
C-4'	150.1	149.0	149.8	148.9
(CH <sub>3</sub> ) <sub>2</sub> N-4'	40.1	39.8	40.3	39.9
C-1'''	129.4	<sup>b</sup>	128.7	136.4
C-2'''	137.9	140.3	137.8	141.7
C-3'''	118.9	118.3	128.7	118.1
C-3a'''	142.5	<sup>b</sup>	139.0	142.6
C-4'''	135.9	135.9	133.5	136.1
C-5'''	123.2	122.9	122.4	123.0
C-6'''	137.5	137.6	138.0	137.2
C-7'''	121.9	122.8	122.4	122.1
C-8'''	134.0	136.6	133.5	136.0
C-8a'''	142.1	<sup>b</sup>	139.0	135.5

<sup>a</sup> For comparative purposes, the numbering schemes of **4**, **5**, and **9** are changed as shown in Chart 3.

<sup>b</sup> The carbon signal is included in another carbon signal.

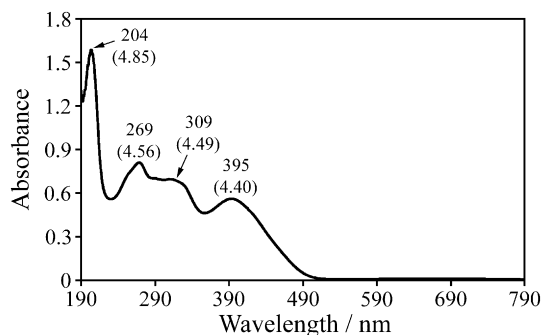


Fig. 2. The UV–vis spectrum of **5** in acetonitrile. Concentration, **5**: 0.14 g L<sup>-1</sup> (223 μmol L<sup>-1</sup>). Length of the cell: 0.1 cm. Log ε values are given in parenthesis.

an ethane unit (>HC–CH<), respectively, all the signals of which were carefully assigned using similar techniques to **3**. The specific <sup>1</sup>H NMR signal(s) (δ) based on an ethane unit (>HC<sup>2</sup>–C<sup>1</sup>H<) showed 5.16 (H-2) and 6.14 (H-1) for **6**, 5.70 (H-1,2) for **7**, and 5.69 (H-1,2) for **8**. The specific <sup>13</sup>C NMR signal(s) (δ) based on an ethane unit (>HC<sup>2</sup>–C<sup>1</sup>H<) revealed 41.8 (C-2) and 57.2 (C-1) for **6** and 49.4 (C-1,2) for **7**. Thus, the spectroscopic data for **6** led to the tetraarylethane structure illustrated in Scheme 1, while the molecular structures of the *meso* form **7** and the two enantiomeric forms **8** could not be determined by only spectroscopic analyses, because their <sup>1</sup>H NMR chemical shifts showed resemble. Fortunately, the crystal structures **6**–**8**, determined by X-ray crystallographic analysis (see Section 2.5), supported their tetraarylethane structures illustrated in Scheme 1, the results of which enabled us to assign their <sup>1</sup>H and <sup>13</sup>C NMR signals completely (see Section 4.1.1). The <sup>1</sup>H NMR chemical shifts of the *meso* form **7**, compared with those of the two enantiomeric forms **8**, are as follows: namely, an equivalent of the H-1 and H-2 proton signals based on the ethane unit (>HC<sup>2</sup>–C<sup>1</sup>H<) and the H-5', H-6', H-7' proton signals based on an equivalent of the two azulene-1-yl groups of **7** coincided with those of **8**. The H-2', H-3', H-4' proton signals based on an equivalent of the two azulene-1-yl groups of **7** showed down-field shifts in comparison with those of **8**, while the H-8' proton signal based on an equivalent of the two azulene-1-yl groups and the H-2'', H-3'', H-5'', H-6'', and (CH<sub>3</sub>)<sub>2</sub>N-4'' proton signals based on an equivalent of the two 4-(dimethylamino)phenyl groups of **7** revealed up-field shifts in comparison with those of **8**.

## 2.2. Reaction of **3** with **1**

We now described that the reaction of **1** with **2** in a mixed solvent of methanol and acetonitrile in the presence of 36% hydrochloric acid at 60 °C for 3 h gave the products **3**–**8** simultaneously (see Section 2.1 and Scheme 1). As a clarification of a reaction pathway for the formation of the tetraarylethane **6**, the reaction of the isolated triarylethylene **3** with **1** under the same reaction conditions as the above was carried out carefully (see Scheme 2). As a result, this reaction provided **6**, in 46% yield, whose molecular structure was identified on the basis of silica gel TLC analysis and FABMS and <sup>1</sup>H NMR spectroscopic analyses. Therefore, a reaction pathway for the formation of **6**, via the addition reaction of **3** with **1**, was supported. Similar to **6**, a reaction pathway for the formation of the *meso* form **7** and the two enantiomeric forms **8**, via the addition reaction of **4** with **1**, can be inferred.

## 2.3. Oxidation of **6** with DDQ

As a basic study on chemical property of the tetraarylethane **6**, the oxidation of **6** with DDQ was carried out carefully (see

Scheme 2). The expected tetraarylethylene **9** (48% yield), possessing an interesting conjugated π-electron system, could be obtained, the molecular structure of which was established on the basis of similar spectroscopic analyses to **3**.

Compound **9** was obtained as a dark yellowish-brown paste. The spectroscopic properties of **9** are described as follows. The UV–vis spectral pattern of **9** resembled that of **3** (see Fig. 3), indicating the formation of the molecule with an extended π-electron system in comparison with parent azulene<sup>17</sup> (**1**). The IR spectrum showed specific bands resulting from the C–N, aromatic C=C, and C–H bonds. The molecular formula C<sub>38</sub>H<sub>34</sub>N<sub>2</sub> was determined by exact EIMS, the spectrum of which showed the M<sup>+</sup> ion peak. The <sup>1</sup>H and <sup>13</sup>C NMR spectra showed signals consistent with an equivalent of the two azulene-1-yl groups and signals based on an equivalent of the two 4-(dimethylamino)phenyl groups, all the signals of which were carefully assigned using similar techniques to **3**. The <sup>13</sup>C NMR spectrum further revealed the C-1 carbon signal of an ethylene unit, while its C-2 carbon signal was included in another signal, the results of which indirectly suggested the existence of a non-equivalent of an ethylene carbons (>C=C<). Thus, the total spectroscopic data for **9** led to the target molecular structure illustrated in Scheme 2. Besides the above, the selected <sup>1</sup>H and <sup>13</sup>C NMR signals of **9** (see Chart 3) compared with those of **3** (see Chart 3) are shown in Tables 2 and 3. An apparent difference between the chemical shifts of **9** and those of **3** was appeared, owing to the difference between the molecular structure of the tetraarylethylene **9** and that of the triarylethylene **3**. The crystal structure determination of **9** has not yet been accomplished because of difficulty in obtaining a single crystal suitable for X-ray crystallographic analysis.

## 2.4. X-ray crystal structure of **3** compared with those of **11**, **12**, and **13**

The recrystallization of **3** from a mixed solvent of benzene and methanol (1:5, v/v) provided stable single crystals suitable for X-ray crystallographic analysis. Then, the crystal structure of **3** could be determined by means of X-ray diffraction, producing accurate structural parameters. The ORTEP drawing of **3** with a numbering scheme is shown in Fig. 4a and further the selected bond lengths of **3** are revealed in Tables 4 and 5. From comparative studies on the structural parameters of the crystal structure **3** with those of the previously reported **11**, **12**, and **13**, the following results were found: namely, although the C1–C2 bond length between the ethylene unit (>C<sup>1</sup>=C<sup>2</sup>H–) of **3** coincided with that of **11**,<sup>19</sup> the bond length of which was slightly longer than those of **12**<sup>10</sup> and **13**.<sup>20</sup> The C1–C1', C1–C1'', and C2–C1''' bond lengths of **3** were slightly shorter than those of **11**, **12**, and **13**. The average C–C bond length for the seven-membered ring of the azulene-1-yl group of **3**

