Synthesis and photochromic behaviour of new dipyrrolylperfluorocyclopentenes

Arnault Heynderickx, Ali Mohamed Kaou, Corinne Moustrou, André Samat* and Robert Guglielmetti

Groupe de Chimie Organique et Matériaux Moléculaires, UMR 6114 CNRS, Université de la Méditerranée, Faculté des Sciences de Luminy, Case 901, 13288, Marseille Cedex 9, France. E-mail: samat@luminy.univ-mrs.fr; Fax: 33 4 91 82 93 01

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The synthesis of new photoswitchable dipyrrolylethenes having different π-conjugated chain lengths, employing Wittig–Horner reaction, Knoevenagel condensation, Suzuki palladium catalyzed cross-coupling or Sonogashira coupling, is reported. Their photochemical behaviour, and in particular, their thermal stability has been investigated upon continuous irradiation with light of appropriate wavelengths.

Introduction

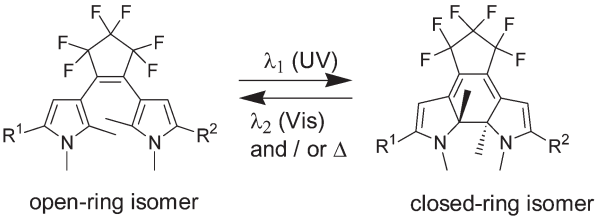
In recent years, organic photochromic compounds that reversibly change their physical and chemical properties upon irradiation have received increasing attention due to their potential applications for optoelectronic devices.[1] So far, various photochromic families, such as spiropyranes,[2] spirooxazines,[3] azobenzenes,[4] fulgides,[5] and diarylethenes[6] have been developed to satisfy the specific needs of each new device.

In the field of the design of materials undergoing variable optical transmission such as ophthalmic plastic lenses, photochromic compounds must cope with several requirements: a thermally reversible colour change, a relatively fast thermal fading at room temperature (few seconds), a low fatigue or chemical instability upon repeated cycling or continuous irradiation, a highly efficient photoresponse in the near-UV, and a minimal quantum yield for bleaching with visible light in order to preserve the colour under sunlight exposure.

Spiropyranes, spironaphthoxazines and naphthopyrans have been studied to these aims, but a major problem arised from their fatigue resistance even if spironaphthoxazines brought important improvement. Further development of new systems is warranted.

Diarylethenes having perfluorocyclopentene moieties may be promising candidates for these practical applications owing to their excellent characteristics regarding degradation even in the presence of air during photocyclisation.[6,7] Various diarylethenes can undergo more than 10^4 cycles of coloration–bleaching before significant evidence of fatigue. It is worthwhile to note that the thermal stability of the colored closed-ring isomers is dependent on the aryl group type. When the aryl groups are furan, thiophene, selenophene or thiazole rings, the closed form are stable and do not return to the open-ring isomer even at 80 °C. On the other hand, photogenerated closed-ring isomers of diarylethenes with pyrrole[7a,b,8] (Scheme 1), indole or phenyl rings undergo thermally reversible reaction.[6] Other parameters such as bulky substituents or strong electron-withdrawing substituents can assist the thermal reversibility.[9]

In that context, the synthesis of new dipyrrolylperfluorocyclopentenes and their photochromic properties having different π-conjugated chain lengths have been investigated.



Scheme 1 Photochromism of dipyrrolylethenes.

Results and discussion

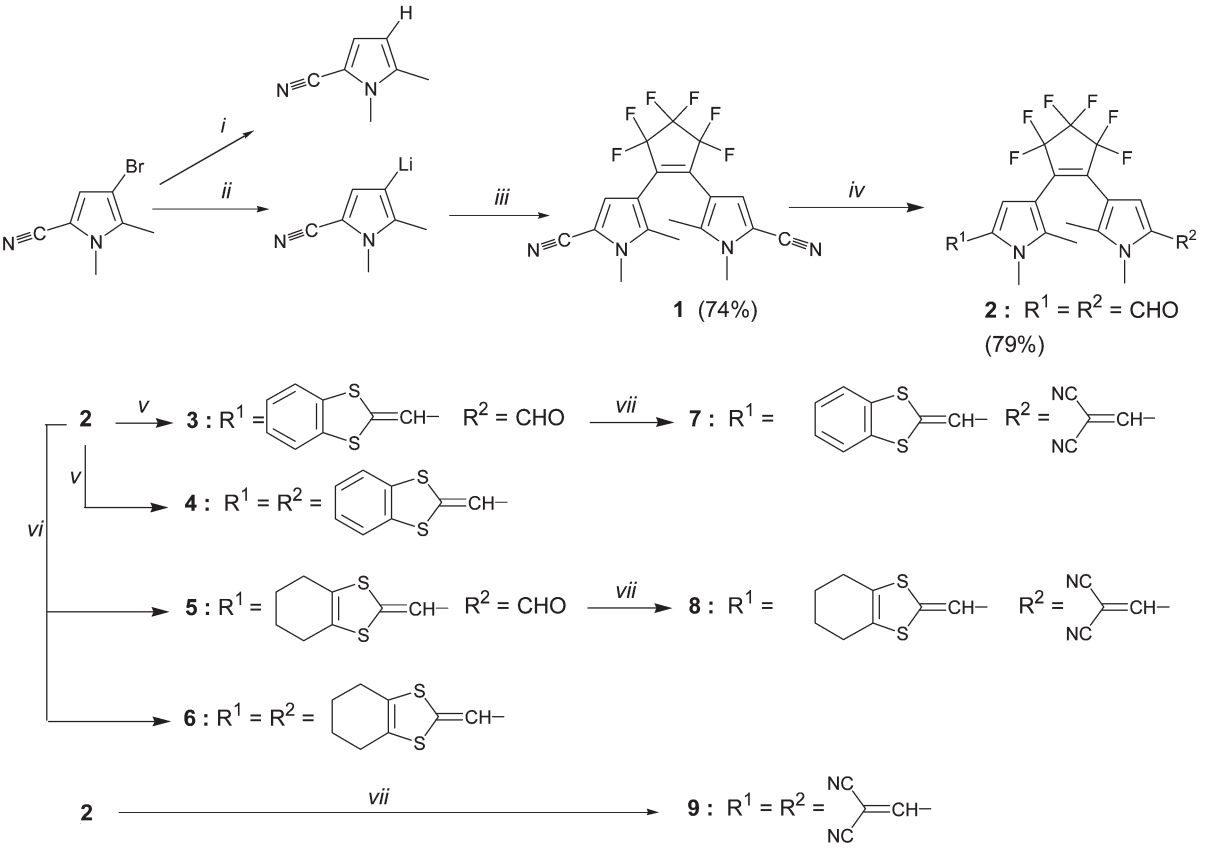
Syntheses

The synthetic approach to these compounds began with Irie's 1,2-bis(2-cyano-1,5-dimethyl-4-pyrrolyl)hexafluorocyclopentene **19**. Despite its highly attractive synthetic interest as precursor, the expensive and rather volatile material octafluorocyclopentene and the low yield (11%) occurring during the double substitution reaction of octafluorocyclopentene with 4-lithio-1,5-dimethyl-2-pyrrolcarbonitrile is a major disadvantage for applications.

