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Synthesis and crystal structure of a *meso*-decene-BODIPY dye as a functional bright fluorophore for silicone matrices

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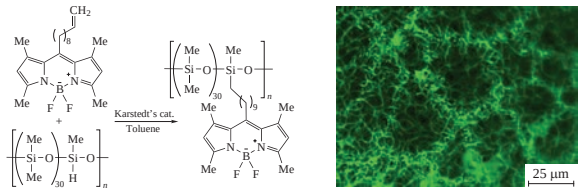
A *meso*-decene-BODIPY dye was synthesized and conjugated to a polydimethylsiloxane. Fluorescence properties of the obtained polymer drastically changed in different solvents. The polymer showed an unusual for other siloxane polymers trend to structuration.

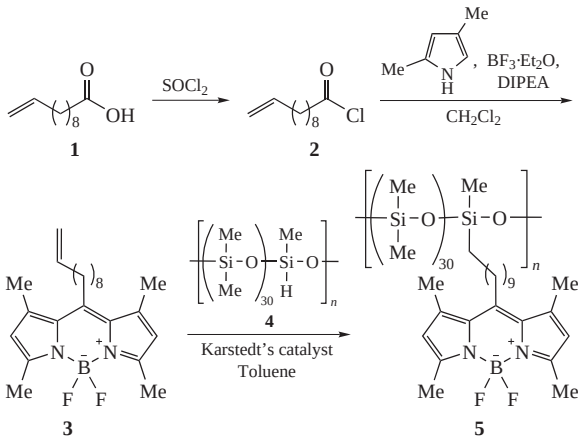


Fluorescent compounds have been long used in various fields of science, from materials chemistry to biosensor development or live systems investigations.[1–3] The last decade has witnessed a significant advance in the synthesis and applications of the boron dipyrromethene (BODIPY) derivatives.[4–6] To date, BODIPY-based fluorescent dyes with the emission from blue to red and further to the infrared spectral range have been synthesized.[7,8] However, green fluorescent BODIPY variants are the most popular ones owing to their high brightness and facile synthesis.[9–11] At present, 1,3,5,7-tetramethyl-BODIPY (TMB) derivatives are in high demand, since their fluorophore core is protected by four methyl groups minimizing fluorescence quenching induced by interfluorophore interactions.[12]

There is a great need for fluorophore–polymer conjugates due to the development of solid-state dye-lasers,[7] mechanochromic materials,[13] light emitting diodes,[14] and nanoscale luminescent materials with well-controlled sizes, shapes and emission colors.[15] Siloxane polymers are of a particular interest owing to their high stability and outstanding thermal and optical characteristics.[16–18] Here, we report the coupling of a TMB derivative to a siloxane polymer. The resulting polymer acquired fluorescence properties, which dramatically changed in different solvents. The obtained compound showed a marked susceptibility to structuration, unusual for other siloxane polymers.

To conjugate to a siloxane polymer, we synthesized a *meso*-decene-TMB derivative equipped with a terminal vinyl group attached to the long aliphatic spacer (Scheme 1), which allowed us to perform subsequent conjugation to target objects by the hydrosilylation reaction using the Karstedt's catalyst. Recently, compound **3** was synthesized in 14% yield and used for labeling of sphingosines[19] and estradiol.[20] In the present work, we improved the earlier reported procedure and raised the yield up to 63%.

In our study, undec-10-enoic acid **1** was converted into its chloride **2** by the treatment with thionyl chloride.[21] Next several steps were performed without isolation of semiproducts. Reaction between undec-10-enoyl chloride **2** and 2,4-dimethylpyrrole followed by the treatment with DIPEA and boron trifluoride diethyl etherate brought about BODIPY derivative **3** in 63% isolated† yield. Compound **3** dissolved in different organic solvents showed characteristic sharp absorbance and emission peaks at



1 **2** **3** **4** **5**

Scheme 1

† All solvents were purified before use. Undec-10-enoic acid, thionyl chloride, 2,4-dimethylpyrrole, DIPEA and $BF_3{\cdot}Et_2O$ were purchased from Acros Organics and used without purification. Platinum(0) 1,3-divinyl-1,1,3,3-tetramethyldisiloxane complex solution (in xylene, 2% Pt) was purchased from Sigma-Aldrich. The reactions were monitored by TLC using Fluka silica gel (60 F 254) plates (0.25 mm). Column chromatography was carried out using Merck 60 (230–400 mesh) silica gel. Visualization was accomplished with UV light. Melting points were determined in capillary tubes. IR spectra were recorded with a Bruker Equinox 55/S spectrometer. ^{1}H, ^{13}C, and ^{19}F NMR spectra were recorded with a Bruker Avance II spectrometer (300 MHz) and a Bruker Avance 600 spectrometer (600 MHz). HRMS spectra (ESI) were measured using a Bruker micrOTOF II instrument (ESI). UV-VIS absorption spectra were recorded with a Cary 50 Bio (Varian) spectrophotometer. Fluorescence spectroscopic measurements were carried out using a Cary Eclipse (Varian) spectrofluorometer. Fluorescence spectra were measured at optical density of ~0.05. The quantum yield of luminescence was determined using fluorescence in 0.1 M NaOH water solution (Φ_F = 0.92) as a standard.

