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Synthesis and photochromism of some mono and bis (thienyl) substituted oxathiine 2,2-dioxides†

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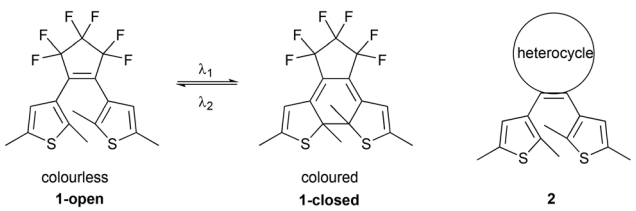
1,2-Oxathiine 2,2-dioxides have been obtained from their respective 3,4-dihydro-4-dimethylamino precursors, for the first time, by a mild Cope elimination of the 4-dimethylamino function. The application of the 1,2-oxathiine 2,2-dioxide scaffold in materials chemistry is exemplified by the efficient P-type photochromism of the 5,6-bis(2,5-dimethyl-3-thienyl) substituted oxathiine 2,2-dioxides.

P-type photochromic dithienylethenes such as **1-open**, which readily undergoes reversible conversion to the coloured isomer **1-closed**, (Scheme 1) are fundamental switching units which have been used to modulate a variety of physical and optical properties.[1] Structural variation of the essential 1,2-bis(2,5-dimethylthiophen-3-yl)ethene core has been frequently explored by modification of the 2,5-dimethylthiophene moiety[1,2] and to a somewhat lesser extent by variation of the perfluorocycle, particularly replacement of the latter with a 5-membered heterocyclic unit to afford **2**, wherein the heterocycle has been selected from imidazole,[3,4] imidazolium,[5] pyrrole,[6] thienophosphole,[7] phosphindolothiophene,[8] thiophene,[9–11] thiopyranothiophene,[12] silole,[13,14] 1,3-dithiole[15] and thiazole[16] and less commonly with a six-membered unit leading to **2** where the heterocyclic unit includes quinoxaline,[17] triazoloquinoline,[18] pyridazine,[19] thiazine,[20] 1,2-oxazine[21] and 1,2,4-triazine.[22]

We have previously studied the synthesis and performance of various T-type photochromic systems, *e.g.* naphthopyrans[23–25] and naphthoxazines,[26,27] and we have recently explored negatively photochromic systems.[28] In this study we describe the preliminary examples of an efficient synthetic route to the relatively little studied 1,2-oxathiine 2,2-dioxide unit and in doing so define a route to new photochromic dithienylethenes with a central 1,2-oxathiine 2,2-dioxide core. This work constitutes part of our ongoing programme of heterocyclic synthesis concerning strategies to 1,2-oxathiine 2,2-dioxides in which we are exploring the versatility of sulfene additions to enaminoketones to afford relatively inaccessible substitution patterns on the 4-dimethylamino-3,4-dihydro-1,2-oxathiine 2,2-dioxide core and subsequent mechanistic investigations concerning the elimination of the 4-dimethylamino function to access diversely substituted unsaturated 1,2-oxathiine 2,2-dioxides.[29]

The addition of sulfenes to enaminoketones to afford 4-amino-3,4-dihydro-1,2-oxathiine 2,2-dioxides has been explored by Schenone *et al.*[30] Interestingly, the formation of the unsaturated 1,2-oxathiine 2,2-dioxides was a relatively scarcely observed feature in these initial studies.[31] Indeed when chlorosulfene was added to an enaminoketone a subsequent facile base-promoted elimination of HCl was observed and the unsaturated 4-amino-1,2-oxathiine 2,2-dioxide resulted[32] and attempts to effect dehydrogenation of 4-amino-3,4-dihydro-1,2-oxathiine 2,2-dioxides using excess DDQ met with variable results.[33] We elected to utilise the foregoing sulfene addition chemistry[30,34] and explore the subsequent elimination step required to obtain the unsaturated 1,2-oxathiine 2,2-dioxides. Fundamental to the present study was access to a series of methylene ketones and whilst deoxybenzoin **11** is widely commercially available the isomeric thienylketones **9** and **10** and the 1,2-bis(2,5-dimethylthiophen-3-yl)ethan-1-one **6** required preparation (Scheme 2). Examination of the literature revealed that the 2,5-dimethylthienyl-3-acetic acid **4** has been prepared from 2,5-dimethylthiophene in three steps, acylation,



Scheme 1 Representative photochromic response of a dithienylethene system.