In order to improve the yield for the preparation of **1**, the bromine–lithium exchange, performed from reaction between 4-bromo-1,5-dimethyl-2-pyrrolcarbonitrile with a slight excess of *n*-butyllithium at −100 °C in THF, was examined (Scheme 2). The lithio derivative was trapped by a mixture of HCl, ethanol and THF, at various reactions times. When the reaction time is less then 15 minutes, a small amount of starting material is still recovered and for longer reaction times, the yield is decreasing.

The most efficient conditions were obtained for a reaction time of 15 minutes, affording 1,5-dimethyl-2-pyrrolcarbonitrile in excellent yield. Then the lithio intermediate was reacted with an equimolar amount of octaperfluorocyclopentene, at low temperature, for longer time than the protocol previously described. With this optimized reaction condition, the diarylethene **1** can be conveniently prepared on a multigram scale, in 74% yield.

Selective reduction of the cyano groups[10] performed with diisobutylaluminium hydride (Dibal-H) in dichloromethane, followed by hydrolysis, gave the key dialdehyde **2** in 79% yield.



Scheme 2 Synthesis of products **1**–**9** by Wittig–Horner reaction and Knoevenagel condensation. Reagents and conditions: (i) 1.05 equiv. *n*-Buli, THF, −100 °C, *t* min then hydrolysis by a mixture (HCl–EtOH–THF; 1 2 2), −78 °C. (ii) 1.05 equiv. *n*-Buli, THF, −100 °C, 15 min; (iii) 0.45 equiv. octaperfluorocyclopentene, −100 °C, 30 min then −78 °C, 4 h and −30 °C, 2 h. (iv) Dibal-H–CH_2Cl_2, −50 °C to 0 °C; (v) 2-dimethoxyphosphinyl-1,3-benzodithiol (1.05 or 2.2 equiv.), *n*-Buli, THF, −78 °C → 20 °C; (vi) 2-dimethoxyphosphinyl-4,5,6,7-tetrahydro-1,3-benzodithiol (1.05 or 2.2 equiv.), *n*-Buli, THF, −78 °C → 20 °C; (vii) malononitrile (1.05 or 2.2 equiv.), benzene, piperidine, 20 °C.

Further Wittig–Horner reaction of **2** with phosphonate carbanion (1.05 or 2.2 equiv.), generated *in vivo* from deprotonation of 2-dimethoxyphosphinyl-1,3-benzodithiol[11] or 2-dimethoxyphosphinyl-4,5,6,7-tetrahydro-1,3-benzodithiol[12] with *n*-butyllithium, was achieved to produce compounds **3**–**6**. Then, the aldehydes **2**, **3** and **5** were converted by Knoevenagel condensation[13] employing malononitrile (1.05 or 2.2 equiv.) to give symmetric and unsymmetric compounds **7**–**9** as illustrated in Scheme 2.

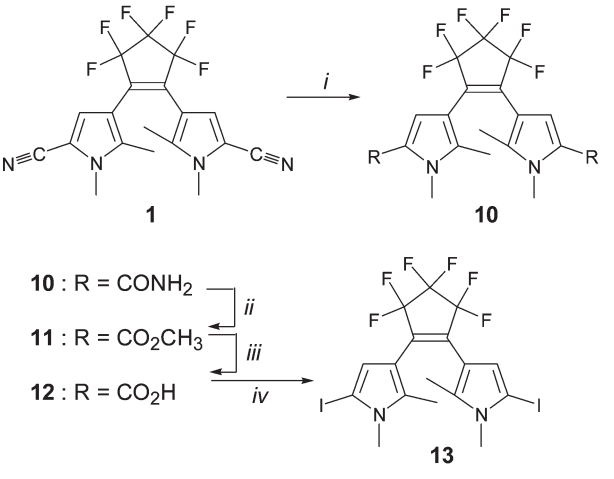
Dipyrrolylethenes **7** and **8** may be expected to display pronouncedly different and reversible nonlinear optical features between the two forms (open and closed), switching being triggered by UV and visible irradiation. They constitute donor-π-acceptor (D-π-A) systems comprising 1,3-dithiol moieties as terminal electron-donating group and dicyanomethylene as electron-accepting group.[14]

The next target was the 1,2-bis(2-iodo-1,5-dimethylpyrrol-4-yl)perfluorocyclopentene **13** which could be regarded as an excellent precursor for the design of future extended π-conjugated systems through palladium-catalyzed coupling reactions. The synthetic approach to the diiodo compound[15] **13** can be performed from the dicyano compound **1** as illustrated in Scheme 3.

Attempts to hydrolyse the cyano group in one step to diacid **12** using the standard method[16] (concentrated potassium hydroxide in water or ethylene glycol at higher temperature), were unsuccessful even prolonging the reaction time, giving diamide **10** as major product (76%) and negligible yield of diacid **12**. Alternative routes, involving oxidation of dialdehyde **2** with alkaline silver oxide[17] for the preparation of **12** or TMSCl in alcohol at reflux[18] for the preparation of diester **11** were unsuccessful.

Finally, the conversion of **10** into the carboxylic ester **11**, was performed according to the method reported by Anelli *et al.*,[19] using dimethylformamide dimethylacetal in alcohol. The compound **11** was isolated in 96% yield starting from **10**, in refluxing methanol, providing that an excess of sodium methylate was added, after one night of reaction, so as to accelerate the reaction of the intermediate *N*-acylformamidine.

The methoxycarbonyl group can easily be hydrolysed,[20] at reflux temperature, to afford the corresponding carboxylic acid **12** in excellent yield.



Scheme 3 Preparation of 1,2-bis(2-iodo-1,5-dimethylpyrrol-4-yl)perfluorocyclopentene, precursor of extended π-conjugated systems. Reagents and conditions: (i) aq. 2M NaOH, EtOH, reflux, 15 h, 76%; (ii) $(CH_3)_2NCH(OCH_3)_2$, CH_3OH, reflux, 10 h then 2 eq CH_3ONa, CH_3OH, 2 h, 85%; (iii) aq. 2M NaOH, H_2O, CH_3OH, reflux, 1 h 30 then HCl, 96%; (iv) I_2, KI, $NaHCO_3$, CH_3OH, H_2O, 60 °C, 2 h, 95%.

The iodinative decarboxylation[15c–e] of diacid **12** (Scheme 3) was performed, by heating at 60 °C for 2 h, a mixture of iodine and potassium iodide diluted in water–methanol solution, to lead to 1,2-bis(2-iodo-1,5-dimethylpyrrol-4-yl)perfluorocyclopentene **13** in near quantitative yield.

