Organic LETTERS

Letter

pubs.acs.org/OrgLett

Fluorescent Photochromic Diarylethene That Turns on with Visible Light

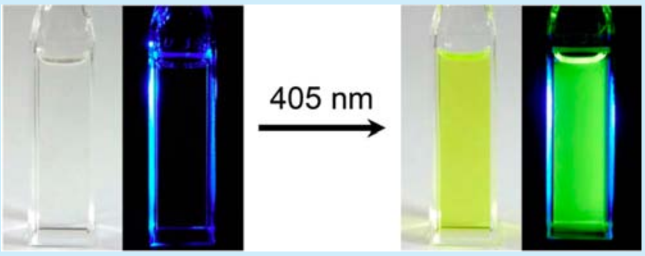
Takaki Sumi,[†] Tomohiro Kaburagi,[†] Masakazu Morimoto,[†] Kanako Une,[‡] Hikaru Sotome,[‡] Syoji Ito,[‡] Hiroshi Miyasaka,[‡] and Masahiro Irie*,[†]

[†]Department of Chemistry and Research Center for Smart Molecules, Rikkyo University, Nishi-Ikebukuro 3-34-1, Toshima-ku, Tokyo 171-8501, Japan

[‡]Division of Frontier Materials Science and Center for Advanced Interdisciplinary Research, Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka 560-8531, Japan

S *Supporting Information*

ABSTRACT: A new fluorescent photochromic diarylethene that can be activated by irradiation with 405 nm light was synthesized. The turn-on mode switching of fluorescence with visible light is favorable for application to biological systems. The fluorescence quantum yield of the photogenerated closed-ring isomer was as high as 0.8 in less or medium polar solvents, and even in polar acetonitrile the yield was higher than 0.6.



Fluorescence is the most convenient tool to detect small amounts of molecules.[1] Even single molecules can be detected using fluorescence.[2] Therefore, fluorescence is widely used for microanalysis[3] and bioimaging.[4] Although highly fluorescent chromophores have already been applied in various fields, their application is expected to be further extended when additional photoswitching property is provided to the chromophores.[5] The photoswitchable fluorescent chromophores offer the opportunity to monitor dynamic processes in real time,[6] to store optical information in memory media,[2b,7] and also to increase the resolution of bioimaging such as PALM[8] (photoactivatable localization microscopy) and RESOLFT[9] (reversible saturable optical fluorescence transition).

Reversible photoisomerization of photochromic molecules between two isomers induces an electronic structure change, and the change in the electronic structure influences the fluorescent property. Therefore, in principle, photochromic molecules are inherently photoswitchable fluorescent chromophores.[10] However, most of photochromic molecules are non- or weakly fluorescent. A convenient and frequently used approach to provide the fluorescent property is to combine a fluorescent unit to the photochromic molecule.[2,11] The photochromic composite is initially fluorescent, while the fluorescence is switched off by energy-transfer or electron-transfer processes upon irradiation with UV light. The turn-off mode switching of fluorescence can be applied to optical memory media, but hardly applied to PALM, because the imaging method requires an initial dark background.

In previous papers,[12] we reported new turn-on mode highly fluorescent diarylethene derivatives, 1,2-bis(2-alkyl-6-phenyl-1-benzothiophene-1,1-dioxide-3-yl)perfluorocyclopentenes. They are initially nonluminous and dark under irradiation with visible ($\lambda > 450$ nm) light, while they are activated to emit strong fluorescence (fluorescence quantum yield > 0.8) upon UV irradiation. Although they fulfill the PALM switching requirement to generate the fluorescent state in the dark background, they can not be activated by visible ($\lambda > 400$ nm) light. Here, we report on a new photoswitchable fluorescent diarylethene derivative that can be activated upon irradiation with visible light. The visible light responsive property is favorable for the application to biological systems.[13]