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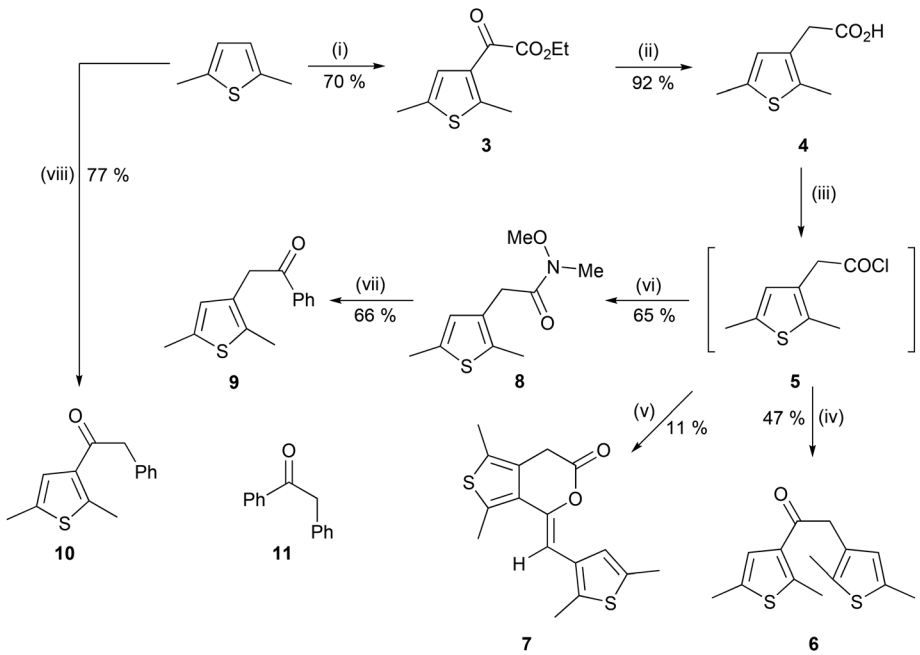


Scheme 2 Synthesis of thienyl ketones **6**, **9** and **10**. Reagents and conditions: (i) Ethyl oxalyl chloride, $AlCl_3$, anyhd., $MeNO_2$, 5 °C–RT; (ii) $NH_2NH_2{\cdot}H_2O$, $HOCH_2CH_2OH$, then KOH, 70 °C – reflux; (iii) $SOCl_2$, cat. DMF, CH_2Cl_2; (iv) 2,5-dimethylthiophene, $AlCl_3$, anyhd., $MeNO_2$, 5 °C–RT; (v) PhH, $AlCl_3$, anyhd., $MeNO_2$, 5 °C–RT; (vi) MeNHOMe·HCl, pyridine, CH_2Cl_2, 0–5 °C–RT; (vii) PhLi in Bu_2O, anhyd., THF, N_2, –78 °C–RT; (viii) $PhCH_2COCl$, $AlCl_3$, anyhd., CH_2Cl_2, $MeNO_2$, 5 °C–RT.