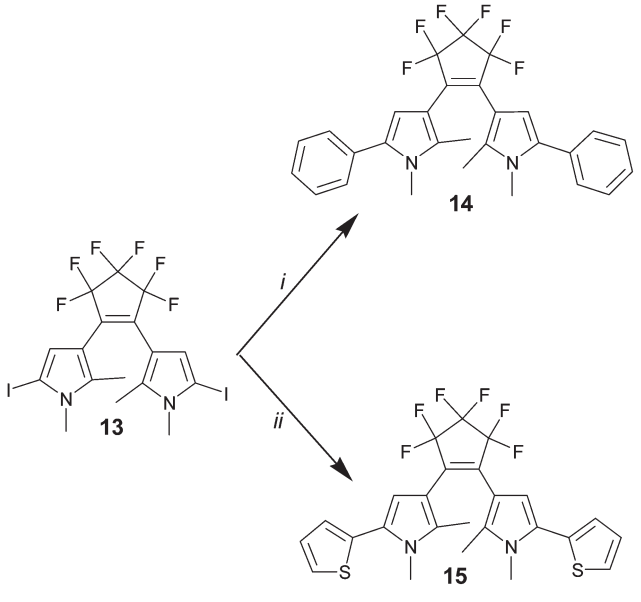
The Suzuki palladium catalyzed cross-coupling between aryl boronic acids and haloarenes or aryl triflates, in the presence of base, is an extremely powerful tool in organic synthesis to access the C_{sp2}–C_{sp2} bond. These coupling reactions work in the presence of many functional groups, give easily removable nontoxic by-products, and use nontoxic and readily available organoboranes. Consequently, this methodology has been already used in the synthesis of biologically active compounds containing the pyrrole ring.[21]

Then, a palladium-catalyzed Suzuki reaction of diiodo compound **13** with phenylboronic acid in DME–water solution in the presence of sodium carbonate and a catalytic amount of $Pd(PPh_3)_4$ gave the corresponding coupled-product **14** in moderated yield (52%). The thiophene analogue **15** has been prepared analogously in 86% yield (Scheme 4).

Among the various methods for introducing alkynyl groups on aromatic nuclei, the most powerful and useful is the Pd-catalyzed cross-coupling reaction of halogenoarenes with terminal alkynes, which was reported for the first time by Sonogashira–Hagihara[22] and Cassar[23] in 1975. Usually, this cross-coupling reaction proceeds in the presence of catalytic amounts of Pd-complexes such as $[Pd(PPh_3)_4]$ or $[PdCl_2(PPh_3)_2]$ in an amine as solvent. A variation of this synthetic procedure involves the use of protecting groups.[24] Coupling of halogenoarenes with the commercially available ethynyltrimethylsilane or with 2-methylbut-3-yn-2-ol provides (2-arylethynyl)trimethylsilane[25] or 3-arylalkynol[26] respectively. The compounds generate a terminal arylacetylene moiety by removal of the protecting group, which can be involved in another Sonogashira coupling to afford diarylalkynes.[27] This approach[28] was extended to the preparation of dipyrrolylethenes **16**–**19** as illustrated in Scheme 5.

Sonogashira–Hagihara reaction of 1,2-bis(2-iodo-1,5-dimethylpyrrol-4-yl)perfluorocyclopentene **13** with the commercially available 2-methylbut-3-yn-2-ol in Et_2NH (room temperature, 15 h), in the presence of $[PdCl_2(PPh_3)_2]$ and CuI as effective catalyst, afforded **16** in nearly quantitative yield. Using an excess of ethynyltrimethylsilane, at 70 °C for 17 h, the coupled alkynylsilane **18** could be prepared in quantitative yield. Deprotection of the trimethylsilyl group was realised under mild conditions by treatment of **18** with KOH in MeOH–CH_2Cl_2 to give **19** in 90% yield.

A modified version of Sonogashira coupling, carried out under phase-transfer condition,[29] allowed the synthesis of compound **17**. Then compound **16** was reacted with the 2-iodothiophene, at reflux for 20 h, in the presence of benzyltriethylammonium chloride as phase-transfer agent, aqueous 5.5 N NaOH as base, benzene as solvent, and a mixture of $[PdCl_2(PPh_3)_2]$ and CuI as catalysts, to lead to **17** in 92% yield. It is noteworthy that the mechanism of the coupling reaction in these conditions is most likely the "retro" version of the "Favorski–Babayau carboxy-ethynylation", in which the diethynyl derivative **19** is primarily formed, reacting then with the 2-iodothiophene to afford the desired product **17**.



Scheme 4 Suzuki coupling reaction. Reagents and conditions: (i) phenylboronic acid, DME, EtOH, $Pd(PPh_3)_4$, aq. 2 M Na_2CO_3, 70 °C, 18 h, 52%; (ii) 2-thienylboronic acid, DME, EtOH, $Pd(PPh_3)_4$, Na_2CO_3, 80 °C, 32 h, 86%.

Photochromic behavior

The photocyclisation of most of these new dipyrrolylethenes was achieved, by irradiation of ethylacetate or toluene solution (3.10^{-5} M) in the presence of air, at wavelengths corresponding to the absorption band of the open-ring isomer (Table 1). Attempts to perform the photocyclisation reaction of the push-pull substances **7**, **8**, their mono aldehyde precursors **3** and **5**, the dialdehyde **2** and the dicyanomethylene **9** were unsuccessful in various solvents (ethyl acetate, toluene and acetonitrile), at different temperatures (283 K to 303 K) between 304 nm to 406 nm. An example of photochromic behavior is given for compound **4** in Fig. 1.

In each case a photostationary state was observed. Indeed, the closed-ring isomers are thermally unstable and the decay of the coloration is greatly dependent on the nature of the substituent. The range of the half-time varies about 10^3 times from 6 s to 6000 s. The most stable cyclised forms are obtained with phenyl or ethynyl substituents.

Colored forms are also sensitive to visible light, leading to the initial open form (Fig. 1f).

Characteristic absorption bands of the closed-ring isomers appeared from 618 nm to 747 nm. Compounds **4** and **6** exhibit red-shifted λ_{max} values compared to the parent dicyanodipyrrolylethene **1**, with λ_{max} located into the near infrared region.