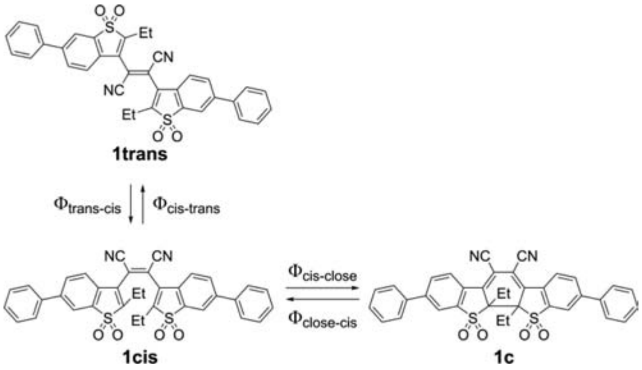
Diarylethenes are composed of heterocyclic aryl groups, such as thiophenes, thiazoles, or benzothiophenes, and an ethene bridge, such as perfluorocyclopentene, cyclopentene, dicyanoethene, or maleic anhydride.[11] The absorption spectra of the derivatives are dependent not only on the aryl groups but also on the ethene bridge. The absorption tails of 1,2-bis(2-methyl-1-benzothiophen-3-yl)ethenes having cyclopentene,[14] perfluorocyclopentene,[15] dicyanoethene,[16] and maleic anhydride[17] as the bridge unit are observed at 310, 370, 460, and 500 nm, respectively. We employed dicyanoethene as the bridge unit to shift the absorption tail of sulfur-oxidized 1,2-bis(2-ethyl-6-phenyl-1-benzothiophen-3-yl)ethene to a visible wavelength region.

Compound **1** (1,2-dicyano-1,2-bis(2-ethyl-6-phenyl-1-benzothiophene-1,1-dioxide-3-yl)ethane, Scheme1) was prepared from 1,2-dicyano-1,2-bis(2-ethyl-1-benzothiophen-3-yl)ethene.[16] The details of the synthesis are shown in the Supporting Information. The final product showed a molecular weight of 614 by mass spectrometry, which indicates that **1** was synthesized, though the configuration was not known. Figure 1

Received: August 15, 2015
Published: September 16, 2015

DOI: 10.1021/acs.orglett.5b02361
Org. Lett. 2015, 17, 4802−4805

Scheme 1. Photoisomerization of Diarylethene 1



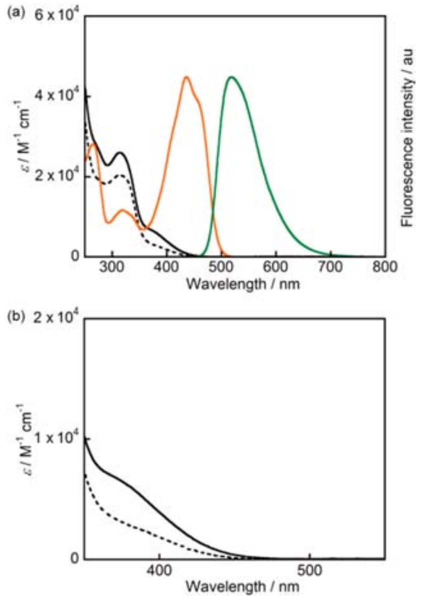


Figure 1. (a) Absorption spectra of **1cis** (black solid line), **1trans** (black dashed line), and **1c** (orange line) and fluorescence spectrum of **1c** (green line, uncorrected) in 1,4-dioxane. (b) Absorption tails of **1cis** (black solid line) and **1trans** (black dashed line). These three isomers were isolated by HPLC, and the spectra correspond to the isolated isomers.

shows the absorption spectra of **1** in the *cis*-configuration (**1cis**), **1** the *trans*-configuration (**1trans**), and closed-ring isomer **1c** and the fluorescence spectrum of **1c**. These three isomers were isolated from UV (365 nm)-irradiated 1,4-dioxane solutions containing product **1** by using high-performance liquid chromatography (HPLC) (see Figure S1). As described in detail next, upon UV irradiation **1cis** undergoes photoisomerization reactions to produce **1trans** and closed-ring isomer **1c**. The three fractions isolated by HPLC were identified by their absorption and NMR spectra and also by X-ray crystallographic analysis.

The absorption spectral measurement indicated that the third fraction is ascribed to **1c** because it has a strong absorption band around 440 nm, which is typical of the closed-ring isomer. The first and second fractions showed very similar absorption spectra below 460 nm. NMR measurements indicated that these two fractions are due to the open-ring isomers, but it was difficult to definitely identify the fractions to **1cis** and **1trans**. Therefore, we carried out X-ray crystallographic analysis to discriminate the two fractions. Fortunately, we succeeded in preparing single crystals of the second fraction suitable for X-ray analysis. The X-ray structure analysis indicated that the second fraction is ascribed to **1cis**, as shown in Figure 2a. Inferring from the results, the first, second, and third fractions were identified as **1trans**, **1cis**, and **1c**, respectively. The structure of **1c** was also confirmed by X-ray crystallographic analysis of the single crystal of **1c**, as shown in Figure 2b.