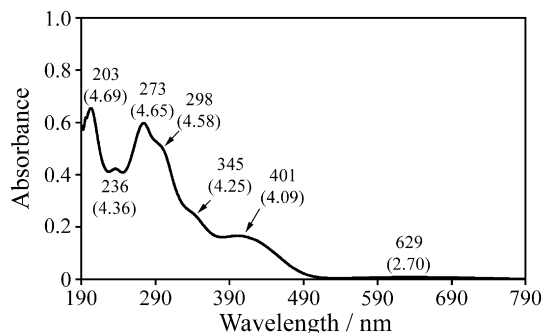
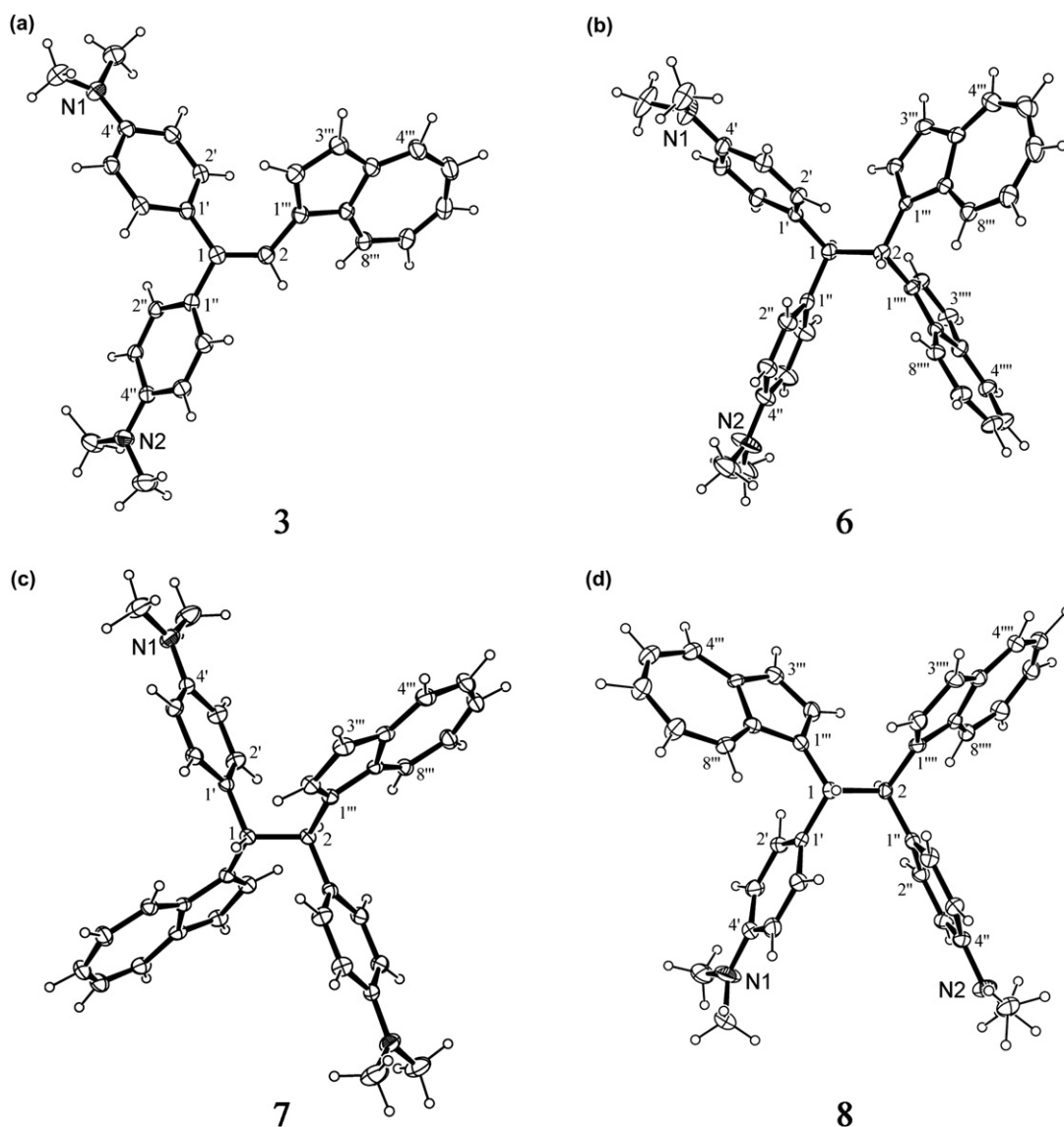


Fig. 3. The UV–vis spectrum of **9** in acetonitrile. Concentration, **9**: 0.07 g L<sup>-1</sup> (135 μmol L<sup>-1</sup>). Length of the cell: 0.1 cm. Log ε values are given in parenthesis.



**Fig. 4.** (a) The ORTEP drawing of **3**. (b) The ORTEP drawing of **6**. (c) The ORTEP drawing of **7**. (d) The ORTEP drawing of **8**. The ORTEP drawings **3** and **6–8**: 30% probability thermal ellipsoids. For comparative purposes on the bond lengths (Å) of the crystal structures **3** and **6–8** (see Tables 4 and 5), the numbering schemes of **6–8** are changed as shown in Fig. 4b–d.

(1.420 Å) was slightly longer than those of **11** (1.410 Å), **12** (1.405 Å), and **13** (1.412 Å); however, the average C–C bond length for the five-membered ring of the azulene-1-yl group of **3** (1.403 Å) was shorter than those of **11** (1.426 Å), **12** (1.427 Å), and **13** (1.422 Å). Similar to **11–13**, the aromatic rings of the two 4'- and 4''-(dimethylamino)phenyl and azulene-1-yl groups of **3** twisted by 56°, 34°, and 44° from the ethylene plane (>C=CH–), owing to a large steric hindrance and repulsion between them. Thus, the crystal structure of **3** supported the molecular structure illustrated in Scheme 1.

## 2.5. X-ray crystal structures of **6**, **7**, and **8**

The recrystallization of **6** from a mixed solvent of benzene and methanol (1:5, v/v) provided stable single crystals suitable for X-ray crystallographic analysis, while the recrystallization of **7** and **8** from a mixed solvent of dichloromethane and methanol (1:5, v/v) yielded stable single crystals suitable for that purpose. The crystal structures of **6–8** were then determined by means of X-ray diffraction, producing accurate structural parameters. The ORTEP

drawings of **6–8**, indicating those molecular structures illustrated in Scheme 1, with a numbering scheme are shown in Fig. 4b–d together with the selected bond lengths (see Tables 4 and 5). The structural parameters of **6–8** revealed that the C–C bond length between the ethane unit (>CH–CH<) of **6** (1.558 Å) coincided with those of **7** (1.558 Å) and **8** (1.554 Å).

## 2.6. Redox potentials of **3**

The electrochemical properties of **3** were measured by means of CV (=Cyclic Voltammogram) and DPV (=Differential Pulse Voltammogram) [Potential (in volts) versus SCE] in CH<sub>3</sub>CN containing 0.1 M [*n*-Bu<sub>4</sub>N]BF<sub>4</sub> as a supporting electrolyte. Three redox potentials observed by DPV were positioned at the *E<sub>p</sub>* values of +1.18, +0.45, and –1.53 V, and the corresponding two reversible oxidation potentials determined by CV were located at the values of +1.11 and +0.43 V (*E*<sub>1/2</sub> each) and the corresponding one irreversible reduction potential determined by CV was located at a value of –1.63 V (*E<sub>pc</sub>*) as shown in Fig. 5a,b. The CV datum of **3**

**Table 4**  
The selected bond lengths (Å) for the azulene-1-ylethenyl units of the X-ray crystal structures **3** and **6–8**<sup>a</sup>

Atom	<b>3</b>	<b>6</b>	<b>7</b> <sup>b</sup>	<b>8</b>	Atom	<b>6</b>	<b>8</b>
C1–C2	1.352(2)	1.558(6)	1.5583(17)	1.554(6)	C2–C1'''	1.505(6)	1.512(6)
C2–C1''	1.458(2)	1.508(7)	1.5131(19)	1.516(5) <sup>c</sup>	C1'''–C2'''	1.394(7)	1.391(7)
C1''–C2''	1.420(2)	1.409(7)	1.4048(18)	1.393(6)	C2'''–C3'''	1.375(7)	1.403(6)
C2''–C3''	1.376(2)	1.389(7)	1.396(2)	1.402(6)	C3'''–C3a'''	1.391(7)	1.381(6)
C3''–C3a''	1.407(2)	1.401(7)	1.3947(18)	1.388(7)	C3a'''–C4'''	1.390(7)	1.389(6)
C3a''–C4''	1.378(2)	1.376(7)	1.385(2)	1.382(6)	C4'''–C5'''	1.397(8)	1.369(7)
C4''–C5''	1.393(2)	1.382(8)	1.383(2)	1.386(7)	C5'''–C6'''	1.366(9)	1.387(8)
C5''–C6''	1.378(2)	1.382(9)	1.378(2)	1.383(7)	C6'''–C7'''	1.380(7)	1.402(7)
C6''–C7''	1.399(2)	1.366(8)	1.401(2)	1.399(7)	C7'''–C8'''	1.396(7)	1.408(7)
C7''–C8''	1.389(2)	1.385(7)	1.391(2)	1.410(7)	C8'''–C8a'''	1.378(7)	1.366(7)
C8''–C8a''	1.391(2)	1.394(11)	1.3872(18)	1.377(6)	C8a'''–C1'''	1.410(6)	1.423(5)
C8a''–C1''	1.405(2)	1.413(7)	1.3994(17)	1.409(6)	C3a'''–C8a'''	1.496(7)	1.490(6)
C3a''–C8a''	1.494(2)	1.496(7)	1.500(2)	1.493(5)			

<sup>a</sup> For comparative purposes, the numbering schemes of **6–8** are changed as shown in Fig. 4b–d.

<sup>b</sup> The two (azulen-1-yl)[4-(dimethylamino)phenyl]methyl units of **7** are symmetrical structures.

<sup>c</sup> The C1–C1'' bond length.

suggested that an electrochemically reactive anion-radical species was generated at the reduction potential of  $-1.63$  V. From the redox potentials ( $E_{\text{red}}^1$  and  $E_{\text{ox}}^1$ ) of **3** compared with those of **11** (Fig. 5c,d), it was found that **3** was susceptible to one-electron reduction than **11**,<sup>19</sup> however, **3** was less susceptible to two-electron oxidation than **11**,<sup>19</sup> owing to the difference between the molecular structure **3** with an azulene-1-yl group at the C-2 position and the molecular structure **11** with a guaiazulene-3-yl group at the C-2 position. The second oxidation potential ( $E_{\text{ox}}^2$ ) of **3** coincided with that of **11**.<sup>19</sup> A similar redox mechanism to **11** proposed previously<sup>19</sup> can be inferred for **3**.