Conclusion

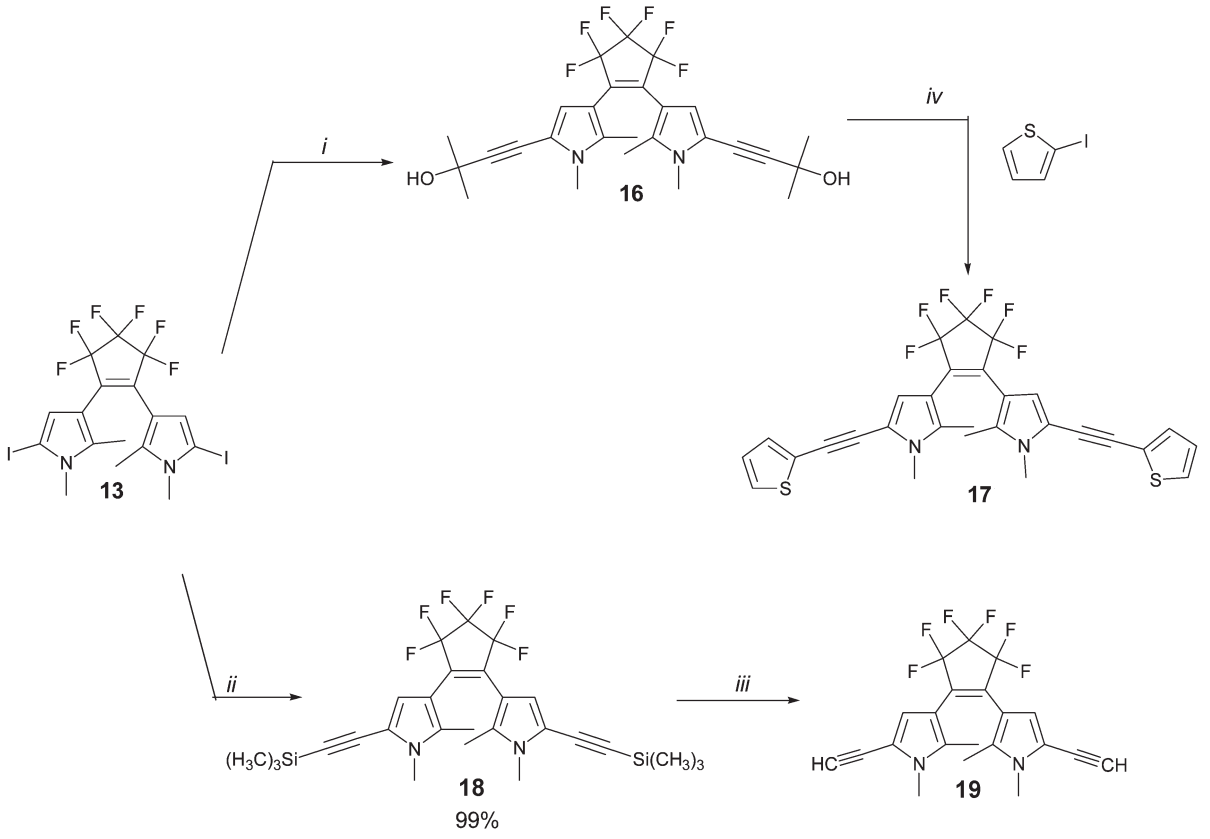
In this work, the improvement of the synthesis of 1,2-bis(2-cyano-1,5-dimethyl-4-pyrrolyl)hexafluorocyclopentene is demonstrated. Using this compound as starting material, we succeeded in the preparation of eighteen new dipyrrolylethenes. Most of these compounds are photochromic, the substitution pattern allowing the half-life time scale for the colored form to be extended.

Further studies aiming at substituting the 2-position of dipyrrolylethenes are currently in progress and will be the subject of a future report.

Experimental

General

Melting points were determined on a Büchi 510 apparatus in capillary tubes and are uncorrected. The ^1H NMR and ^{13}C NMR spectra were recorded in deuterated solvent on a Brücker AM 250 spectrometer (250 and 62.5 MHz, respectively) using tetramethylsilane as the internal standard. Column chromatography was carried out using silica gel Merck 60 (230–400 mesh from Merk Co.). Silica TLC was conducted



Scheme 5 Sonogashira–Hagihara coupling reaction. Reagents and conditions: (i) $[PdCl_2(PPh_3)_2]$, CuI, Et_2NH, $HC{\equiv}C(CH_3)_2OH$, 20 °C, 15 h, 94%; (ii) $[PdCl_2(PPh_3)_2]$, CuI, Et_3N, $HC{\equiv}CSi(CH_3)_3$, 70 °C, 17 h, 98%; (iii) KOH, MeOH, CH_2Cl_2, 20 °C, 14 h, 90%; (iv). $[Pd(PPh_3)_4]$, CuI, benzene, aq. 5.5 N NaOH, $PhCH_2NEt_3^+Cl^-$, reflux, 20 h, 92%.

on precoated aluminium sheets (60 F_{254}) with a 0.2 mm thickness (Aldrich Chemical Co.). The electron impact mass spectra (Ms) were obtained on a spectrometer HP 5973 Masse Selective Detector. Elemental analysis was performed using a Perking-Elmer EA 240 instrument.

Solvents (SDS Company, France) were used without further purification and were dried over sieves if necessary.

Table 1 Photochromic behavior of new dipyrrolylperfluorocyclopentenes

Compound	λ_{max} (nm) of the open-ring isomer ($\varepsilon \times 10^{-3}$ M^{-1} cm^{-1})	λ_{max} (nm) of the closed-ring isomer	Half-life time (s) (293 K)
1[a]	311 (13)	630	59 (lit 37)
2[b]	312 (27)	—	—
4[b]	336 (17)	735	174
5[b]	304 (50)	—	—
6[b]	352 (33)	747	63
7[b]	333 (8), 394 (10)	—	—
8[b]	399 (30)	—	—
9[b]	388 (38), 406 (36)	—	—
10[a]	322 (8.9)	631	597
11[a]	312 (14)	660	6
12[a]	312 (12)	644	9
14[a]	337 (10)	618	5400[c]
15[a]	302 (16), 342 (9)	656	660[c]
17[a]	328 (33)	694	4350
18[a]	337 (9)	657	134[c]
19[a]	333 (6.8)	636	5991

[a] Ethyl acetate solution (3.10–5 M). [b] Toluene solution (3.10^{-5} M). The symbol — means that the studied compound is not photosensible. The thermal bleaching constant of the colored closed-form, measured at λmax, obeys a first-order kinetic. [c] 333 K.

Tetrahydrofuran was distilled prior to use, under argon, from sodium benzophenone ketyl and used immediately. Metalation was performed under an argon atmosphere and reagents were handled with syringes through septa.

Photoirradiation was carried out by using a Xenon lamp (150 W) equipped with a monochromator.

Syntheses

1,2-bis(2-cyano-1,5-dimethylpyrrol-4-yl)perfluorocyclopentene (1)[8]. To a stirred and cooled (−100 °C) solution of

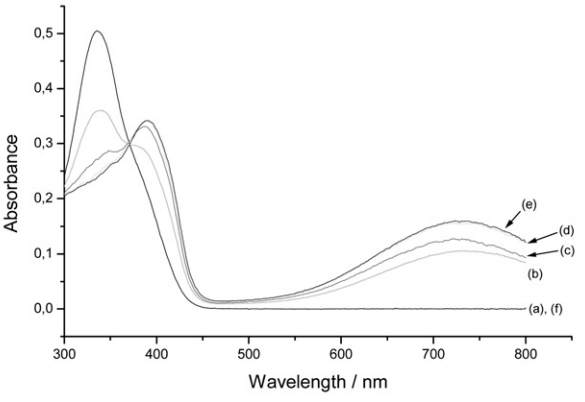


Fig. 1 UV-Vis absorption spectra change of **4** (3.10^{-5} M in EtOAc) measured at room temperature at different stages of the photochromic reaction. Irradiation (λ = 336 nm) intervals are every 2 minutes: (a) starting from open-ring isomer; (b) after irradiation for 2 minutes; (c) 4 minutes; (d) 6 minutes; (e) photostationary state under irradiation; (f) 30 minutes after irradiation was stopped or after irradiation with 735 nm light for 5 minutes, starting from the photostationary state.