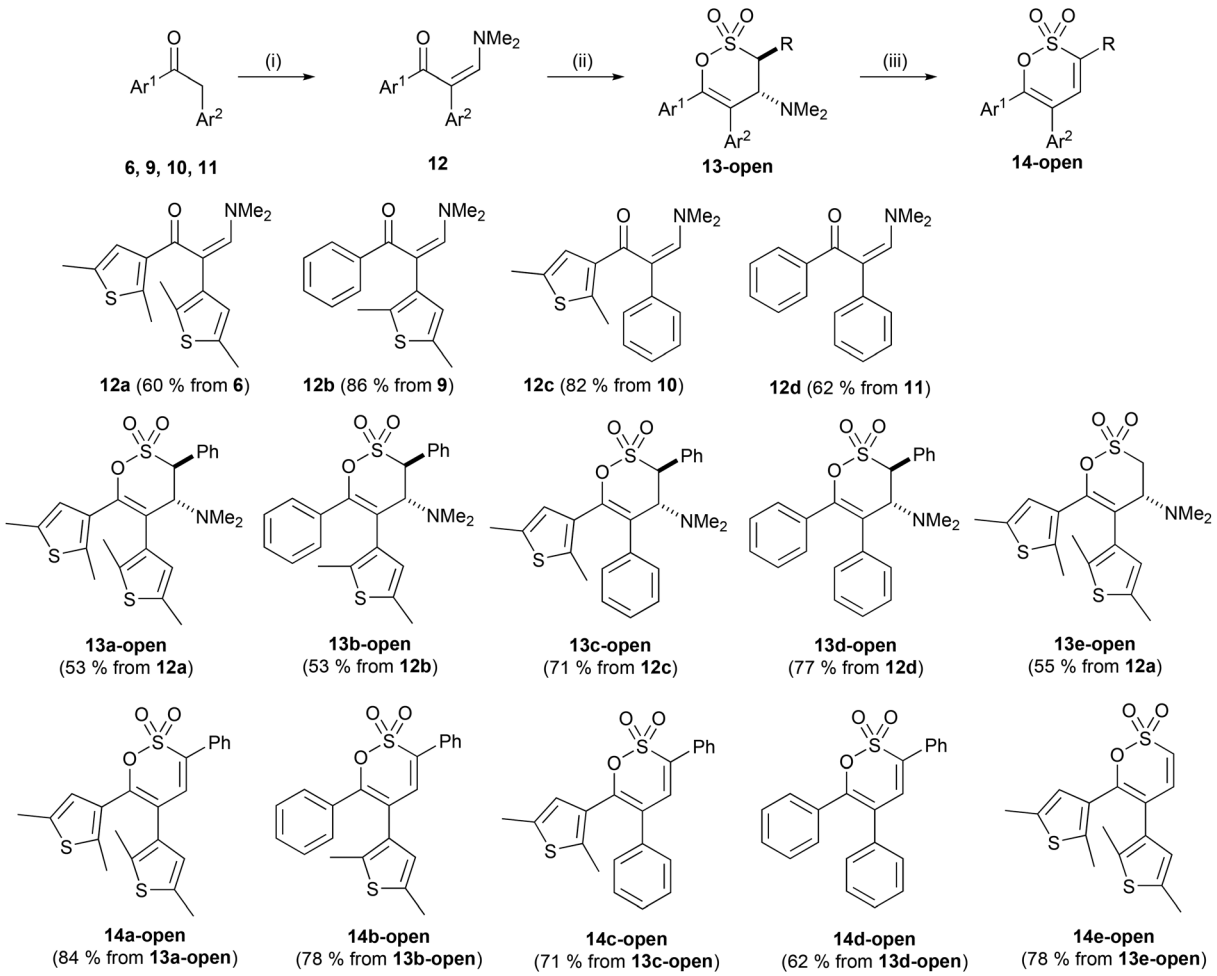
Willgerodt–Kindler reaction and hydrolysis, in moderate overall yield.[35] Given the unappealing nature of this sequence we elected to examine an alternative protocol. Friedel–Crafts acylation of 2,5-dimethylthiophene with ethyl oxalyl chloride gave the glyoxalate **3** which underwent a smooth Wolff–Kishner reduction with concomitant hydrolysis to afford **4** in 64% yield (two-steps). The acid chloride **5** was prepared and used directly in a Friedel–Crafts acylation with 2,5-dimethylthiophene to afford **6** (47%) which displayed a characteristic singlet in its ^{1}H NMR spectrum at δ 3.92 assigned to the methylene unit. Interestingly, applying this Friedel–Crafts strategy to benzene failed to afford **9** and instead **5** underwent a 'homo Friedel–Crafts' reaction followed by cyclisation to afford the novel thieno[3,4-*c*]pyranone **7** (δ_{CH} 7.41; $\delta_{methylene}$ 3.67; $\delta_{C=O}$ 166.44); the geometry of which was established as the *Z*-isomer by a NOESY experiment. Evidently the thiophene moiety of **5** is more electron rich than benzene and is thus the favoured substrate in the foregoing acylation reaction. Undeterred by this setback, the Weinreb amide **8** (δ_{OMe} 3.60; δ_{NMe} 3.18; $\delta_{methylene}$ 3.59) was obtained (65%) from **5** by standard methodology.[36] The addition of PhLi to **8** proceeded without complication to afford target ketone **9** ($\delta_{methylene}$ 4.12) in 66% yield (Scheme 2).