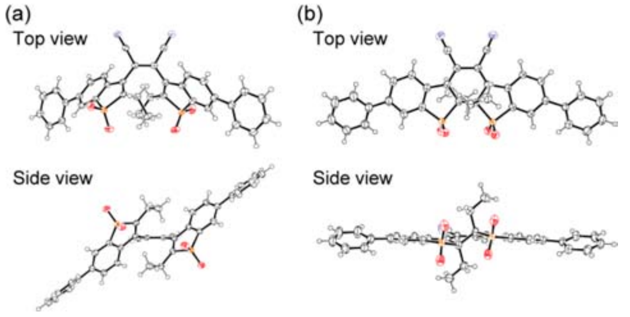


Figure 2. Crystal structures of (a) **1cis** and (b) **1c**.

The molar absorption coefficients of these three isomers were determined by isolation of the fractions by HPLC. The coefficient of the *cis*-isomer is larger than that of the *trans*-isomer, which agrees with the result reported for 1,2-dicyano-1,2-bis(2,4,5-trimethyl-3-theinyl)ethene.[17] The absorption tails of the *cis*- and *trans*-isomers are also shown in Figure 1. The tails extend to 460 nm. This indicates both *cis*- and *trans*-isomers can absorb visible 405 nm light and undergo photoisomerization reactions. Figure 3 shows the absorption and fluorescence spectral changes of **1cis** upon irradiation with 405 nm light. New absorption and fluorescence bands appear in the wavelength region of 400−500 and 500−600 nm, respectively. The new bands are ascribed to closed-ring isomer **1c**. The present dicyanoethene derivative **1cis** can be activated upon irradiation with visible 405 nm light.

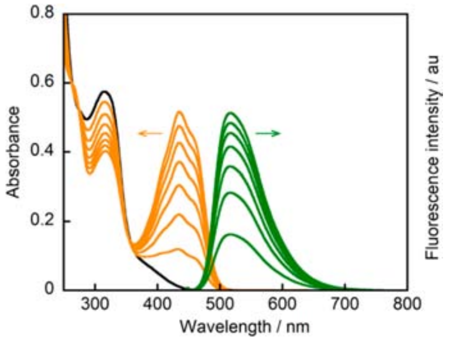


Figure 3. Absorption and fluorescence spectral changes of **1cis** upon irradiation with 405 nm light (1 mW/cm^2) in 1,4-dioxane (2.2×10^{-5} M). The irradiation time for each step was 1 min. The excitation wavelength of the fluorescence was 450 nm.

The closed-ring isomer **1c** gave relatively strong fluorescence at around 510 nm. The fluorescence quantum yields in 1,4-dioxane, chloroform, dichloromethane, and acetonitrile were measured to be 0.78 (τ_f = 3.01 ns), 0.81, 0.82 (τ_f = 2.98 ns), and 0.62 (τ_f = 2.81 ns), respectively. These values are similar to those observed for 1,2-bis(2-ethyl-6-phenyl-1-benzothiophene-1,1-dioxide-3-yl)perfluorocyclopentene.[12] As described above, photoexcitation of **1cis** results in the formation of **1c**. At the

DOI: 10.1021/acs.orglett.5b02361
Org. Lett. 2015, 17, 4802−4805

same time, **1cis** can undergo photoisomerization reaction to produce **1trans**. For the use of compound **1** as a photoswitchable fluorescent chromophore it is indispensable to know the reaction processes to produce fluorescent **1c**.

Parts a and b of Figure 4 show the changes of the contents of **1cis**, **1trans**, and **1c** upon irradiation with 313 nm light starting from **1cis** and **1trans**, respectively. The contents of **1cis**, **1trans**, and **1c** were measured by using HPLC. As can be seen from Figure 4, **1cis** to **1trans** as well as **1trans** to **1cis** isomerization efficiently takes place. In both cases, however, the final product is closed-ring isomer **1c**. From these reaction processes, we determined the reaction quantum yields of cis to trans ($\Phi_{\text{cis-trans}}$), trans to cis ($\Phi_{\text{trans-cis}}$), cyclization ($\Phi_{\text{cis-close}}$), and cycloreversion ($\Phi_{\text{close-cis}}$) reactions (for details, see the Supporting Information), as shown in Table 1.[18] $\Phi_{\text{cis-trans}}$, $\Phi_{\text{trans-cis}}$, and $\Phi_{\text{cis-close}}$ are relatively large, while $\Phi_{\text{close-cis}}$ is very low. This is the reason why the final product is the fluorescent closed-ring isomer **1c**. Similar changes in the contents were observed when irradiated with 405 nm light (see the Supporting Information). **1cis** was soluble in a water/1,4-dioxane (50/50 volume ratio) mixed solvent and turned on to fluorescent **1c** upon irradiation with 405 nm light.