4-bromo-1,5-dimethyl-2-pyrrolcarbonitrile[8] (2 g, 10.05 mmol) in anhydrous THF (25 mL) was added a 2.5 M solution of *n*-butyllithium in hexane (4.22 mL, 10.55 mmol). The bromine–lithium exchange was completed after 15 minutes. Then, octafluorocyclopentene (0.61 mL, 4.52 mmol) was introduced *via* a syringe. The resulting solution was maintained at −100 °C for 30 min, then allowed to warm to −78 °C for another 3 h and finally to warm gently to −30 °C. After quenching with a cold (−30 °C) mixture of HCl–EtOH–THF (1 : 2 : 2 in volume, 1 mL), water (10 mL) was added at room temperature. The layers were separated and the aqueous layer extracted CH_2Cl_2 (2 × 15 mL). The combined organic layers were dried over $MgSO_4$, filtered, and concentrated *in vacuo*. The crude product was purified by chromatography on silica gel (eluent, CH_2Cl_2–toluene 5 : 2) to afford the dipyrrolylethene **1** (1.38 g, 3.34 mmol, 74%). Spectroscopic and analytical measurements were entirely consistent with those reported previously.[8]

1,2-bis(2-formyl-1,5-dimethylpyrrol-4-yl)perfluorocyclopentene (2). To a stirred and cooled (−50 °C) solution of **1** (1.39 g; 3.37 mmol), in anhydrous CH_2Cl_2 (60 mL) was added dropwise a 1 M solution of diisobutylaluminium hydride in hexane (16.86 mL, 16.85 mmol). After completion of the addition, the solution was allowed to warm to 0 °C and the stirring was continued for 5 h at the same temperature. Excess of aqueous sulfuric acid (5%) was added and the resulting solution was adjusted to pH 8 with potassium carbonate. After decanting, the aqueous layer was extracted with dichloromethane (2 × 20 mL). The combined organic layers were washed with brine (10 mL), dried over $MgSO_4$ and filtered.

Concentration *in vacuo* followed by purification of the crude solid with silica gel chromatography (eluent, CH_2Cl_2–cyclohexandiethyl ether 4 : 4 : 2) provided dialdehyde **2** (1.03 g, 2.46 mmol, 73%) as a clear brown solid; mp: 209 °C. ^{1}H NMR ($CDCl_3$): δ 1.69 (s, 3H, CH_3), 3.77 (s, 3H, CH_3N), 6.96 (s, 1H, H_3), 9.42 (s, 1H, CHO). MS: m/z = 418 (molecular ion). Analysis calculated for $C_{19}H_{16}F_6N_2O_2$ (418.33): C, 54.55; H, 3.86; N, 6.70%. Found: C, 54.28; H, 3.72; N, 6.67%.

Wittig–Horner reaction of 2-dimethoxyphosphinyl-1,3-benzodithiol or 2-dimethoxyphosphinyl-4,5,6,7-tetrahydro-1,3-benzodithiol with aldehyde (2). General procedure for preparation of compounds (3)–(6). Freshly distilled trimethylphosphite (0.03 mL, 0.24 mmol) and sodium iodine (36 mg, 0.24 mmol) were added successively to a stirred solution of 1,3-benzodithiolium tetrafluoroborate (57 mg, 0.24 mmol) or 4,5,6,7-tetrahydro-1,3-benzodithiolium hexafluorophosphate (72 mg, 0.24 mmol) in dry acetonitrile (1 mL), under a argon atmosphere at 20 °C. The reaction took place rapidly and was slightly exothermic. Stirring was continued for 2 h, whereupon the solvent was evaporated under reduced pressure. The residue was dissolved in dry THF (10 mL) under argon and a 2.5 M solution of *n*-butyllithium in hexane (96 µl, 0.24 mmol) was syringed dropwise at −78 °C. After 30 min, a solution of aldehyde **2** (0.33 equiv. or 1 equiv.) in dry THF (10 mL) was added to the solution of phosphonate carbanion. The resulting mixture was stirred for 10 min at −78 °C, and then allowed to warm to 20 °C for 2 h. THF was evaporated under reduced pressure, water (10 mL) added and the residue was extracted with CH_2Cl_2(3 × 10 mL). The combined extracts were dried over $MgSO_4$, filtered, and concentrated under reduced pressure. Purification of products was achieved by column chromatography (Silica gel or neutral Alumina) with eluents as indicated below. Further purification, if necessary, could be achieved by recrystallization.

*1-[2-(1,3-benzodithiol-2-ylidenemethyl)-1,5-dimethylpyrrol-4-yl]-2-(2-formyl-1,5-dimethylpyrrol-4-yl)perfluorocyclopentene (***3***).* The general procedure with **2** (100 mg, 0.24 mmol) gave 74 mg (0.13 mmol, 56%) of the title compound after column chromatography (Neutral Alumina, CH_2Cl_2–cyclohexane 1 : 1) as a brownish solid; mp: 155 °C. ^{1}H NMR ($CDCl_3$): δ 1.72 (s, 3H, CH_3), 1.85 (s, 3H, CH_3), 3.33 (s, 3H, CH_3), 3.80 (s, 3H, CH_3), 6.15 (s, 1H), 6.22 (s, 1H), 7.03–7.18 (m, 7H), 9.44 (s, 1H, CHO). Analysis calculated for $C_{26}H_{20}F_6N_2OS_2$ (554.57): C, 56.31; H, 3.64; N, 5.05%. Found: C, 56.18; H, 3.37; N, 4.80%.

*1,2-bis[2-(1,3-benzodithiol-2-ylidenemethyl)-1,5-dimethylpyrrol-4-yl]perfluorocyclopentene (***4***).* The general procedure with **2** (33 mg, 0.08 mmol) gave 46 mg (0.066 mmol, 83%) of the title compound after column chromatography (Silica gel, CH_2Cl_2–cyclohexane 1 : 1). Recrystallization from methanol–toluene provided analytically pure product **4** as brownish needles; mp: 249 °C. ^{1}H NMR ($CDCl_3$): δ 1.74 (s, 3H, CH_3), 3.33 (s, 3H, CH_3), 6.28 (s, 1H), 6.35 (s, 1H), 7.00–7.19 (m, 8H). Analysis calculated for $C_{33}H_{24}F_6N_2S_4$ (690.81): C, 57.37; H, 3.50; N, 4.06%. Found: C, 57.45; H, 3.62; N, 4.22%.