Ketone **10** was readily prepared by the Friedel–Crafts reaction of phenylacetyl chloride with 2,5-dimethylthiophene in 77% yield. Here the characteristic methylene singlet appeared at δ 4.11 in the ^{1}H NMR spectrum.

Ketones **6**, **9–11** were transformed into their respective enaminoketones **12a–d** (60–86% yield) upon reaction with *N*,*N*-dimethylformamide dimethylacetal (DMFDMA) (Scheme 3). Phenylsulfene, generated *in situ* by the action of Et_3N on phenylmethanesulfonyl chloride, added cleanly to the foregoing enaminoketones to afford the 3,4-dihydro-1,2-oxathiine 2,2-dioxides **13a-open–d-open** (53–77%) after either chromatography or recrystallization. Oxathiine 2,2-dioxide **13e-open** was obtained in a similar manner in 55% yield from the addition of sulfene to **12a**. The ^{1}H NMR spectrum of **13e-open** revealed an AA′B spin pattern for the C-3 and C-4 hydrogens with $J_{3,4(trans)}$ = 9.1 Hz, $J_{3',4(cis)}$ = 7.8 Hz and $^2J_{3,3'}$ = 13.8 Hz.

Attempts to effect the acid elimination of dimethylamine from **13d-open** using increasing amounts of 4-TsOH (0.05–5 eq.) at either RT or reflux in PhMe were unsuccessful and at elevated temperature some yellowing of the reaction mixture was observed together the formation of minor amounts of polar 'degradation' material as indicated by TLC. The magnitude of the coupling constants between 3-H and 4-H ($^3J_{3,4}$ = 7.8–8.1 Hz) of the 3-phenyl substituted series **13a-open–13d-open** suggest that these protons occupy an *anti-peri*-planar arrangement.

A crystal of **13a-open** was obtained from Et_2O and hexane (stored at −20 °C for 24 h) and an X-ray crystal structure (Fig. 1) confirmed the arrangement of 3-H and 4-H which have a torsion angle of *ca*. 39.5° with the torsion angle between the 3-Ph and 4-NMe_2 moieties as 78.9°. The SO_2 unit of the oxathiine 2,2-dioxide ring protruded out of the main oxathiine ring plane (O1–C3–C4–C5–C6) with C3–S2–O1 angle of *ca*. 110°. The thiophene rings adopt an *anti*-parallel conformation which favours the reversible photocyclistion process.[1,2,37]



Scheme 3 Synthesis of thienyl substituted 1,2-oxathiine 2,2-dioxides. Reagents and conditions: (i) DMFDMA, reflux; (ii) either phenylmethanesulfonyl chloride (for **13a–d**) or methanesulfonyl chloride (for **13e**), Et_3N, anhyd. THF, 0 °C–RT; (iii) *m*-CPBA, CH_2Cl_2, 0 °C–RT.