## 2.7. Redox potentials of **9**

For comparative purposes, the electrochemical properties of **9** were measured under the same electrochemical measurement conditions as for **3**. Five redox potentials observed by DPV were positioned at the  $E_p$  values of  $+1.14$ ,  $+0.26$ ,  $-1.62$ ,  $-1.76$ , and  $-2.23$  V, and the corresponding two reversible oxidation potentials determined by CV were located at the values of  $+1.10$  and  $+0.24$  V ( $E_{1/2}$  each) and the corresponding three irreversible reduction potentials determined by CV were located at the values of  $-1.69$ ,  $-1.82$ , and  $-2.32$  V ( $E_{\text{pc}}$  each) as shown in Fig. 6. Similar to **3**, the CV datum of **9** suggested that three electrochemically reactive species were generated at the above stepwise three reduction potentials. From the redox potentials ( $E_{\text{red}}^1$  and  $E_{\text{ox}}^1$ ) of **9** compared with those of **3** (see Fig. 5a,b), it was found that **9** was less susceptible to one-electron reduction than **3**; however, **9** was susceptible to two-electron oxidation than **3**. The second oxidation potential ( $E_{\text{ox}}^2$ ) of **9** coincided with that of **3** and further **9** underwent stepwise two-electron reduction at the above potentials

( $E_{\text{red}}^2$  and  $E_{\text{red}}^3$ ). On the other hand, in 1999 Hünig et al. reported that the CV of tetrakis[4-(dimethylamino)phenyl]ethylene revealed two completely reversible redox potentials at the  $E_{1/2}$  values of  $+0.67$  and  $-0.30$  V.<sup>59</sup> Thus, it is noteworthy that similar to tetrakis[4-(dimethylamino)phenyl]ethylene,<sup>59</sup> the tetraarylethylene **9** serves as a more strong two-electron donor in comparison with the triarylethylenes **3** and **11**.<sup>19</sup>

## 2.8. Reactions of **11–13** with **1**

Similar to the reaction shown in Scheme 2, the reaction of **11** with **1** in a mixed solvent of methanol and acetonitrile in the presence of 36% hydrochloric acid at  $60$  °C for 3 h was carried out carefully (see Scheme 3). Interestingly, this reaction did not give a similar product to **6** (i.e., an azulene-adduct), while the reaction of which afforded **10**<sup>1</sup> (91% yield), the triarylethylenes **3** (46% yield) and **5** (19% yield), and the tetraarylethane **6** (13% yield) together with dark brown-colored polar resinous substances. The product **3** yielded from the reaction of **11** with **1** (see Scheme 3) could be easily isolated in comparison with **3** derived from the reaction of **2** with **1** (see Scheme 1). The molecular structures of the products **3**, **5**, **6**, and **10** were identified on the basis of silica gel TLC analysis and EI (or FAB) MS and <sup>1</sup>H NMR spectral data. Similarly, the reactions of **12** (and **13**) with **1** under the same reaction conditions as for **11** were undertaken (see Scheme 3), the reactions of which produced **10** (93% yield) and the previously reported two triarylethylenes **16**<sup>10</sup> (34% yield) and 1,3-bis[2,2-bis(4-methoxyphenyl)ethenyl]azulene<sup>10</sup> (**17**) (19% yield) from **12** [and **10** (97% yield) and a new triarylethylene **18** (58% yield) from **13**], together with dark brown-colored polar resinous substances, respectively. The molecular structures of the products **10**, **16**, and **17** were identified on the basis

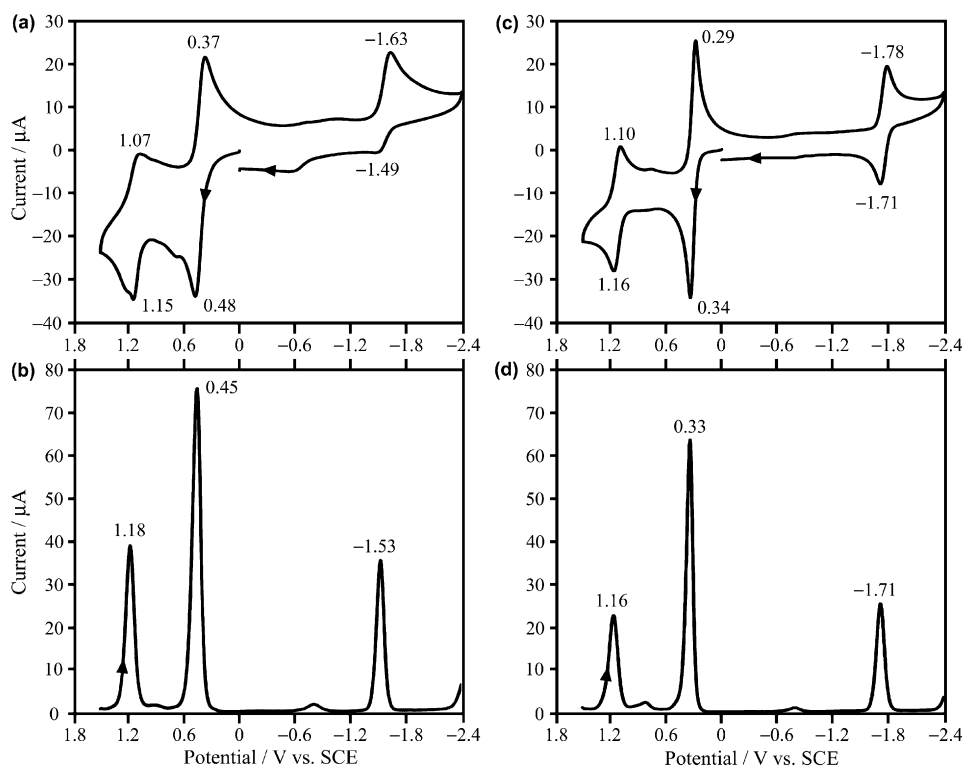
**Table 5**  
The selected bond lengths (Å) for the two 4-(dimethylamino)phenyl groups of the X-ray crystal structures **3** and **6–8**<sup>a</sup>

Atom	<b>3</b>	<b>6</b>	<b>7</b> <sup>b</sup>	<b>8</b>	Atom	<b>3</b>	<b>6</b>	<b>8</b>
C1–C1'	1.483(2)	1.513(6)	1.524(2)	1.501(5)	C1–C1''	1.478(2)	1.544(6)	1.524(5) <sup>c</sup>
C1'–C2'	1.399(2)	1.391(7)	1.3886(17)	1.375(7)	C1''–C2''	1.398(2)	1.358(7)	1.370(7)
C2'–C3'	1.374(2)	1.370(7)	1.386(2)	1.400(6)	C2''–C3''	1.380(2)	1.400(8)	1.384(6)
C3'–C4'	1.403(2)	1.402(7)	1.401(2)	1.413(6)	C3''–C4''	1.398(2)	1.396(9)	1.408(7)
C4'–C5'	1.404(2)	1.383(8)	1.401(2)	1.390(7)	C4''–C5''	1.398(2)	1.384(8)	1.386(7)
C5'–C6'	1.385(2)	1.385(7)	1.381(2)	1.389(6)	C5''–C6''	1.376(2)	1.400(7)	1.402(6)
C6'–C1'	1.391(2)	1.386(6)	1.382(2)	1.389(6)	C6''–C1''	1.397(2)	1.384(7)	1.384(7)
C4'–N1	1.386(2)	1.407(7)	1.384(2)	1.381(6)	C4''–N2	1.394(2)	1.383(8)	1.387(6)

<sup>a</sup> For comparative purposes, the numbering schemes of **6–8** are changed as shown in Fig. 4b–d.

<sup>b</sup> The two (azulen-1-yl)[4-(dimethylamino)phenyl]methyl units of **7** are symmetrical structures.

<sup>c</sup> The C2–C1'' bond length.



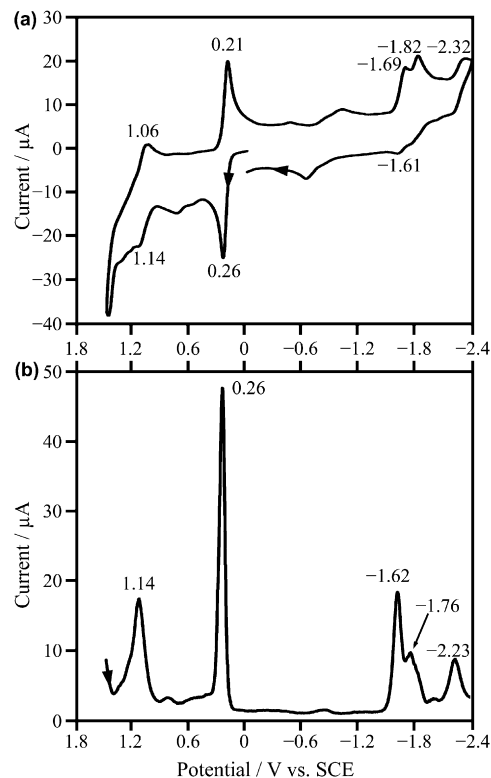
**Fig. 5.** Cyclic and differential pulse voltammograms of **3** (3.0 mg, 7.6  $\mu\text{mol}$ ) (a, b) and **11** (3.0 mg, 6.5  $\mu\text{mol}$ ) (c, d) in 0.1 M  $[n\text{-Bu}_4\text{N}]\text{BF}_4$ ,  $\text{CH}_3\text{CN}$  (10 mL) at a glassy carbon (ID: 3 mm) and a platinum wire served as working and auxiliary electrodes; scan rates 100  $\text{mV s}^{-1}$  at 25  $^\circ\text{C}$  under argon. For comparative purposes, the oxidation potential using ferrocene as a standard material showed +0.45 V ( $E_p$ ) by DPV and +0.42 V ( $E_{1/2}$ ) by CV under the same electrochemical measurement conditions as for **3** and **11**.

of silica gel TLC analysis and similar spectroscopic analyses to the above. The molecular structure of a new product **18** was established on the basis of exact EIMS and  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectral data. Similar to **12**<sup>10</sup> and **13**,<sup>20</sup> studies on the estrogenic activity of **16**, compared with that of **14** (see Chart 2), and the anti-estrogenic activity of **18**, compared with that of **15** (see Chart 2), are noteworthy.

Compound **18** was obtained as a green powder. The molecular formula  $\text{C}_{32}\text{H}_{36}\text{O}_2\text{N}_2$  was determined by exact EIMS, the spectrum of which showed the  $\text{M}^+$  ion peak. The  $^1\text{H}$  NMR spectrum showed signals consistent with an azulene-1-yl group, signals consistent with a non-equivalent of the two 4-[2-(dimethylamino)ethoxy] phenyl groups, and a signal based on an ethylene unit ( $>\text{C}=\text{CH}-$ ), all the signals of which were carefully assigned using NOE, DQF COSY, and computer-assisted simulation based on first-order analysis. The  $^{13}\text{C}$  NMR spectrum exhibited 21 carbon signals assigned using HSQC and HMBC as shown in Experimental section (see Section 4.1.10). Thus, the spectroscopic data for **18** led to the target molecular structure illustrated in Scheme 3.