*1-[2-(4,5,6,7-tetrahydro-1,3-benzodithiol-2-ylidenemethyl)-1,5-dimethylpyrrol-4-yl]-2-(2-formyl-1,5-dimethylpyrrol-4-yl)perfluorocyclopentene (***5***).* The general procedure with 2 (100 mg, 0.24 mmol) gave 84 mg (0.15 mmol, 63%) of the title compound after column chromatography (Silica gel, CH_2Cl_2–cyclohexane 1 : 1) as a solid; mp: 192 °C. ^{1}H NMR ($CDCl_3$): δ 1.35 (s, 3H, CH_3), 1.70 (m, 4H, CH_2), 1.83 (s, 3H, CH_3), 2.20 (m, 4H, CH_2), 3.29 (s, 3H, CH_3), 3.77 (s, 3H, CH_3), 6.03 (s, 1H), 6.15 (s, 1H), 7.00 (s, 1H). MS: m/z = 558 (molecular ion). Analysis calculated for $C_{26}H_{24}F_6N_2OS_2$ (558.60): C, 55.90; H, 4.33; N, 5.01%. Found: C, 55.95; H, 4.36; N, 4.90%.

*1,2-bis[2-(4,5,6,7-tetrahydro-1,3-benzodithiol-2-ylidenemethyl)-1,5-dimethylpyrrol-4-yl]perfluorocyclopentene (***6***).* The general procedure with **2** (33 mg, 0.08 mmol) gave 37 mg (0.05 mmol, 67%) of the title compound after column chromatography (Neutral Alumina, CH_2Cl_2–cyclohexane 1 : 3) as a dark-brown solid; mp: 239 °C. ^{1}H NMR ($CDCl_3$): δ 1.68 (m, 4H, CH_2), 2.09 (s, 3H, CH_3), 2.19 (m, 4H, CH_2), 3.27 (s, 3H, CH_3), 6.17 (s, 1H), 6.20 (s, 1H). Analysis calculated for $C_{33}H_{32}F_6N_2S_4$ (698.88): C, 56.71; H, 4.01; N, 5.01%. Found: C, 56.65; H, 3.88; N, 4.96%.

Knoëvenagel reaction of aldehydes (2), (3) and (5) with malononitrile. General procedure for preparation of compounds (7)–(9). To a stirred solution of aldehyde **2**, **3**, or **5** (0.45 mmol) and malononitrile (66 mg, 1 mmol) in dry benzene (5 mL) at 20 °C was added a catalytic amount of piperidine. The resulting mixture was stirred at 20 °C for 48 h. After cooling, the reaction mixture was poured into water (5 mL). The organic layer was separated and the aqueous layer was extracted with CH_2Cl_2 (3 × 10 mL). The combined organic layers were dried over $MgSO_4$ and the solvent were removed under reduced pressure. Neutral alumina or silica gel column chromatography of the residue afforded the desired products.

*1-[2-(1,3-benzodithiol-2-ylidenemethyl)-1,5-dimethylpyrrol-4-yl]-2-[2-(2,2-dicyanoethen-1-yl)-1,5-dimethylpyrrol-4-yl]perfluorocyclopentene (***7***).* The general procedure with **3** (252 mg, 0.45 mmol) gave 233 mg (0.38 mmol, 84%) of the title compound after two successive recrystallizations, from methanol–cyclohexane and from CH_2Cl_2–cyclohexane as a red-brown solid; mp: 235 °C. ^{1}H NMR ($CDCl_3$): δ 1.92 (s, 6H, CH_3), 3.42 (s, 3H, CH_3), 3.63 (s, 3H, CH_3), 6.26 (s, 1H), 6.32 (s, 1H), 7.17–7.30 (m, 2H), 7.48 (s, 1H), 7.84 (s, 1H). Analysis calculated for $C_{29}H_{20}F_6N_4S_2$ (602.62): C, 57.80; H, 3.35; N, 9.30%. Found: C, 57.85; H, 3.38; N, 9.22%.

*1-[2-(4,5,6,7-tetrahydro-1,3-benzodithiol-2-ylidenemethyl)-1,5-dimethylpyrrol-4-yl]-2-[2-(2,2-dicyanoethen-1-yl)-1,5-dimethylpyrrol-4-yl]perfluorocyclopentene (***8***).* The general procedure with **5** (254 mg, 0.45 mmol) gave 145 mg (0.23 mmol, 52%) of the title compound after column chromatography (Neutral Alumina, CH_2Cl_2–cyclohexane 1 : 1) as a orange solid; mp: 256 °C. ^{1}H NMR ($CDCl_3$): δ 1.72 (m, 4H, CH_2), 1.81 (s, 3H, CH_3), 1.87 (s, 3H, CH_3), 2.18 (m, 4H, CH_2),

3.29 (s, 3H, CH_3), 3.49 (s, 3H, CH_3), 5.98 (s, 1H), 6.14 (s, 1H), 7.37 (s, 1H), 7.74 (s, 1H). Analysis calculated for $C_{29}H_{24}F_6N_4S_2$ (606.65): C, 57.42; H, 3.99; N, 9.24%. Found: C, 57.32; H, 3.90; N, 9.09%.

*1,2-bis[2-(2,2-dicyanoethen-1-yl)-1,5-dimethylpyrrol-4-yl]perfluorocyclopentene (***9***).* The general procedure with **2** (190 mg, 0.45 mmol) gave 178 mg (0.34 mmol, 77%) of the title compound after column chromatography (Silica gel CH_2Cl_2–diethyl ether 5 : 1) and recrystallisation from benzene–cyclohexane as a solid; mp: 256 °C. ^{1}H NMR (acetone d_6): δ 2.02 (s, 3H, CH_3), 3.79 (s, 3H, CH_3), 7.72 (s, 1H, H_3), 8.14 (s, 1H). Analysis calculated for $C_{25}H_{16}F_6N_6$ (514.43): C, 58.37; H, 3.13; N, 16.34 Found: C, 58.32; H, 3.11; N, 16.26.

1,2-bis(2-carboxamide-1,5-dimethylpyrrol-4-yl) perflurocyclopentene (10). To a solution of **1** (2 g, 4.85 mmol) in ethanol (30 mL) was poured 20 mL of aqueous NaOH (2M). The resulting mixture was refluxed and stirred for 15 h. After cooling, the solvents were evaporated under vaccum. Water (20 mL) was added and the mixture extracted with AcOEt (4×20 mL). The collected organic layer were dried over $MgSO_4$, filtered, and concentrated *in vacuo*. The crude product was purified by chromatography on silica gel (AcOEt–EtOH 18 : 1 as eluent) to afford the diamide **10** (1.653 g, 3.7 mmol, 76%) as a dark-yellow solid; mp $>$ 250 °C. ^{1}H NMR (DMSO): δ 1.43 (s, 3H, CH_3), 3.60 (s, 3H, CH_3N), 6.88 (m, 2H, H_3, NH), 7.51 (m, 1H, NH). MS: $m/z = 448$ (molecular ion). Analysis calculated for $C_{19}H_{18}F_6N_4O_2$ (448.36): C, 50.90; H, 4.05; N, 12.50%. Found: C, 51.38; H, 4.34; N, 11.84%.