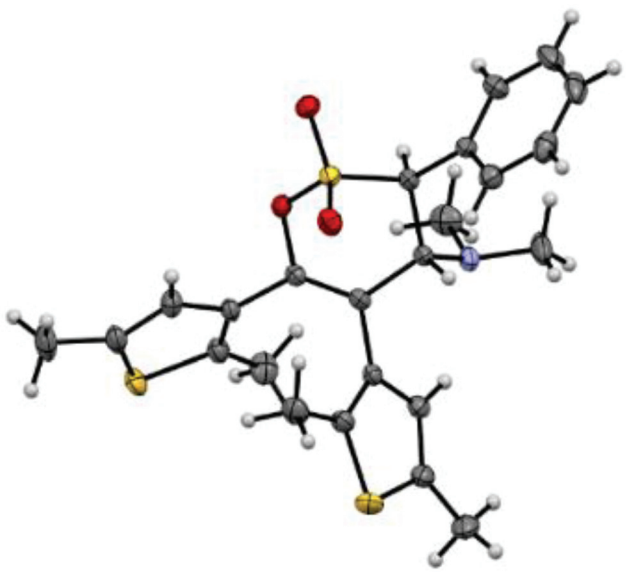


Fig. 1 Crystal structure of **13a-open** (thermal ellipsoids shown at 50% probability level and disordered Et_2O solvent molecule omitted for clarity).[38]

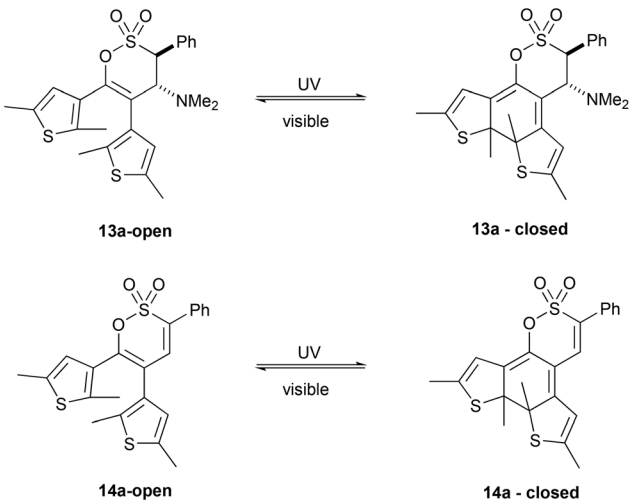
Given the *syn*-relationship between 3-H and the 4-NMe_2 moiety a Cope elimination protocol was adopted to affect the *syn*-elimination of the dimethylamine unit.[39] Pleasingly, treating a DCM solution of **13d-open** with an excess of *m*-CPBA (0–5 °C → RT, 4 h) afforded **14d-open** ($\delta_{4\text{-H}}$ 7.01) as pale-yellow crystals in 62% yield. Repeating this procedure enabled the isolation of **14a-open** (84%, $\delta_{4\text{-H}}$ 6.89), **14b-open** (78%, $\delta_{4\text{-H}}$ 6.89), **14c-open** (71%, $\delta_{4\text{-H}}$ 7.04) and **14e-open** (78%, $\delta_{3\text{-H}}$ 6.61, $\delta_{4\text{-H}}$ 6.90 ($J_{3,4}$ = 10.2 Hz)) without the detection of any S oxidised products (Scheme 3). This facile elimination protocol provides an efficient strategy to form unsaturated 1,2-oxathiine 2,2-dioxides from the 4-dialkylamino substituted 3,4-dihydro-1,2-oxathiine 2,2-dioxides which are easily obtained from sulfene additions to enaminoketones.

With the series of oxathiine 2,2-dioxides **13-open** and **14-open** to hand their photochromic response was examined. Irradiating hexane solutions of **13a-open**, **b-open**, **c-open** and **e-open** revealed very weak to moderate yellow – orange colour development (Table 1) due to photoinduced ring closure (Scheme 4) with λ_{max} in the range 413 to 441 nm after prolonged irradiation to a steady state (*ca.* 145 min, λ_{irr} =