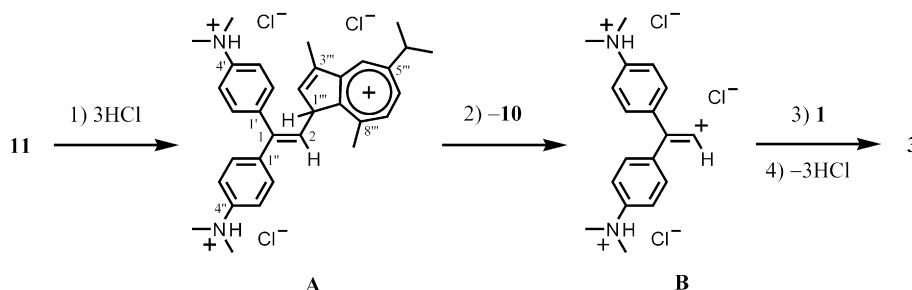
## 2.9. A possible reaction pathway for the formation of **3**, **16**, and **18**

A possible reaction pathway for the formation of the resulting product **3** is shown in Scheme 4: namely, upon heating **11** in a mixed solvent of methanol and acetonitrile in the presence of 36% hydrochloric acid at 60  $^\circ\text{C}$  for 3 h, it is gradually converted into **3** via (1) the protonated compound **A**,<sup>62</sup> (2) the deguaiazulenizing structure **B**, (3) the azulene-added structure, and (4) dehydrochlorination. A similar reaction pathway to **3** is proposed for the formation of the resulting products **16**, which upon reaction with **12** gives **17**, and **18**.



**Fig. 6.** Cyclic and differential pulse voltammograms of **9** (3.0 mg, 5.8  $\mu\text{mol}$ ) (a, b) in 0.1 M  $[n\text{-Bu}_4\text{N}]\text{BF}_4$ ,  $\text{CH}_3\text{CN}$  (10 mL) at a glassy carbon (ID: 3 mm) and a platinum wire served as working and auxiliary electrodes; scan rates 100  $\text{mV s}^{-1}$  at 25  $^\circ\text{C}$  under argon. For comparative purposes, the oxidation potential using ferrocene as a standard material showed +0.45 V ( $E_p$ ) by DPV and +0.42 V ( $E_{1/2}$ ) by CV under the same electrochemical measurement conditions as for **9**.





**Scheme 4.** A possible reaction pathway for the formation of **3** yielded by the reaction of **11** with **1** in a mixed solvent of methanol and acetonitrile with 36% HCl at 60 °C for 3 h.

### 3. Conclusion

We have reported the following three interesting points (i)–(iii) in this paper: namely, (i) the reaction of azulene (**1**) with the 1,2-diaryl-1,2-ethanediol **2** in methanol in the presence of 36% hydrochloric acid at 60 °C for 3 h provided no product; however, this reaction in a mixed solvent of methanol and acetonitrile in the presence of 36% hydrochloric acid at 60 °C for 3 h gave the three new triarylethylenes **3** (8% yield), **4** (28% yield), and **5** (9% yield). Besides the above products, this reaction afforded the four new tetraarylethanes **6** (15% yield), via the addition reaction of **3** with **1**, and a *meso* form **7** (6% yield) and the two enantiomeric forms **8** (6% yield), via the addition reaction of **4** with **1**, respectively. Thus, an apparent difference between the previously reported reaction behavior of guaiazulene (**10**) with **2** and the reaction behavior of **1** with **2** was discovered; (ii) the reaction of **3** with **1** under the same reaction conditions as the above (i) provided the tetraarylethane **6**, in 46% yield, which upon oxidation with DDQ in dichloromethane at 25 °C for 24 h yielded a new tetraarylethylene **9** in 48% yield; and further (iii) the reaction of 1,1-bis[4-(dimethylamino)phenyl]-2-(3-guaiazulenyl)ethylene (**11**) with **1** under the same reaction conditions as the above (ii) did not give a similar tetraarylethane to **6**; however, this reaction afforded **10** and **3**, owing to the replacement of a guaiazulene-3-yl group by an azulene-1-yl group, in 91 and 46% yields together with **5** (19% yield) and **6** (13% yield). The product **3** yielded from the reaction of **11** with **1** could be easily isolated in comparison with **3** derived from the reaction of **2** with **1**. Similarly, the reactions of 2-(3-guaiazulenyl)-1,1-bis[4-(dimethylamino)phenyl]ethylene (**12**) and 1,1-bis[4-[2-(dimethylamino)ethoxy]phenyl]-2-(3-guaiazulenyl)ethylene (**13**) with **1** under the same reaction conditions as the above (ii) gave **10** and the two known triarylethylenes **16** and **17** (93, 34 and 19% yields) from **12** and **10** and a new triarylethylene **18** (97 and 58% yields) from **13**.

### 4. Experimental

#### 4.1. General

Thermal analysis (TGA and DTA) was taken on a Shimadzu DTG–50H thermal analyzer. EI (and FAB) MS spectra were taken on a JEOL The Tandem Mstation JMS–700 TKM data system. UV–vis and IR spectra were taken on a Beckman DU640 spectrophotometer and a Shimadzu FTIR–4200 Grating spectrometer. NMR spectra were recorded with a JEOL JNM–ECA500 (500 MHz for  $^1\text{H}$  and 125 MHz for  $^{13}\text{C}$ ), JNM–ECA600 (600 MHz for  $^1\text{H}$  and 150 MHz for  $^{13}\text{C}$ ), or JNM–ECA700 (700 MHz for  $^1\text{H}$  and 176 MHz for  $^{13}\text{C}$ ) cryospectrometer at 25 °C  $^1\text{H}$  NMR spectra were assigned using computer-assisted simulation (software: gNMR developed by Adept Scientific plc) on a DELL Dimension 9150 personal computer with a Pentium IV processor. Cyclic and differential pulse voltammograms were measured by an ALS Model 600 electrochemical analyzer.

**4.1.1. Reaction of azulene (**1**) with 1,2-bis[4-(dimethylamino)phenyl]-1,2-ethanediol (**2**).** To a solution of a commercially available azulene (**1**) (53 mg, 414  $\mu\text{mol}$ ) in acetonitrile (2.0 mL) was added a solution of 1,2-bis[4-(dimethylamino)phenyl]-1,2-ethanediol<sup>19</sup> (**2**) (123 mg, 410  $\mu\text{mol}$ ) in methanol (1.5 mL). The mixture containing 36% hydrochloric acid (0.1 mL) was stirred at 60 °C for 3 h. After the reaction, distilled-water was added to the mixture and then the resulting products were extracted with dichloromethane (10 mL  $\times$  3). The extract was washed with distilled-water, dried ( $\text{MgSO}_4$ ), and evaporated in vacuo. The residue thus obtained was carefully separated by silica gel column chromatography with hexane–ethyl acetate–benzene (90:5:5, v/v/v) as an eluant. The starting material **1** (10 mg, 78  $\mu\text{mol}$ , 19%) was recovered and further the following products, i.e., a chromatographically inseparable mixture of the two structural isomers 2-(azulene-1-yl)-1,1-bis[4-(dimethylamino)phenyl]ethylene (**3**) and 1-(azulene-1-yl)-(E)-1,2-bis[4-(dimethylamino)phenyl]ethylene (**4**) as a green powder (58 mg, 148  $\mu\text{mol}$ , 36% yield), 1,3-bis[2,2-bis[4-(dimethylamino)phenyl]ethenyl]azulene (**5**) as a dark yellowish-brown paste (24 mg, 37  $\mu\text{mol}$ , 9% yield), 1,1-di(azulene-1-yl)-2,2-bis[4-(dimethylamino)phenyl]ethane (**6**) as a blue paste (31 mg, 60  $\mu\text{mol}$ , 15% yield), a *meso* form (1*R*,2*S*)-1,2-di(azulene-1-yl)-1,2-bis[4-(dimethylamino)phenyl]ethane (**7**) as a blue paste (12 mg, 23  $\mu\text{mol}$ , 6% yield), and the two enantiomeric forms (1*R*,2*R*)- and (1*S*,2*S*)-1,2-di(azulene-1-yl)-1,2-bis[4-(dimethylamino)phenyl]ethane (**8**) as a blue paste (12 mg, 23  $\mu\text{mol}$ , 6% yield), were separated. A mixture of **3** and **4** was recrystallized from benzene–methanol (1:5, v/v) to provide only **3** as stable single crystals. Similarly, the product **6** was recrystallized from benzene–methanol (1:5, v/v) to provide **6** as stable single crystals, while the products **7** and **8** were recrystallized from dichloromethane–methanol (1:5, v/v) to provide **7** and **8** as stable single crystals, respectively. Along with the above products, this reaction gave a chromatographically inseparable mixture of dark brown-colored polar resinous substances.