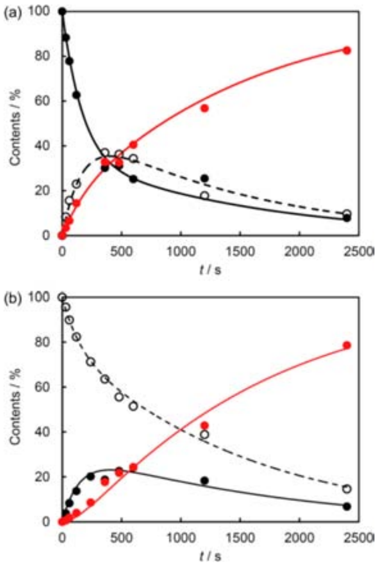


Figure 4. Changes in the contents of **1cis** (black circles), **1trans** (open circles), and **1c** (red circles) upon irradiation with 313 nm light (0.1 mW/cm^2) started from (a) **1cis** and (b) **1trans**. The solid and broken lines were calculated on the basis of the reaction kinetic equations (for details, see the Supporting Information).

Table 1. Photophysical Properties of 1 in 1,4-Dioxane

	$\lambda_{\max}$ (nm) ($\varepsilon/10^4$ M^{-1} cm^{-1})	$\Phi_{\text{cis-trans}}$	$\Phi_{\text{cis-close}}$	$\Phi_{\text{trans-cis}}$	$\Phi_{\text{close-cis}}$
1cis	314 (2.60)	0.55	0.28		
1trans	312 (2.04)			0.34	
1c	266 (2.81), 318 (1.17), 436 (4.49)				1.7×10^{-4}

In conclusion, a new photoswitchable fluorescent diarylethene that can be activated by irradiation with 405 nm light was prepared. The photogenerated closed-ring isomer emitted strong fluorescence. The fluorescence quantum yield was as high as 0.8 in less or medium polar solvents, and even in polar acetonitrile the yield was higher than 0.6. The photoswitchable diarylethene can be potentially used to monitor dynamic processes in real time as well as to reconstruct images with nanometer-scale resolution, such as PALM and RESOLFT.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.5b02361.

Experimental details, ^{1}H and ^{13}C NMR spectra, HPLC chromatograms, and X-ray crystallographic data analysis (PDF)
X-ray crystallographic data for **1cis** (CIF)
X-ray crystallographic data for **1c** (CIF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: iriem@rikkyo.ac.jp.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by Grants-in-Aid for Scientific Research on Innovative Areas "Photosynergetics" (No. 15H01096) and Scientific Research (C) (No. 26410101) from MEXT, Japan, and MEXT-Supported Program for the Strategic Research Foundation at Private Universities.

■ REFERENCES

(1) Lakowicz, J. R. *Principles of Fluorescence Spectroscopy*, 3rd ed.; Springer: New York, 2010.

(2) (a) Rigler, R.; Oritt, M.; Basché, T. *Single Molecule Spectroscopy. Nobel Conference Lectures*; Springer-Verlag: Berlin, 2001. (b) Irie, M.; Fukaminato, T.; Sasaki, T.; Tamai, N.; Kawai, T. *Nature* **2002**, *420*, 759−760. (c) Fukaminato, T. *J. Photochem. Photobiol., C* **2011**, *12*, 177−208.

(3) Roeffaers, M. B. J.; Sels, B. F.; Uji-i, H.; De Schryver, F. C.; Jacobs, P. A.; De Vos, D. E.; Hofkens, J. *Nature* **2006**, *439*, 572−575.

(4) (a) *Fluorescence Imaging Spectroscopy and Microscopy*; Wang, X. F., Herman, B., Eds.; John Wiley & Sons: New York, 1996. (b) Stender, A. S.; Marchuk, K.; Liu, C.; Sander, S.; Meyer, M. W.; Smith, E. A.; Neupane, B.; Wang, G.; Li, J.; Cheng, J.-X.; Huang, B.; Fang, N. *Chem. Rev.* **2013**, *113*, 2469−2527.

(5) Raymo, F. M. *Phys. Chem. Chem. Phys.* **2013**, *15*, 14840−14850.

(6) Dakin, K.; Zhao, Y.; Li, W.-H. *Nat. Methods* **2005**, *2*, 55−62.