Table 1 Photochromic response of series **13-open** and series **14-open**

	λ_{max}[a] (nm) Hexane	Absorbance at λ_{max}[b]		ε_m at PSS[c] (mol^{-1} dm^3 cm^{-1})	% closed form[d]
		A_0	A_{PSS}		
13a-open/13a-closed	414	0.01	0.55	1300	2
14a-open/14a-closed	503	0.03	0.82	1708	38
13b-open/13b-closed	413	0.01	0.23	489	5
14b-open/14b-closed	481	0.01	0.07	125	0.5
13c-open/13c-closed	474	0	0.03	61	2
14c-open/14c-closed	513	0	0.01	25	2
13e-open/13e-closed	441	0.01	0.38	1524	8
14e-open/14e-closed	494	0.01	0.94	1541	9

[a] Wavelength of maximum absorption of the closed species. [b] Absorbance A_0 before UV irradiation and absorbance A_{PSS} at photostationary state (PSS) for hexane solution of *ca.* 0.5 mmol dm^{-3}. [c] Molar extinction coefficient of closed form at photostationary state as calculated using the Beer–Lambert Law. [d] % closed form determined by comparison of the relative integrals of the signals for the thiophene ring methyl group protons in the original open forms and the closed forms at PSS.



Scheme 4 Structures of **13a-open/14a-open** before and after irradiation.

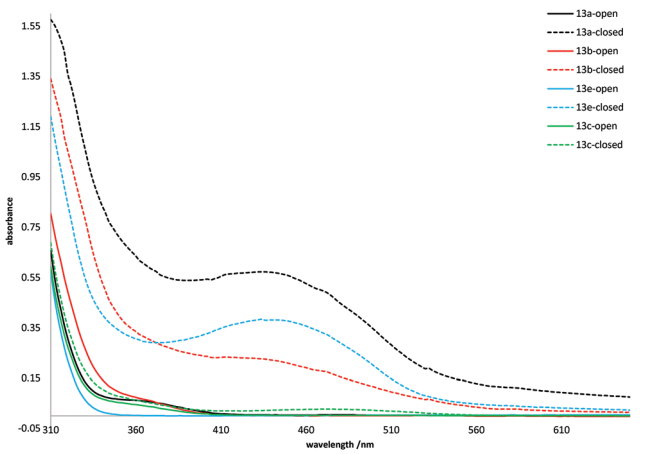


Fig. 2 Absorption spectra (in hexane) of 3,4-dihydro-1,2-oxathiine 2,2-dioxides **13a-open, b-open, c-open, e-open** before irradiation and at photostationary state.

260–380 nm, 150 W) (Fig. 2). ^{1}H NMR spectra for **13a-open** before and after irradiation are provided in the ESI.† The remaining 5,6-diphenyl analogue **13d-open** showed no photochromic response.

The photochromic behaviour of the unsaturated series **14a-open–e-open** was next examined in hexane solution. Irradiation of a hexane solution of **14a-open** resulted in the generation of an intense red hue (λ_{max} = 503 nm, PSS 45 min) (Fig. 3 and insert 1, Table 1) which is assigned to the ring-closed isomer **14a-closed** (Scheme 4). Visible light bleaching (455–650 nm) of the foregoing red solution of **14a-closed** was efficiently accomplished after 25 min. The colouration and bleaching of **14a-open** (PhMe solution) was repeated 10 times to illustrate the reversibility of the system (insert 2 on Fig. 3).

Repeating the irradiation experiment of **14a-open** in $CDCl_3$ and recording the ^{1}H NMR spectra over time revealed the presence of new signals attributed to **14a-closed** at δ 2.05 (Th-Me), 2.11 (Th-Me), 2.12 (Th-Me), 2.22 (Th-Me), 5.96 (Th-H) 6.07 (Th-H) and 6.83 (4-H) (Fig. 4). Comparison of the integrals for