**4.1.1.1. Compound 3.** Dark green blocks [ $R_f$  = 0.60 on silica gel TLC (solvent: hexane/ethyl acetate = 50:50, v/v)], mp 156 °C; UV–vis  $\lambda_{\text{max}}$ /nm (log  $\epsilon$ ) in  $\text{CH}_3\text{CN}$ , 246 (4.53), 285 (4.69), 329 (4.56), 387 (4.47), 410 (4.45), and 651 (2.64); IR  $\nu_{\text{max}}$ /cm $^{-1}$  (KBr), 2793 (C–H), 1601, 1516 (C=C), and 1346 (C–N); exact EIMS (70 eV), found  $m/z$  392.2239, calcd for  $\text{C}_{28}\text{H}_{28}\text{N}_2$ :  $\text{M}^+$ ,  $m/z$  392.2252;  $^1\text{H}$  NMR (benzene- $d_6$ ): signals based on an azulene-1-yl group:  $\delta$  6.60 (1H, dd,  $J$  = 9.8, 9.0 Hz, H-5'''), 6.68 (1H, dd,  $J$  = 9.8, 9.7 Hz, H-7'''), 7.08 (1H, d,  $J$  = 4.0 Hz, H-3'''), 7.09 (1H, dd,  $J$  = 9.8, 9.8 Hz, H-6'''), 7.71 (1H, d,  $J$  = 9.0 Hz, H-4'''), 7.78 (1H, d,  $J$  = 4.0 Hz, H-2'''), and 8.33 (1H, d,  $J$  = 9.7 Hz, H-8'''); signals based on a non-equivalent of two 4-(dimethylamino)phenyl groups:  $\delta$  2.52 (6H, s,  $(\text{CH}_3)_2\text{N}-4'$ ), 2.55 (6H, s,  $(\text{CH}_3)_2\text{N}-4''$ ), 6.62 (2H, dd,  $J$  = 8.9, 2.5 Hz, H-3',5'), 6.68 (2H, dd,  $J$  = 8.9, 2.5 Hz, H-3'',5''), 7.49 (2H, dd,  $J$  = 8.9, 2.5 Hz, H-2',6'), and 7.67 (2H, dd,  $J$  = 8.9, 2.5 Hz, H-2'',6''); a signal based on an ethylene unit ( $>\text{C}=\text{C}-\text{H}$ ):  $\delta$  7.66 (1H, s, H-2);  $^{13}\text{C}$  NMR (benzene- $d_6$ ):  $\delta$  150.2 (C-4''), 150.1 (C-4'), 142.5 (C-3a'''), 142.1 (C-8a'''), 141.3 (C-1),

137.9 (C-2'''), 137.5 (C-6'''), 135.9 (C-4'''), 134.0 (C-8'''), 132.1 (C-2',6'), 130.5 (C-1'), 129.4 (C-1'''), 129.2 (C-2'',6''), 127.9 (C-1''), 123.2 (C-5'''), 121.9 (C-7'''), 118.9 (C-3'''), 117.2 (C-2), 113.0 (C-3',5'), 112.7 (C-3'',5''), 40.2 ((CH<sub>3</sub>)<sub>2</sub>N-4''), and 40.1 ((CH<sub>3</sub>)<sub>2</sub>N-4'). The numbering scheme of **3** is shown in Scheme 1.

**4.1.1.2. Compound 4.** Dark green powder [*R<sub>f</sub>*=0.60 on silica gel TLC (solvent: hexane/ethyl acetate=50:50, v/v)]; <sup>1</sup>H NMR (benzene-*d*<sub>6</sub>): signals based on an azulene-1-yl group: δ 6.59 (1H, dd, *J*=9.8, 9.7 Hz, H-7'), 6.72 (1H, dd, *J*=9.6, 9.4 Hz, H-5'), 7.05 (1H, dd, *J*=9.7, 9.6 Hz, H-6'), 7.45 (1H, d, *J*=3.8 Hz, H-3'), 8.02 (1H, d, *J*=9.4 Hz, H-4'), 8.05 (1H, d, *J*=3.8 Hz, H-2'), and 8.38 (1H, d, *J*=9.8 Hz, H-8'); signals based on a non-equivalent of two 4-(dimethylamino)phenyl groups: δ 2.32 (6H, s, (CH<sub>3</sub>)<sub>2</sub>N-4'''), 2.49 (6H, s, (CH<sub>3</sub>)<sub>2</sub>N-4''), 6.22 (2H, dd, *J*=8.9, 2.5 Hz, H-3''',5'''), 6.54 (2H, dd, *J*=8.9, 2.5 Hz, H-3'',5''), 7.00 (2H, dd, *J*=8.9, 2.5 Hz, H-2''',6'''), and 7.42 (2H, dd, *J*=8.9, 2.5 Hz, H-2'',6''); a signal based on an ethylene unit (>HC<sup>2</sup>=C<sup>1</sup><): δ 7.45 (1H, s, H-2); <sup>13</sup>C NMR (benzene-*d*<sub>6</sub>): δ 149.0 (C-4'''), 145.0 (C-4''), 140.3 (C-2'), 137.6 (C-6'), 136.6 (C-8'), 135.9 (C-4'), 134.1 (C-1''), 133.7 (C-1), 130.3 (C-2'',6'''), 128.1 (C-2'',6''), 127.9 (C-1'''), 127.8 (C-2), 122.9 (C-5'), 122.8 (C-7'), 118.3 (C-3'), 112.7 (C-3''',5'''), 112.3 (C-3'',5''), 40.2 ((CH<sub>3</sub>)<sub>2</sub>N-4''), and 39.8 ((CH<sub>3</sub>)<sub>2</sub>N-4''). The C-1', C-3a', and C-8a' carbon signals were included in other carbon signals. The numbering scheme of **4** is shown in Scheme 1. The <sup>1</sup>H and <sup>13</sup>C NMR spectral analyses of **4** (containing **3**) were carried out because of difficulty in obtaining a pure **4** by silica gel column chromatography and recrystallization (several times).

**4.1.1.3. Compound 5.** Dark yellowish-brown paste [*R<sub>f</sub>*=0.40 on silica gel TLC (solvent: hexane/ethyl acetate=50:50, v/v)]; UV–vis λ<sub>max</sub>/nm (log ε) in CH<sub>3</sub>CN, 204 (4.85), 269 (4.56), 309 (4.49), and 395 (4.40); IR ν<sub>max</sub>/cm<sup>-1</sup> (KBr), 2847, 2797 (C–H), 1609, 1520 (C=C), and 1350 (C–N); exact FABMS (3-nitrobenzyl alcohol matrix), found *m/z* 657.3932, calcd for C<sub>46</sub>H<sub>49</sub>N<sub>4</sub>: [M+H]<sup>+</sup>, *m/z* 657.3957; <sup>1</sup>H NMR (benzene-*d*<sub>6</sub>): signals based on an azulene possessing two substituents at the C-1 and C-3 positions: δ 6.55 (2H, dd, *J*=9.8, 9.4 Hz, H-5,7), 7.02 (1H, dd, *J*=9.8, 9.8 Hz, H-6), 7.76 (1H, s, H-2), and 8.16 (2H, d, *J*=9.4 Hz, H-4,8); signals based on an equivalent of two 2,2-bis[4-(dimethylamino)phenyl]ethylene substituents: δ 2.51 (12H, s, (CH<sub>3</sub>)<sub>2</sub>N-4''), 2.55 (12H, s, (CH<sub>3</sub>)<sub>2</sub>N-4''), 6.51 (4H, dd, *J*=8.8, 2.5 Hz, H-3'',5''), 6.61 (4H, dd, *J*=8.8, 2.5 Hz, H-3''',5'''), 7.32 (4H, dd, *J*=8.8, 2.5 Hz, H-2'',6''), 7.45 (2H, s, >C<sup>2</sup>=C<sup>1</sup>H–), and 7.53 (4H, dd, *J*=8.8, 2.5 Hz, H-2''',6'''); <sup>13</sup>C NMR (benzene-*d*<sub>6</sub>): δ 150.1 (C-4'''), 149.8 (C-4''), 141.7 (C-2'), 139.0 (C-3a,8a), 138.0 (C-6), 137.8 (C-2), 134.2 (C-1'''), 133.5 (C-4,8), 131.7 (C-2'',6''), 130.3 (C-1''), 129.4 (C-2''',6'''), 128.7 (C-1,3), 122.4 (C-5,7), 117.2 (C-1'), 113.3 (C-3',5'), 112.6 (C-3''',5'''), 40.3 ((CH<sub>3</sub>)<sub>2</sub>N-4''), and 40.2 ((CH<sub>3</sub>)<sub>2</sub>N-4''). The numbering scheme of **5** is shown in Scheme 1.

**4.1.1.4. Compound 6.** Dark blue blocks [*R<sub>f</sub>*=0.50 on silica gel TLC (solvent: hexane/ethyl acetate=50:50, v/v)], mp 216 °C; IR ν<sub>max</sub>/cm<sup>-1</sup> (KBr), 2878, 2797 (C–H), 1612, 1516 (C=C), and 1353 (C–N); exact FABMS (3-nitrobenzyl alcohol matrix), found *m/z* 521.2945, calcd for C<sub>38</sub>H<sub>37</sub>N<sub>2</sub>: [M+H]<sup>+</sup>, *m/z* 521.2957; <sup>1</sup>H NMR (benzene-*d*<sub>6</sub>): signals based on an equivalent of two azulene-1-yl groups: δ 6.59 (2H, dd, *J*=9.6, 8.9 Hz, H-5'), 6.64 (2H, dd, *J*=9.8, 9.8 Hz, H-7'), 7.03 (2H, dd, *J*=9.8, 9.6 Hz, H-6'), 7.21 (2H, d, *J*=4.0 Hz, H-3'), 7.81 (2H, d, *J*=8.9 Hz, H-4'), 8.04 (2H, d, *J*=4.0 Hz, H-2'), and 8.53 (2H, d, *J*=9.8 Hz, H-8'); signals based on an equivalent of two 4-(dimethylamino)phenyl groups: δ 2.38 (12H, s, (CH<sub>3</sub>)<sub>2</sub>N-4''), 6.36 (4H, dd, *J*=8.8, 2.5 Hz, H-3'',5''), and 7.13 (4H, dd, *J*=8.8, 2.5 Hz, H-2'',6''); signals based on an ethane unit (>HC<sup>2</sup>–C<sup>1</sup>H<): δ 5.16 (1H, d, *J*=11.3 Hz, H-2) and 6.14 (1H, d, *J*=11.3 Hz, H-1); <sup>13</sup>C NMR (benzene-*d*<sub>6</sub>): δ 148.9 (C-4''), 141.2 (C-3a'), 136.7 (C-6'), 136.3 (C-2',4'), 135.5 (C-8a'), 134.6 (C-1'), 133.8 (C-1''), 133.4 (C-8'), 129.6 (C-2'',6''), 122.1 (C-5'), 121.5 (C-7'), 117.7 (C-

3'), 112.9 (C-3'',5''), 57.2 (C-1), 41.8 (C-2), and 40.4 ((CH<sub>3</sub>)<sub>2</sub>N-4''). The numbering scheme of **6** is shown in Scheme 1.