Table 1 Spectral characteristics of monomer *meso*-decene-TMB **3** and TMB–PDMS polymer **5** in various solvents.

Compound	Solvent	λ^{abs}_{max}/nm	λ^{em}_{max}/nm	ε/dm^3 mol^{-1} cm^{-1}	Φ_f (%)
Mono-TMB **3**	THF	498	505	97500	95
	CH_2Cl_2	498	505	89300	93
	EtOAc	496	503	96200	98
	MeCN	494	501	93700	94
	DMSO	498	506	88200	93
TMB–PDMS **5**	THF	498	506	–[a]	75
	CH_2Cl_2	498	506	–[a]	76
	EtOAc	496	505	–[a]	62
	MeCN	498 (br.)	555 (br.)	–[a]	14
	DMSO	499 (br.)	508 (br.)	–[a]	18

[a] Not determined.

498 and 505 nm, respectively, and exhibited customary for TMB high fluorescence quantum yield around 95% (Table 1). Evaporating solvent from the toluene solution of compound **3** caused formation of large red crystals. According to X-ray diffraction analysis,‡ it crystallized in centrosymmetric space group $P\bar{1}$ with four crystallographically independent molecules. Bond lengths and angles were similar to those previously reported for derivatives of BODIPY.[22] In the crystal, molecules of **3** formed dimers *via* weak stacking interactions between diazaborinine cycles (Figure 1). Averaged distances between the planes of these cycles and centroids of the cycles were 3.26 and 4.71 Å, respectively.

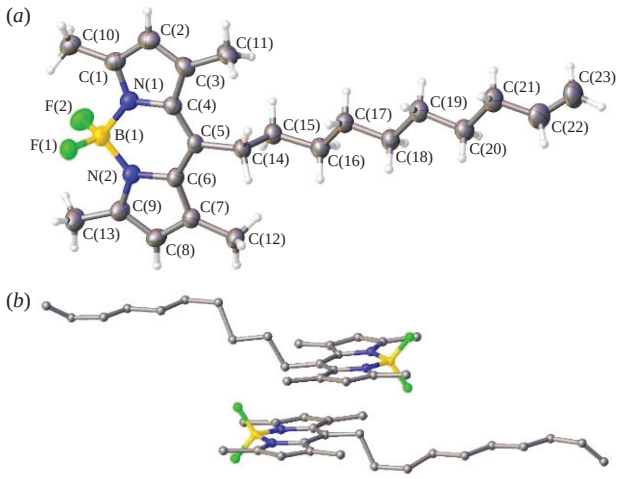


Figure 1 X-ray crystal structure of **3**. (*a*) Molecular structure of **3** presented in ADP ellipsoids at 50% probability. (*b*) Stacking interaction between diazaborinine cycles in the dimer.

Fluorescent microscopy experiments were performed with Leica DMI6000I microscope with a 63× oil immersion objective lens and fluorescence filter cube for GFP/FITC.

Meso-*decene-BODIPY* **3**. Undec-10-enoyl chloride **2** (2.638 g, 0.018 mol) was added to a solution of 2,4-dimethylpyrrole (5 g, 0.053 mol) in dry dichloromethane (60 ml) under argon at room temperature. The mixture was stirred at room temperature for 24 h. Triethylamine (12.5 ml, 0.09 mol) was then added and after additional 15 min of stirring the mixture was supplemented with BF_3·Et_2O (15 g, 0.105 mol). The mixture was stirred at room temperature for 1 h and then passed through a short pad of silica. The solvent was evaporated *in vacuo* and the residue was purified by column chromatography on silica (toluene was used as eluent). Yield 4.38 g (63%). ^{1}H NMR (600 MHz, $CDCl_3$) δ: 1.26–1.39 (m, 8H, CH_2), 1.47 (quintet, 2H, CH_2, J 7.3 Hz), 1.59–1.64 (m, 2H, CH_2), 2.03 (q, 2H, CH_2, J 7.0 Hz), 2.40 (s, 6H, Me), 2.50 (s, 6H, Me), 2.92 (t, 2H, CH_2, J 8.5 Hz).