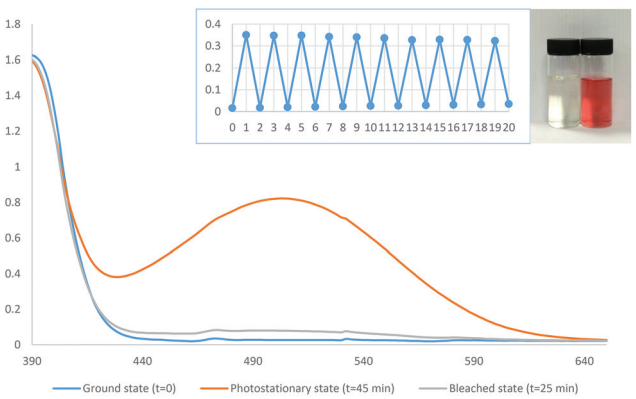


Fig. 3 Absorption spectra of **14a-open** (initial, after UV activation and after visible light bleaching); inset shows recyclability with UV activation and visible light bleaching cycles.

4-H in **14a-open** (δ = 6.89) and **14a-closed** (δ = 6.83) of the $CDCl_3$ solution revealed a ratio of *ca.* 5 : 3 (**14a-open/14a-closed**) at the photostationary state (Fig. 4, Table 1).

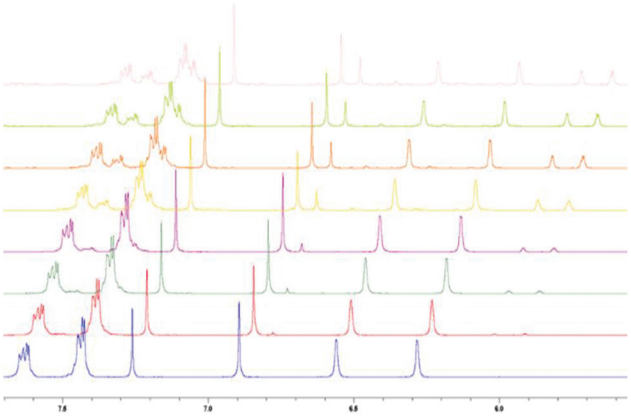


Fig. 4 ^{1}H NMR spectra (δ 5.5–7.7, $CDCl_3$) showing evolution of signals for photochemical ring-closure of **14a-open**.

Irradiation of **14e-open**, similarly substituted with 2,5-dimethylthiophen-3-yl units, offered inferior performance to **14a-open** with λ_{max} at 494 nm (50 min irradiation, ratio **14e-open : 14e-closed** *ca.* 10 : 1 based on the relative integrals of the doublets for 3-H at δ 6.61 (open) and δ 6.38 (closed) (see ESI† for ^{1}H NMR spectra for **14e-open** before and after irradiation). In the ^{1}H NMR spectrum of **14e-closed** signals were observed at δ 2.18, 2.31, 2.39 and 2.64 for the methyl groups, at *ca.* δ 5.95 for the thiophene ring protons and at δ 6.82 (d, J = 10.3 Hz) for 4-H. Unfortunately, **14b-open** and **14c-open** only showed an exceptionally weak red hue upon irradiation to generate their ring-closed forms (Fig. 5) and the diphenyl analogue **14d** showed no photochromism, emphasising the requirement for at least one 2,5-dimethylthiophene unit on the central ethene bond.

Interestingly, the introduction of the C-3–C-4 double bond induced a bathochromic shift in λ_{max} of **14a-closed** (503 nm) and **14e-closed** (494 nm) relative to their dihydro precursors [**13a-closed** (414 nm), **13e-closed** (441 nm)] presumably as a result of the extended lateral conjugation. It should be noted that the conjugation with the C-3 phenyl group (**14a-open**)

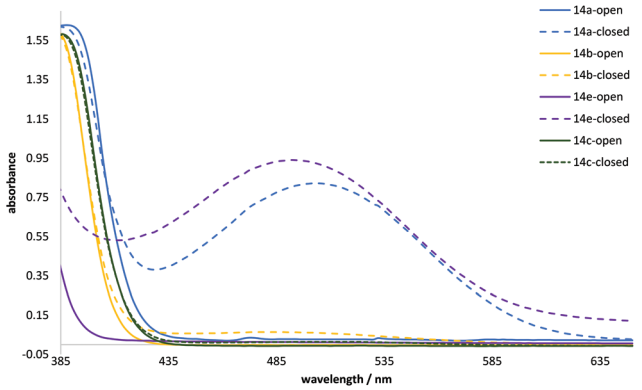


Fig. 5 Absorption spectra (in hexane) of oxathiine 2,2-dioxides **14a-open, b-open, c-open, e-open** before irradiation and at photostationary state.