**4.1.1.5. Compound 7.** Blue needles [*R<sub>f</sub>*=0.55 on silica gel TLC (solvent: hexane/ethyl acetate=50:50, v/v)]; IR ν<sub>max</sub>/cm<sup>-1</sup> (KBr), 2878, 2793 (C–H), 1616, 1519 (C=C), and 1357 (C–N); exact FABMS (3-nitrobenzyl alcohol matrix), found *m/z* 521.2986, calcd for C<sub>38</sub>H<sub>37</sub>N<sub>2</sub>: [M+H]<sup>+</sup>, *m/z* 521.2957; <sup>1</sup>H NMR (benzene-*d*<sub>6</sub>): signals based on an equivalent of two azulene-1-yl groups: δ 6.64 (2H, dd, *J*=9.8, 9.7 Hz, H-5'), 6.73 (2H, dd, *J*=9.8, 9.7 Hz, H-7'), 7.09 (2H, dd, *J*=9.8, 9.7 Hz, H-6'), 7.31 (2H, d, *J*=3.7 Hz, H-3'), 7.88 (2H, d, *J*=9.7 Hz, H-4'), 8.19 (2H, d, *J*=3.7 Hz, H-2'), and 8.36 (2H, d, *J*=9.8 Hz, H-8'); signals based on an equivalent of two 4-(dimethylamino)phenyl groups: δ 2.32 (12H, s, (CH<sub>3</sub>)<sub>2</sub>N-4''), 6.27 (4H, dd, *J*=8.9, 2.6 Hz, H-3'',5''), and 7.12 (4H, dd, *J*=8.9, 2.6 Hz, H-2'',6''); a signal based on an equivalent of an ethane unit (>HC<sup>1</sup>–C<sup>1</sup>H<): δ 5.70 (2H, s, H-1); <sup>13</sup>C NMR (benzene-*d*<sub>6</sub>): δ 148.8 (C-4'), 141.3 (C-3a'), 137.7 (C-2'), 136.8 (C-6'), 136.3 (C-4''), 135.8 (C-8a'), 135.0 (C-1''), 134.0 (C-1'), 133.6 (C-8'), 129.2 (C-2'',6''), 122.1 (C-5'), 121.6 (C-7'), 117.6 (C-3'), 112.9 (C-3'',5''), 49.4 (C-1), and 40.3 ((CH<sub>3</sub>)<sub>2</sub>N-4''). The numbering scheme of **7** is shown in Scheme 1.

**4.1.1.6. Compound 8.** Dark blue needles [*R<sub>f</sub>*=0.50 on silica gel TLC (solvent: hexane/ethyl acetate=50:50, v/v)]; IR ν<sub>max</sub>/cm<sup>-1</sup> (KBr), 2851, 2797 (C–H), 1612, 1520 (C=C), and 1346 (C–N); exact FABMS (3-nitrobenzyl alcohol matrix), found *m/z* 521.2987, calcd for C<sub>38</sub>H<sub>37</sub>N<sub>2</sub>: [M+H]<sup>+</sup>, *m/z* 521.2957; <sup>1</sup>H NMR (benzene-*d*<sub>6</sub>): signals based on an equivalent of two azulene-1-yl groups: δ 6.61 (2H, dd, *J*=9.8, 9.2 Hz, H-5'), 6.74 (2H, dd, *J*=9.8, 9.8 Hz, H-7'), 7.03 (2H, d, *J*=3.7 Hz, H-3'), 7.09 (2H, dd, *J*=9.8, 9.7 Hz, H-6'), 7.78 (2H, d, *J*=9.7 Hz, H-4'), 7.95 (2H, d, *J*=3.7 Hz, H-2'), and 8.44 (2H, d, *J*=9.8 Hz, H-8'); signals based on an equivalent of two 4-(dimethylamino)phenyl groups: δ 2.43 (12H, s, (CH<sub>3</sub>)<sub>2</sub>N-4''), 6.46 (4H, dd, *J*=8.9, 2.6 Hz, H-3'',5''), and 7.19 (4H, dd, *J*=8.9, 2.6 Hz, H-2'',6''); a signal based on an equivalent of an ethane unit (>HC<sup>1</sup>–C<sup>1</sup>H<): δ 5.69 (2H, s, H-1). The numbering scheme of **8** is shown in Scheme 1.

**4.1.2. X-ray crystal structure of 2-(azulene-1-yl)-1,1-bis[4-(dimethylamino)phenyl]ethylene (**3**).** A total of 10,568 reflections with 2θ<sub>max</sub>=55.0° were collected on a Rigaku AFC-5R automated four-circle diffractometer with graphite monochromated Mo Kα radiation (λ=0.71069 Å, rotating anode: 50 kV, 180 mA) at –75 °C. The structure was solved by direct methods (SIR92) and expanded using Fourier techniques (DIRDIF94). Non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included but not refined. The final cycle of full-matrix least-squares refinement was based on *F*<sup>2</sup>. All calculations were performed using the teXsan crystallographic software package. Crystallographic data have been deposited with Cambridge Crystallographic Data Center: Deposition number CCDC-634525 for compound No. **3**. Copies of the data can be obtained free of charge via <http://www.ccdc.cam.ac.uk/conts/retrieving.html> (or from the Cambridge Crystallographic Data Center, 12, Union Road, Cambridge, CB2 1EZ, UK; Fax: +44 1223 336033; e-mail: [deposit@ccdc.cam.ac.uk](mailto:deposit@ccdc.cam.ac.uk)).

Crystallographic data for **3**: C<sub>28</sub>H<sub>28</sub>N<sub>2</sub> (FW=392.54), dark green block (crystal size, 0.50×0.50×0.40 mm), triclinic, *P*-1 (#2), *a*=14.574(5) Å, *b*=14.619(4) Å, *c*=10.482(4) Å, α=95.60(3)°, β=94.53(3)°, γ=89.48(3)°, *V*=2215.6(13) Å<sup>3</sup>, *Z*=4, *D*<sub>calcd</sub>=1.177 g/cm<sup>3</sup>, μ(Mo Kα)=0.683 cm<sup>-1</sup>, scan width=(1.15+0.30 tanθ)°, scan type=ω–2θ, scan rate=8.0°/min, measured reflections=10,168, observed reflections=6601, No. of parameters=598, *R*<sub>1</sub>=0.0533, *wR*<sub>2</sub>=0.1472, and goodness of fit indicator=0.949.

**4.1.3. X-ray crystal structure of 1,1-d(iazulene-1-yl)-2,2-bis[4-(dimethylamino)phenyl]ethane (**6**).** A total 4405 reflections with 2θ<sub>max</sub>=55.0° were collected on a Rigaku AFC-5R automated

four-circle diffractometer with graphite monochromated Mo  $K\alpha$  radiation ( $\lambda=0.71069$  Å, rotating anode: 50 kV, 180 mA) at  $-75$  °C. The structure was solved by direct methods (SIR92) and expanded using Fourier techniques (DIRDIF94). Non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included but not refined. The final cycle of full-matrix least-squares refinement was based on  $F^2$ . All calculations were performed using the teXsan crystallographic software package. Crystallographic data have been deposited with the Cambridge Crystallographic Data Center: Deposition number CCDC-629473 for compound No. **6**.

Crystallographic data for **6** with benzene as a recrystallization solvent:  $C_{44}H_{42}N_2$  (FW=598.83), dark blue block (crystal size,  $0.60 \times 0.40 \times 0.40$  mm), orthorhombic,  $P2_12_12_1$  (#19),  $a=11.162(4)$  Å,  $b=28.320(3)$  Å,  $c=10.834(9)$  Å,  $\alpha=\beta=\gamma=90.00(0)^\circ$ ,  $V=3424.6(15)$  Å<sup>3</sup>,  $Z=4$ ,  $D_{\text{calcd}}=1.161$  g/cm<sup>3</sup>,  $\mu(\text{Mo } K\alpha)=0.667$  cm<sup>-1</sup>, scan width= $(0.73+0.30 \tan\theta)^\circ$ , scan type= $\omega$ , scan rate= $16.0^\circ/\text{min}$ , measured reflections=4405, observed reflections=1735, No. of parameters=458,  $R1=0.0453$ ,  $wR2=0.1709$ , and goodness of fit indicator=1.043.

**4.1.4. X-ray crystal structure of (1R,2S)-1,2-di(azulen-1-yl)-1,2-bis[4-(dimethylamino)phenyl]ethane (7).** A total 3469 reflections with  $2\theta_{\text{max}}=55.0^\circ$  were collected on a Rigaku AFC-5R automated four-circle diffractometer with graphite monochromated Mo  $K\alpha$  radiation ( $\lambda=0.71069$  Å, rotating anode: 50 kV, 180 mA) at  $-75$  °C. The structure was solved by direct methods (SIR92) and expanded using Fourier techniques (DIRDIF94). Non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included but not refined. The final cycle of full-matrix least-squares refinement was based on  $F^2$ . All calculations were performed using the teXsan crystallographic software package. Crystallographic data have been deposited with the Cambridge Crystallographic Data Center: Deposition number CCDC-704014 for compound No. **7**.

Crystallographic data for **7**:  $C_{38}H_{36}N_2$  (FW=520.72), blue needle (crystal size,  $0.30 \times 0.30 \times 0.20$  mm), triclinic,  $P-1$  (#19),  $a=10.5320(16)$  Å,  $b=10.852(2)$  Å,  $c=6.6627(9)$  Å,  $\alpha=107.364(12)^\circ$ ,  $\beta=96.203(13)^\circ$ ,  $\gamma=94.3326(14)^\circ$ ,  $V=717.86(20)$  Å<sup>3</sup>,  $Z=2$ ,  $D_{\text{calcd}}=1.204$  g/cm<sup>3</sup>,  $\mu(\text{Mo } K\alpha)=0.694$  cm<sup>-1</sup>, scan width= $(1.10+0.30 \tan\theta)^\circ$ , scan type= $\omega-2\theta$ , scan rate= $16.0^\circ/\text{min}$ , measured reflections=3283, observed reflections=2338, No. of parameters=200,  $R1=0.0452$ ,  $wR2=0.1678$ , and goodness of fit indicator=0.911.