(7) (a) Fukaminato, T.; Kobatake, S.; Kawai, T.; Irie, M. *Proc. Jpn. Acad., Ser. B* **2001**, *77*, 30−35. (b) Corredor, C. C.; Huang, Z.-L.; Belfield, K. D. *Adv. Mater.* **2006**, *18*, 2910−2914. (c) Corredor, C. C.; Huang, Z.-L.; Belfield, K. D.; Morales, A. R.; Bondar, M. V. *Chem. Mater.* **2007**, *19*, 5165−5173. (d) Yun, C.; You, J.; Kim, J.; Huh, J.; Kim, E. *J. Photochem. Photobiol., C* **2009**, *10*, 111−129. (e) Fukaminato, T.; Doi, T.; Tamaoki, N.; Okuno, K.; Ishibashi, Y.; Miyasaka, H.; Irie, M. *J. Am. Chem. Soc.* **2011**, *133*, 4984−4990.

(8) (a) Betzig, E.; Patterson, G. H.; Sougrat, R.; Lindwasser, O. W.; Olenych, S.; Bonifacino, J. S.; Davidson, M. W.; Lippincott-Schwartz, J.; Hess, H. F. *Science* **2006**, *313*, 1642−1645. (b) Hess, S. T.; Girirajan, T. P. K.; Mason, M. D. *Biophys. J.* **2006**, *91*, 4258−4272. (c) Sengupta, P.; van Engelenburg, S. B.; Lippincott-Schwartz, J. *Chem. Rev.* **2014**, *114*, 3189−3202.

(9) Dedecker, P.; Hotta, J.; Flors, C.; Sliwa, M.; Uji-i, H.; Roeffaers, M. B. J.; Ando, R.; Mizuno, H.; Miyawaki, A.; Hofkens, J. *J. Am. Chem. Soc.* **2007**, *129*, 16132−16141.

(10) (a) Wyman, G. M.; Zarnegar, B. M. *J. Phys. Chem.* **1973**, *77*, 831−837. (b) Zhu, M.-Q.; Zhu, L.; Han, J. J.; Wu, W.; Hurst, J. K.; Li, A. D. Q. *J. Am. Chem. Soc.* **2006**, *128*, 4303−4309. (c) Hu, D.; Tian, Z.; Wu, W.; Wan, W.; Li, A. D. Q. *J. Am. Chem. Soc.* **2008**, *130*, 15279−15281.

(11) Irie, M.; Fukaminato, T.; Matsuda, K.; Kobatake, S. *Chem. Rev.* **2014**, *114*, 12174−12277.

(12) (a) Uno, K.; Niikura, H.; Morimoto, M.; Ishibashi, Y.; Miyasaka, H.; Irie, M. *J. Am. Chem. Soc.* **2011**, *133*, 13558−13564. (b) Takagi, Y.; Kunishi, T.; Katayama, T.; Ishibashi, Y.; Miyasaka, H.; Morimoto, M.; Irie, M. *Photochem. Photobiol. Sci.* **2012**, *11*, 1661−1665.

(13) (a) Lee, M. K.; Rai, P.; Williams, J.; Twieg, R. J.; Moerner, W. E. *J. Am. Chem. Soc.* **2014**, *136*, 14003−14006. (b) Guo, X.; Zhou, J.; Siegler, M. A.; Bragg, A. E.; Katz, H. E. *Angew. Chem., Int. Ed.* **2015**, *54*, 4782−4786.

(14) Yamaguchi, T.; Hosaka, M.; Shinohara, K.; Ozeki, T.; Fukuda, M.; Takami, S.; Ishibashi, Y.; Asahi, T.; Morimoto, M. *J. Photochem. Photobiol., A* **2014**, *285*, 44−51.

(15) Hanazawa, M.; Sumiya, R.; Horikawa, Y.; Irie, M. *J. Chem. Soc., Chem. Commun.* **1992**, 206−207.

(16) Uchida, K.; Nakayama, Y.; Irie, M. *Bull. Chem. Soc. Jpn.* **1990**, *63*, 1311−1315.

(17) Erko, F. G.; Berthet, J.; Patra, A.; Guillot, R.; Nakatani, K.; Métivier, R.; Delbaere, S. *Eur. J. Org. Chem.* **2013**, *2013*, 7809−7814.

(18) Sumi, T.; Takagi, Y.; Yagi, A.; Morimoto, M.; Irie, M. *Chem. Commun.* **2014**, *50*, 3928−3930.