Fig. 6 Photograph of **14a-open** powdered sample on white paper background (LHS pre-irradiated, RHS post-irradiation).

resulted in the largest (89 nm) shift. The photochromic response of the series **13-open** and **14-open** is summarised in Table 1.

The solid-state photochromism of **14a-open** was also briefly examined; with a powdered sample irradiated for 30 s with a TLC inspection lamp (Spectroline E Series 365 nm, 8 Watt). The change in appearance of the sample is clearly visible from the photograph presented in Fig. 6 with the unirradiated sample appearing pale yellow and a post-irradiated sample developing a red/brown hue.

In summary, 1,2-oxathiine 2,2-dioxides with combinations of aryl and heteroaryl substituents have been efficiently obtained for the first time by a Cope elimination protocol from their respective 4-dimethylamino-3,4-dihydro precursors which were derived from sulfene additions to enaminoketones. The 3,4-dihydro-1,2-oxathiine 2,2-dioxide series **13** exhibited very weak photo-colouration (low percentage ring closed form and hence weak molar extinction coefficients), perhaps due to limited activation as a consequence of a relatively low degree of unsaturation resulting in a low absorption in the activating UV region. Of the series **13** the 5,6-bis(2,5-dimethylthien-3-yl) analogues **13a-open** and **13e-open** exhibited the best photochromism with UV irradiation generating their closed ring isomers which exhibited a weak yellow – orange hue. The series of unsaturated oxathiines **14** typically exhibited better photochromism then the dihydro precursors **13**. The oxathiine 2,2-dioxides **14a-open** and **14e-open** offered the best photochromism with λ_{max} of their closed ring forms bathochromically shifted relative to their dihydro-precursors, leading to moderately intense red-brown hues as a consequence of the extended lateral conjugation. The presence of a phenyl substituent on the oxathiine ring lead to a further small bathochromic shift in λ_{max} *viz.* **14a-open** (503 nm) and **14e-open** (494 nm). The photochromic response of **14a-open** and **14e-open** of this preliminary series of novel dithienylethenes containing a 1,2-oxathiine 2,2-dioxide core offered comparable performance to other heterocyclic bridged dithienylethenes.[17–22] However, it is clear from this study that for good photochromic performance the presence of two substituted thiophene units at the termini of the central ethene bond combined with further unsaturation in the central oxathiine moiety is essential.[1,2] Our exploration of the appli-

cation of the oxathiine moiety as the central core in photochromic systems continues and is presently focussed on both further extending the lateral conjugation using substituted (hetero)aromatic systems and enhancing the photocolouration process.

Conflicts of interest

There are no conflicts to declare.

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38 Crystal for **13a**. Crystal data for $C_{26}H_{32}NO_{3.50}S_3$, M = 510.70, triclinic, a = 9.869 (5), b = 11.897 (5), c = 13.181 (5) Å, α = 113.322 (17), β = 109.14 (2), γ = 90.79 (2)°, V = 1324.1 (10) Å^3, T = 150 K, space group $P\bar{1}$, Z = 2, 19 176 reflections measured, 8011 independent reflections (R_{int} = 0.0392). The final R_1 values were 0.0519 ($I > 2\sigma(I)$). The final w$R(F^2)$ values were 0.1309 ($I > 2\sigma(I)$). The final R_1 values were 0.0778 (all data). The final w$R(F^2)$ = 0.1481 (all data). The goodness of fit on F^2 was 1.027. Peak and hole = 0.823/−1.120. CCDC 1905437† contains the supplementary crystallographic data for this paper. The structure contained a disordered diethyl ether solvent molecule which was modelled in two positions using the *PART* instruction in the refinement. The anisotropic displacement parameters were restrained using the *DELU* and *SIMU* instructions.

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