**4.1.5. X-ray crystal structure of (1R,2R)- and (1S,2S)-1,2-di(azulen-1-yl)-1,2-bis[4-(dimethylamino)phenyl]ethane (8).** A total 3797 reflections with  $2\theta_{\text{max}}=55.0^\circ$  were collected on a Rigaku AFC-5R automated four-circle diffractometer with graphite monochromated Mo  $K\alpha$  radiation ( $\lambda=0.71069$  Å, rotating anode: 50 kV, 180 mA) at  $-75$  °C. The structure was solved by direct methods (SIR92) and expanded using Fourier techniques (DIRDIF94). Non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included but not refined. The final cycle of full-matrix least-squares refinement was based on  $F^2$ . All calculations were performed using the teXsan crystallographic software package. Crystallographic data have been deposited with the Cambridge Crystallographic Data Center: Deposition number CCDC-704013 for compound No. **8**.

Crystallographic data for **8**:  $C_{38}H_{36}N_2$  (FW=520.72), blue needle (crystal size,  $0.30 \times 0.20 \times 0.20$  mm), monoclinic,  $P2_1$  (#4),  $a=10.363(3)$  Å,  $b=6.699(4)$  Å,  $c=20.815(3)$  Å,  $\alpha=\gamma=90.00(0)^\circ$ ,  $\beta=91.661(15)^\circ$ ,  $V=1444.5(9)$  Å<sup>3</sup>,  $Z=2$ ,  $D_{\text{calcd}}=1.197$  g/cm<sup>3</sup>,  $\mu(\text{Mo } K\alpha)=0.690$  cm<sup>-1</sup>, scan width= $(0.89+0.30 \tan\theta)^\circ$ , scan type= $\omega-2\theta$ , scan rate= $12.0^\circ/\text{min}$ , measured reflections=3600, observed reflections=1796, No. of parameters=399,  $R1=0.0475$ ,  $wR2=0.0928$ , and goodness of fit indicator=0.996.

**4.1.6. Reaction of 2-(azulen-1-yl)-1,1-bis[4-(dimethylamino)phenyl]ethylene (3) with azulene (1).** To a solution of a commercially

available azulene (**1**) (4 mg, 31  $\mu\text{mol}$ ) in methanol (1.5 mL) was added a solution of 2-azulen-1-yl-1,1-bis[4-(dimethylamino)phenyl]ethylene (**3**) (10 mg, 26  $\mu\text{mol}$ ) in acetonitrile (2.0 mL). The mixture containing 36% hydrochloric acid (50  $\mu\text{L}$ ) was stirred at 60 °C for 3 h. After the reaction, distilled-water was added to the mixture and then the resulting products were extracted with dichloromethane (10 mL $\times$ 3). The extract was washed with distilled-water, dried (MgSO<sub>4</sub>), and evaporated in vacuo. The residue thus obtained was carefully separated by silica gel column chromatography with hexane–ethyl acetate–benzene (90:5:5, v/v/v) as an eluant. The starting materials **1** (1 mg, 8  $\mu\text{mol}$ , 26%) and **3** (3 mg, 8  $\mu\text{mol}$ , 31%) were recovered. The product 1,1-di(azulen-1-yl)-2,2-bis[4-(dimethylamino)phenyl]ethane (**6**) (6 mg, 12  $\mu\text{mol}$ , 46% yield) was isolated, the molecular structure of which was identified on the basis of silica gel TLC analysis and FABMS and <sup>1</sup>H NMR spectral data. Along with the product **6**, this reaction gave a chromatographically inseparable mixture of dark brown-colored polar resinous substances.

**4.1.7. Reaction of 1,1-di(azulen-1-yl)-2,2-bis[4-(dimethylamino)phenyl]ethane (6) with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ).** To a solution of 1,1-di(azulen-1-yl)-2,2-bis[4-(dimethylamino)phenyl]ethane (**6**) (11 mg, 21  $\mu\text{mol}$ ) in dichloromethane (2.0 mL) was added a solution of DDQ (13 mg, 56  $\mu\text{mol}$ ) in dichloromethane (2.0 mL). The mixture was stirred at 25 °C for 24 h. After the reaction, triethylamine was added to the mixture and then the mixture was stirred at 25 °C for 10 min. The reaction solvent was evaporated in vacuo and the residue thus obtained was carefully separated by silica gel column chromatography with hexane–ethyl acetate–benzene (90:5:5, v/v/v) as an eluant. The product 1,1-di(azulen-1-yl)-2,2-bis[4-(dimethylamino)phenyl]ethylene (**9**) was isolated as a dark yellowish-brown paste (5 mg, 10  $\mu\text{mol}$ , 48% yield). Along with the product **9**, this reaction gave a chromatographically inseparable mixture of dark brown-colored polar resinous substances.

**4.1.7.1. Compound 9.** Dark yellowish-brown paste [ $R_f=0.60$  on silica gel TLC (sol. hexane/ethyl acetate=50:50, v/v)], UV–vis  $\lambda_{\text{max}}/\text{nm}$  (log  $\epsilon$ ) in CH<sub>3</sub>CN, 203 (4.69), 236 (4.50), 273 (4.65), 298 (4.58), 345 (4.25), 401 (4.09), and 629 (2.70); IR  $\nu_{\text{max}}/\text{cm}^{-1}$  (KBr), 2843, 2797 (C–H), 1605, 1516 (C=C), and 1350 (C–N); exact EIMS (70 eV), found  $m/z$  518.2742, calcd for  $C_{38}H_{34}N_2$ :  $M^+$ ,  $m/z$  518.2722; <sup>1</sup>H NMR (benzene-*d*<sub>6</sub>): signals based on an equivalent of two azulene-1-yl groups:  $\delta$  6.44 (2H, dd,  $J=10.0, 9.8$  Hz, H-7'), 6.54 (2H, dd,  $J=9.7, 9.5$  Hz, H-5'), 6.88 (2H, dd,  $J=9.8, 9.7$  Hz, H-6'), 7.22 (2H, d,  $J=4.0$  Hz, H-3'), 7.80 (2H, d,  $J=9.5$  Hz, H-4'), 7.98 (2H, d,  $J=4.0$  Hz, H-2'), and 8.27 (2H, d,  $J=10.0$  Hz, H-8'); signals based on an equivalent of two 4-(dimethylamino)phenyl groups:  $\delta$  2.34 (12H, s, (CH<sub>3</sub>)<sub>2</sub>N-4''), 6.31 (4H, dd,  $J=8.9, 2.5$  Hz, H-3'',5''), and 7.38 (4H, dd,  $J=8.9, 2.5$  Hz, H-2'',6''); <sup>13</sup>C NMR (benzene-*d*<sub>6</sub>):  $\delta$  148.9 (C-4''), 144.0 (C-1), 142.6 (C-3a'), 141.7 (C-2'), 137.2 (C-6'), 136.4 (C-1'), 136.1 (C-4'), 136.0 (C-8'), 135.5 (C-8a'), 133.9 (C-1''), 132.9 (C-2'',6''), 123.0 (C-5'), 122.1 (C-7'), 118.1 (C-3'), 112.0 (C-3'',5''), and 39.9 ((CH<sub>3</sub>)<sub>2</sub>N-4''). The C-2 carbon signal was included in another signal. The numbering scheme of **9** is shown in Scheme 2.

**4.1.8. Reaction of 1,1-bis[4-(dimethylamino)phenyl]-2-(3-guaiazulenyl)ethylene (11) with azulene (1).** To a solution of a commercially available **1** (22 mg, 172  $\mu\text{mol}$ ) in methanol (2 mL) was added a solution of **11** (74 mg, 160  $\mu\text{mol}$ ) in acetonitrile (3 mL). The mixture containing 36% hydrochloric acid (50  $\mu\text{L}$ ) was stirred at 60 °C for 3 h. After the reaction, distilled-water was added to the mixture and then the resulting products were extracted with dichloromethane (10 mL $\times$ 3). The extract was washed with distilled-water, dried (MgSO<sub>4</sub>), and evaporated in vacuo. The

residue thus obtained was carefully separated by silica gel column chromatography with hexane–ethyl acetate–benzene (90:5:5, v/v/v) as an eluant. Guaiazulene<sup>1</sup> (**10**) (29 mg, 146 μmol, 91% yield), 2-(azulen-1-yl)-1,1-bis[4-(dimethylamino)phenyl]ethylene (**3**) (28 mg, 72 μmol, 46% yield), 1,3-bis[2,2-bis[4-(dimethylamino)phenyl]ethenyl]azulene (**5**) (20 mg, 30 μmol, 19% yield), and 1,1-di(azulen-1-yl)-2,2-bis[4-(dimethylamino)phenyl]ethane (**6**) (11 mg, 21 μmol, 13% yield) were isolated. The structures of the products **3**, **5**, **6**, and **10** were identified on the basis of silica gel TLC analysis and EI (or FAB) MS and <sup>1</sup>H NMR spectral data. Along with the above products, this reaction gave a chromatographically inseparable mixture of dark brown-colored polar resinous substances.

**4.1.9. Reaction of 2-(3-guaiazulenyl)-1,1-bis(4-methoxyphenyl)ethylene (**12**) with azulene (**1**).** To a solution of a commercially available **1** (17 mg, 133 μmol) in methanol (2 mL) was added a solution of **12** (59 mg, 135 μmol) in acetonitrile (3 mL). The mixture containing 36% hydrochloric acid (50 μL) was stirred at 60 °C for 3 h. After the reaction, distilled-water was added to the mixture and then the resulting products were extracted with dichloromethane (10 mL×3). The extract was washed with distilled-water, dried (MgSO<sub>4</sub>), and evaporated in vacuo. The residue thus obtained was carefully separated by silica gel column chromatography with hexane–ethyl acetate–benzene (90:5:5, v/v/v) as an eluant. Guaiazulene<sup>1</sup> (**10**) (25 mg, 126 μmol, 93% yield) and the previously reported compounds 2-(azulen-1-yl)-1,1-bis(4-methoxyphenyl)ethylene<sup>10</sup> (**16**) (17 mg, 46 μmol, 34% yield) and 1,3-bis[2,2-bis(4-methoxyphenyl)ethenyl]azulene<sup>10</sup> (**17**) (15 mg, 25 μmol, 19% yield) were isolated. The structures of the products **10**, **16**, and **17** were identified on the basis of silica gel TLC analysis and EI (or FAB) MS and <sup>1</sup>H NMR spectral data. Along with the above products, this reaction gave a chromatographically inseparable mixture of dark brown-colored polar resinous substances.