1,2-bis(2-methoxycarbonyl-1,5-dimethylpyrrol-4-yl)perflurocyclopentene (11). To a solution of diamide 10 (1.26 g, 2.81 mmol) in methanol (40 mL) was added dimethylformamide dimethylacetal (2.26 mL, 16.8 mmol). The reaction was refluxed overnight and a solution of MeONa, prepared from Na (650 mg, 28 mmol) in 10 mL of MeOH, was introduced. The mixture was heated for another 3 h. After cooling, 10 mL of a saturated aqueous NH_4Cl solution was added and the solvents were removed under reduced pressure. The aqueous layer was extracted with CH_2Cl_2 (3×20 mL). The organic phase was dried over $MgSO_4$, filtered and concentrated to give a crude residue, which was purified by chromatography on silica gel (dichloromethane–diethyl ether; 8 : 2 as eluent) leading to **11** in 85% yield (1.14 g, 2.39 mmol) as a white solid; mp: 151 °C. ^{1}H NMR ($CDCl_3$): δ 1.72 (s, 3H, CH_3), 3.83 (s, 3H, CH_3), 3.86 (s, 3H, CH_3), 7.13 (s, H, H_3). MS: $m/z = 478$ (molecular ion). Analysis calculated for $C_{21}H_{20}F_6N_2O_4$ (478.38): C, 52.72; H, 4.21; N, 5.86%. Found: C, 52.66; H, 4.11; N, 5.78%.

1,2-bis(2-carboxy-1,5-dimethylpyrrol-4-yl)perflurocyclopentene (12). A stirred mixture of compound **11** (900 mg, 1.9 mmol), a 2 M aqueous NaOH solution (5.6 mL) and methanol (15 mL) was refluxed for 1 h 30 min. The resulting solution was concentrated to approx. 2/3 of its volume, cooled with an ice bath and cautiously acidified with concentrated HCl. The resulting precipitate was collected, washed with cold water and dried to yield pure diacid **12** (0.821 g, 1.82 mmol, 96%) as a white solid; mp $>$ 250 °C. ^{1}H NMR (DMSO): δ 1.54 (s, 3H, CH_3), 3.67 (s, 3H, CH_3N), 6.85 (s, 1H, H_3), 12.60 (m, 1H, CO_2H). Analysis calculated for $C_{19}H_{16}F_6N_2O_4$ (450.33): C, 50.67; H, 3.58; N, 6.22%. Found: C, 50.52; H, 3.49; N, 6.11%.

1,2-bis(2-iodo-1,5-dimethylpyrrol-4-yl)perfluorocyclopentene (13). To a solution of diacid 12 (100 mg; 0.21 mmol) in methanol (5 mL) and water (2 mL) containing $NaHCO_3$(93 mg, 1.11 mmol), at 60 °C, was treated dropwise with a solution of I_2 (118 mg, 0.47 mmol), KI (206 mg, 1.24 mmol) in methanol (3 mL) and water (1 mL). The mixture was stirred at 60 °C for 5 h. The progress of the reaction was monitored by either TLC or GC. After cooling, the resulting solution was concentrated to near dryness *in vacuo* and water was added (10 mL). The residue was extracted with AcOEt (3×20 mL). The organic phase was vigorously stirred with a saturated aqueous solution of $Na_2S_2O_3 \cdot 5H_2O$ (10 mL), washed with water (10 mL), dried over $MgSO_4$ then filtered and evaporated. The crude product was purified by column chromatography (silica gel, eluted by CH_2Cl_2–cyclohexane 1 : 1) to give **13** (122 mg, 0.2 mmol) in 95% yield as an oil which crystallised slowly upon storage to a yellow solid; mp: 210 °C. ^{1}H NMR ($CDCl_3$): δ 1.67 (s, 3H, CH_3), 3.37 (s, 3H, CH_3N), 6.41 (s, 1H, H_3). MS: $m/z = 614$ (molecular ion). Analysis calculated for $C_{17}H_{14}F_6I_2N_2$ (614.11): C, 33.25; H, 2.30; N, 4.56%; Found: C, 33.28; H, 2.36; N, 4.62%.

1,2-bis(1,5-dimethyl-2-phenylpyrrol-4-yl)perfluorocyclopentene (14). To a mixture of 1,2-bis(2-iodo-1,5-dimethylpyrrol-4-yl)-perfluorocyclopentene **13** (200 mg, 0.32 mmol), DME (4 mL) and a 2 M aqueous solution of Na_2CO_3 (1 mL, 2 mmol) was added phenylboronic acid (119 mg, 9.98 mmol) dissolved in a minimum of ethanol (0.5 mL). The resulting solution was degassed and flushed with an argon flow for 30 minutes. Then, the catalyst $Pd(PPh_3)_4$ (37 mg; 0.032 mmol) was quickly added and the resulting suspension was degassed again for 15 min. The mixture was heated and stirred under positive nitrogen pressure, at 70 °C, for 18 h. After cooling, the solvents were evaporated to near dryness and water (5 mL) was added. The aqueous layer was extracted with ether (2×20 mL). The organic layers were combined and dried over $MgSO_4$ and filtered on Celite. After evaporation of the solvent *in vacuo*, the crude product was purified by chromatography on silica gel (CH_2Cl_2–cyclohexane 3 : 7) to afford 14 (87 mg; 0.17 mmol, 52%) as a white solid; mp: 186 °C. ^{1}H NMR ($CDCl_3$): δ 1.71 (s, 3H, CH_3), 3.39 (s, 3H, CH_3N), 6.29 (s, 1H, H_3), 7.24 (m, 5H, phenyl). MS: $m/z = 514$ (molecular ion). Analysis calculated for $C_{29}H_{24}F_6N_2$ (514.50): C, 67.70; H, 4.70; N, 5.44%. Found: C, 67.72; H, 4.81; N, 5.46%.