**4.1.10. Reaction of 1,1-bis[4-[2-(dimethylamino)ethoxy]phenyl]-2-(3-guaiazulenyl)ethylene (**13**) with azulene (**1**).** To a solution of a commercially available **1** (5 mg, 39 μmol) in methanol (2 mL) was added a solution of **13** (20 mg, 36 μmol) in acetonitrile (3 mL). The mixture containing 36% hydrochloric acid (50 μL) was stirred at 60 °C for 3 h. After the reaction, distilled-water was added to the mixture and then the resulting products were extracted with dichloromethane (10 mL×3). The extract was washed with distilled-water, dried (MgSO<sub>4</sub>), and evaporated in vacuo. The residue thus obtained was carefully separated by silica gel column chromatography with methanol–dichloromethane (30:70, v/v) as an eluant. Guaiazulene<sup>1</sup> (**10**) (7 mg, 35 μmol, 97% yield) and a new compound 2-(azulen-1-yl)-1,1-bis[4-[2-(dimethylamino)ethoxy]phenyl]ethylene (**18**) (10 mg, 21 μmol, 58% yield) were isolated. The structure of the product **10** was identified on the basis of silica gel TLC analysis and EIMS and <sup>1</sup>H NMR spectral data. Along with the above products, this reaction gave a chromatographically inseparable mixture of dark brown-colored polar resinous substances.

**4.1.10.1. Compound 18.** Green powder [*R*<sub>f</sub>=0.09 on silica gel TLC (solvent: methanol/dichloromethane=50:50, v/v)]; exact EIMS (70 eV), found *m/z* 480.2770, calcd for C<sub>32</sub>H<sub>36</sub>O<sub>2</sub>N<sub>2</sub>: M<sup>+</sup>, *m/z* 480.2776; <sup>1</sup>H NMR (benzene-*d*<sub>6</sub>): signals based on an azulene-1-yl group: δ 6.98 (1H, d, *J*=4.2 Hz, H-3'''), 7.09 (1H, dd, *J*=9.8, 9.2 Hz, H-5'''), 7.10 (1H, d, *J*=4.2 Hz, H-2'''), 7.12 (1H, dd, *J*=9.9, 9.8 Hz, H-7'''), 7.57 (1H, dd, *J*=9.8, 9.8 Hz, H-6'''), 8.16 (1H, d, *J*=9.2 Hz, H-4'''), and 8.56 (1H, d, *J*=9.9 Hz, H-8'''); signals based on a non-equivalent of two 4-[2-(dimethylamino)ethoxy]phenyl groups: δ 2.24 (6H, s, (CH<sub>3</sub>)<sub>2</sub>N-8''), 2.26 (6H, s, (CH<sub>3</sub>)<sub>2</sub>N-8'), 2.64 (2H, t, *J*=5.8 Hz, H-8''), 2.67 (2H, t, *J*=5.8 Hz, H-8'), 4.06 (2H, t, *J*=5.8 Hz, H-7''), 4.08 (2H, t, *J*=5.8 Hz,

H-7'), 6.88 (2H, dd, *J*=8.8, 2.5 Hz, H-3',5''), 6.94 (2H, dd, *J*=8.6, 2.5 Hz, H-3',5'), 7.11 (2H, dd, *J*=8.6, 2.5 Hz, H-2',6'), and 7.32 (2H, dd, *J*=8.8, 2.5 Hz, H-2',6''); a signal based on an ethylene unit (>C<sup>1</sup>=C<sup>2</sup>H–): δ 7.50 (1H, s, H-2); <sup>13</sup>C NMR (benzene-*d*<sub>6</sub>): δ 159.4 (C-4'), 159.3 (C-4''), 142.7 (C-3a'''), 139.8 (C-1), 139.3 (C-6'''), 137.8 (C-8a'''), 137.4 (C-4'''), 137.3 (C-1''), 137.1 (C-2'''), 134.9 (C-1',8''), 132.4 (C-2',6'), 129.2 (C-2'',6''), 128.0 (C-1'''), 124.8 (C-5'''), 123.5 (C-7'''), 119.2 (C-2,3'''), 115.9 (C-3',5'), 115.2 (C-3'',5''), 67.2 (C-7',7''), 59.0 (C-8',8''), and 46.1 ((CH<sub>3</sub>)<sub>2</sub>N-8',8''). The numbering scheme of **18** is shown in Scheme 3.

## Acknowledgements

This work was partially supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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- Dipole moment (D): azulene (**1**) (1.512); guaiazulene (**10**) (1.574). Both dipole moments were calculated using a WinMOPAC (Ver. 3.0) program (semi-empirical Hamiltonian: AM1 and keywords: PRECISE, VECTORS, ALLVEC, BONDS, GEO-OK, EF, PL, LET, T=10D, GNORM=10<sup>-4</sup>, and SCFCRT=10<sup>-10</sup>), the program of which was developed by Fujitsu Ltd., Japan. The final values of the gradient norms for the optimized structures **1** and **10** showed 0.043 and 0.033, respectively.
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60. Permittivity of methanol: 32.6 at 25 °C. Permittivity of acetonitrile: 37.5 at 20 °C. Thus, it can be inferred that this reaction, owing to the influence of the mixed solvent possessing a larger permittivity in comparison with methanol, gives the products **3–8**. This reaction in acetonitrile was not carried out, because compound **2** was insoluble in acetonitrile.
61. The  $\pi$ -HOMO and  $\pi$ -LUMO energy levels and the atomic charges for the azulene rings **1** and **10** were calculated using the same MO calculation program and conditions as for References and notes No. 2. **1**:  $\pi$ -HOMO (–0.4211 eV) and  $\pi$ -LUMO (2.0171 eV); the order of larger negative charge was C-1 (–0.187)>C-3 (–0.183)>C-5 (–0.159)>C-7 (–0.157)>C-2 (–0.113)>C-3a (–0.068)>C-6 (–0.063)>C-8a (–0.053)>C-4 (–0.037)>C-8 (–0.024). **10**:  $\pi$ -HOMO (–0.3815 eV) and  $\pi$ -LUMO (2.0235 eV); the order of larger negative charge was C-3 (–0.182)>C-5 (–0.160)>C-1 (–0.132)>C-2 (–0.116)>C-7 (–0.095)>C-3a (–0.066)>C-6 (–0.059)>C-8a (–0.047)>C-8 (–0.021)>C-4 (0.023).
62. The formation of the protonated structure **A** was established, indirectly, on the basis of  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectral analyses of **11** using a strong organic acid  $\text{CF}_3\text{COOD}$  as a measurement solvent at 25 °C:  $^1\text{H}$  NMR: signals based on a 5-isopropyl-3,8-dimethylazulen-1-ylum moiety:  $\delta$  7.22 (1H, s, H-2''), 2.36 (3H, s, Me-3''), 8.57 (1H, d,  $J=2.0$  Hz, H-4''), 3.43 (1H, sept,  $J=7.0$  Hz,  $(\text{CH}_3)_2\text{CH-5}''$ ), 1.44 (6H, d,  $J=7.0$  Hz,  $(\text{CH}_3)_2\text{CH-5}''$ ), 8.45 (1H, dd,  $J=11.0, 2.0$  Hz, H-6''), 8.48 (1H, d,  $J=11.0$  Hz, H-7''), and 2.79 (1H, s, Me-8''); signals based on a deuterated 4-(dimethylamino)phenyl group on the nitrogen atom:  $\delta$  7.31 (2H, dd,  $J=8.9, 2.5$  Hz, H-2',6'), 7.46 (2H, dd,  $J=8.9, 2.5$  Hz, H-3',5'), and 3.31 (6H, s,  $(\text{CH}_3)_2\text{N}^+\text{D-4}'$ ); signals based on the other deuterated 4-(dimethylamino)phenyl group on the nitrogen atom:  $\delta$  7.63 (2H, dd,  $J=8.9, 2.5$  Hz, H-2'',6''), 7.80 (2H, dd,  $J=8.9, 2.5$  Hz, H-3'',5''), and 3.43 (6H, s,  $(\text{CH}_3)_2\text{N}^+\text{D-4}''$ ); and a signal based on an ethylene unit ( $\text{>C}^1=\text{C}^2\text{H-}$ ):  $\delta$  5.38 (1H, s, H-2);  $^{13}\text{C}$  NMR: signals based on a 5-isopropyl-3,8-dimethylazulen-1-ylum moiety:  $\delta$  56.3 (C-1''), 152.7 (C-2''), 170.6 (C-3''), 14.1 (Me-3''), 148.0 (C-3a''), 141.4 (C-4''), 179.6 (C-5''), 42.9 ( $(\text{CH}_3)_2\text{CH-5}''$ ), 24.5 ( $(\text{CH}_3)_2\text{CH-5}''$ ), 148.5 (C-6''), 152.7 (C-7''), 161.8 (C-8''), 27.0 (Me-8''), and 169.6 (C-8a''); signals based on a deuterated 4-(dimethylamino)phenyl group on the nitrogen atom:  $\delta$  145.1 (C-1'), 131.6 (C-2',6'), 122.6 (C-3',5'), 143.9 (C-4'), and 49.3 ( $(\text{CH}_3)_2\text{N}^+\text{D-4}'$ ); signals based on the other deuterated 4-(dimethylamino)phenyl group on the nitrogen atom:  $\delta$  143.3 (C-1''), 134.1 (C-2'',6''), 123.7 (C-3'',5''), 144.5 (C-4''), and 49.4 ( $(\text{CH}_3)_2\text{N}^+\text{D-4}''$ ); and signals based on an ethylene unit ( $\text{>C}^1=\text{C}^2\text{H-}$ ):  $\delta$  149.2 (C-1) and 123.6 (C-2).