1,2-bis(1,5-dimethyl(2-(2-thienyl)pyrrol-4-yl)perfluorocyclopentene (15). To a mixture of 1,2-bis(2-iodo-1,5-dimethylpyrrol-4-yl)perfluorocyclopentene **13** (150 mg; 0.24 mmol), DME (10 mL) and a 2 M aqueous solution of Na_2CO_3 (7.5 mL, 15 mmol) was added 2-thienylboronic acid (94 mg; 0.732 mmol) dissolved in a minimum of ethanol (1 mL). The resulting solution was degassed and flushed with an argon flow for 30 min. Then, the catalyst $Pd(PPh_3)_4$ (56 mg; 0.049 mmol) was quickly added and the resulting suspension was degassed again for 15 min. The mixture was heated and stirred under positive nitrogen pressure, at 80 °C for 32 h. After cooling, the solvents were evaporated to near dryness and water (5 mL) was added. The aqueous layer was extracted with ether (2×20 mL). The combined organic layers were dried over $MgSO_4$ and filtered on Celite. After evaporation of the solvent *in vacuo*, the crude product was purified by chromatography on silica gel (diethyl ether–cyclohexane 3 : 7) to afford 15 (110 mg; 0.21 mmol) in 86% yield as a brown solid; mp: 164 °C. ^{1}H NMR ($CDCl_3$): δ 2.21 (s, 3H, CH_3); 3.56 (s, 3H, CH_3); 6.48 (s, 1H, H_3), 7.05 (dd, 1H, $J =$ 1.2, 3.6 Hz); 7.11 (dd, 1H, $J =$ 3.4, 5.1 Hz); 7.34 (dd, 1H, $J = 1.2$, 5.1 Hz, 1H). MS: $m/z = 526$ (molecular ion). Analysis calculated for $C_{25}H_{20}F_6N_2S_2$ (526.56): C, 57.02; H, 3.83; N, 5.32%. Found: C, 56.96; H, 3.79; N, 5.30%.

1,2-bis(2-(3-hydroxy-3-methylbut-1-ynyl)-1,5-dimethylpyrrol-4-yl)perfluorocyclopentene (16). A round-bottomed flask, equipped with a magnetic stirrer was charged with $[PdCl_2(PPh_3)_2]$ (365 mg; 0.52 mmol) and CuI (49.6 mg; 0.26 mmol), 13 (800 mg; 1.3 mmol), and 2-methylbut-3-yn-2-ol (656 mg; 7.8 mmol), in Et_2NH (8 mL), purged with argon and stirred at 20 °C for 15 h. Et_2NH was removed *in vacuo*, the residue diluted with benzene (10 mL). The mixture was filtered

through a Celite pad thoroughly rinsed with benzene (2 × 7 mL). The combined filtrate were evaporated, and the residue was purified by chromatography on silica gel (cyclohexane–acetone 100 : 0 to 30 : 70) to give 16 (645 mg, 1.22 mmol) in 94% yield as a brown solid; mp: 165 °C. ^{1}H NMR ($CDCl_3$): δ 1.44 (s, 6H), 1.49 (s, 3H), 3.29 (s, 3H), 6.33 (s, 1H). Analysis calculated for $C_{27}H_{28}F_6N_2O_2$ (526.51): C, 61.59; H, 5.36; N, 5.32%. Found: C, 61.52; H, 5.31; N, 5.25%.

1,2-bis(2-(2-thienylethynyl)-1,5-dimethylpyrrol-4-yl)perfluorocyclopentene (17). To a deaerated solution of **16** (160 mg; 0.3 mmol) and 2-iodothiophene (153 mg; 0.73 mmol) in benzene (8 mL), CuI (5 mg; 0.272 mmol), $Pd(PPh_3)_4$ (31 mg; 0.72 mmol), and $PhCH_2NEt_3^+Cl^-$ (4 mg; 0.193 mmol) were rapidly added. Deaerated aq. 5.5 N NaOH (8 mL) was then added, and the mixture was stirred for 20 h at reflux. The biphasic mixture was allowed to cool and filtered through Celite and the latter washed carefully with benzene (2 × 10 mL) and the aqueous layer of the filtrate extracted with benzene (2 × 10 mL). The combined organic layers were washed with water (2 × 10 mL) and brine (2 × 10 mL), dried over $MgSO_4$, filtered and evaporated. The residue was purified by chromatography on silica gel (gradient elution, cyclohexane–diethyl ether 100 : 0 → 60 : 40) to afford 17 (158 mg, 0.28 mmol) in 92% yield as a yellow solid; mp: 213 °C. ^{1}H NMR ($CDCl_3$): δ 1.66 (s, 3H, CH_3), 3.48 (s, 3H, CH_3), 6.57 (s, 1H), 6.94 (dd, J = 3.7, 5.1 Hz, 1H), 7.15–7.25 (m, 2H). MS: m/z = 574 (molecular ion). Analysis calculated for $C_{29}H_{20}F_6N_2S_2$ (574.60): C, 60.62; H, 3.51; N, 4.88%. Found: C, 60.58; H, 3.41; N, 4.76%.

1,2-bis(2-trimethylsilylethynyl-1,5-dimethylpyrrol-4-yl)perfluorocyclopentene (18). A mixture of 16 (179 mg; 0.34 mmol), ethynyltrimethylsilane (133 mg; 1.35 mmol), $[PdCl_2(PPh_3)_2]$ (100 mg; 0.014 mmol), CuI (13 mg; 0.07 mmol) and anhydrous Et_3N (10 mL) was stirred at 70 °C for 17 h. After cooling, the solvent was evaporated and the residue was diluted with benzene (10 mL). The resulting solution was washed with water (3 × 5 mL), the organic layer was dried over $MgSO_4$, filtered through Celite and the filtrate was evaporated. The residue was purified by chromatography on silica gel (gradient elution, cyclohexane–diethyl ether 100 : 0 → 80 : 20), to afford **18** (189 mg, 0.34 mmol) in 98% yield as a brown solid; mp: 165–166 °C. ^{1}H NMR ($CDCl_3$): δ 0.287 (s, 9H, $SiMe_3$); 2.20 (s, 3H, CH_3); 3.52 (s, 3H, NCH_3); 6.63 (s, 1H, H_3). MS: m/z = 554 (molecular ion). Analysis calculated for $C_{27}H_{32}F_6N_2Si_2$ (554.72): C, 58.46; H, 5.81; N, 5.05%. Found: C, 58.42; H, 5.83; N, 4.98%.

1,2-bis(2-ethynyl-1,5-dimethylpyrrol-4-yl)perfluorocyclopentene (19). To a solution of **18** (150 mg; 0.27 mmol) in CH_2Cl_2 (8 mL) was added dropwise at 0 °C a solution of KOH (45 mg, 0.8 mmol) in MeOH (5 mL). The mixture was stirred for 14 h at 20 °C. The progress of the reaction was monitored by either TLC or GC (cyclohexane–acetone 1 : 1). After evaporation, the residue was diluted with diethyl ether (15 mL) and the resulting solution was washed with water (3 × 15 mL), dried over $MgSO_4$, filtered and evaporated. After purification by column chromatography on silica gel (cyclohexane–diethyl ether 8 : 2), the compound **19** was isolated in 90% yield (100 mg; 0.24 mmol) as a brown solid; mp: 128 °C. ^{1}H NMR ($CDCl_3$): δ 1.618 (s, 3H, CH_3); 3.33 (s, 1H); 3.44 (s, 3H, NCH_3); 6.52 (s, 1H, H_3). MS: m/z = 410 (molecular ion) Analysis calculated for $C_{21}H_{16}F_6N_2$ (410.36): C, 61.46; H, 3.93; N, 6.83%. Found: C, 61.42; H, 3.87; N, 6.79%.

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