‡ *Crystal data for* **3**. $C_{23}H_{33}N_2F_2B$, M = 386.32, space group $P\bar{1}$, a = = 13.091(8), b = 17.670(11) and c = 18.786(11) Å, α = 91.948(8)°, β = 91.429(8)°, γ = 102.615(8)°, V = 4236(4) Å^3, Z = 8, T = 120 K, μ(MoKα) = 0.104 mm^{-1}, d_{calc} = 1.212 g cm^{-3}. Total of 37083 reflections were measured (3.274° ⩽ 2θ ⩽ 52.044°) using a Bruker APEX II diffractometer at 120 K, 16679 unique reflections (R_{int} = 0.1101, R_σ = = 0.1595) which were used in all calculations. The final R_1 = 0.0722 [for 6186 reflections with $I > 2\sigma(I)$] and wR_2 = 0.1986 (all data). The structure was solved with the SHELXT[24] structure solution program using Direct Methods and Olex2[25] program and refined with the SHELXL[26] refinement package using least-squares minimization.

CCDC 1522766 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre *via* http://www.ccdc.cam.ac.uk.

Compound **3** was conjugated to Si–H-containing polydimethylsiloxane (PDMS) **4** (M_n = 17500) by the hydrosilylation reaction in dry toluene under an inert atmosphere at room temperature (see Scheme 1).§ Polymer **5** (M_n = 32000 and PDI = 2.68) was purified by precipitation from toluene solution by addition of acetonitrile. The fluorescence and absorbance spectra of the polymer in nonpolar solvents were virtually the same as those of monomeric TMB **3**, except for a slightly reduced to ~70% quantum yield (Table 1). Drastic alterations of the optical properties were revealed in polar solvents (Figure 2). In DMSO and acetonitrile, slight broadening of the absorption peaks (not shown) was observed, whereas the fluorescence emission maximum was considerably broadened and shifted to longer wavelengths [see Figure 2(*a*)]. The use of polar solvents also resulted in a quantum yield drop (Table 1). Due to the well-known propensity of PDMS to collapse in polar solvents, fluorescence decrease might be the consequence of fluorophore closest approach to each other with subsequent aggregation and quenching.[23] The nonpolar character of TMB might be an additional factor favoring aggregation and fluorescence decrease in polar media.

Introduction of fluorescent groups into PDMS would allow one to visualize this compound by fluorescence microscopy. To test this assumption, a dilute solution of TMB–PDMS in THF was overlaid onto a cover glass and visualized using the filter set for green fluorophores (GFP/FITC). After the solvent had been evaporated, the polymer showed a tendency to filamentation, which further led to higher order network texture [Figure 2(*b*)].

In conclusion, we have accomplished the synthesis of *meso*-decene–TMB **3** in high yield. In the crystal state, compound **3** forms dimers *via* the stacking interaction between diazaborinine cycles. Presumably, interfluorophore interactions are also a characteristic feature for TMB–PDMS **5**, which was obtained by the hydrosilylation reaction of a polydimethylsiloxane with **3**. Formation of interfluorophore aggregates leads to considerable fluorescence quenching of **5** in polar solvents. Furthermore,

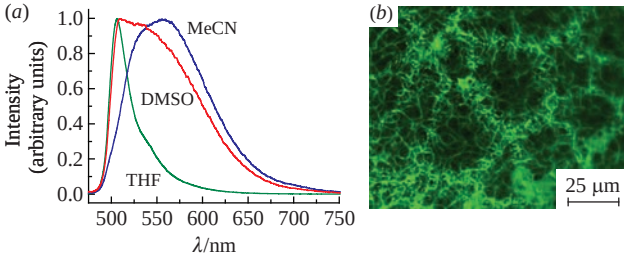


Figure 2 Properties of polymer **5**: (*a*) fluorescence emission spectra and (*b*) fluorescence microscopy image of dried polymer.

§ *BODIPY–PDMS* **5**. The Karstedt's catalyst (30 μl) was added to a solution of PDMS **4**[27] (4.56 g, 0.002 mol) and BODIPY **3** (0.966 g, 0.0025 mol) in dry toluene (20 ml) and the mixture was stirred under argon at room temperature for 24 h. Then acetonitrile (20 ml) was added, and, after settling the polymer, the solvent was decanted. Yield 4.32 g (81%). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 0.03–0.08 (m, 230H, SiMe), 0.48 (m, 2H, $SiCH_2$), 1.21–1.68 (m, 18H, CH_2), 2.40 (s, 6H, Me), 2.50 (s, 6H, Me), 2.91 (m, 2H, CH_2), 6.03 (s, 2H, Pyr).

interfluorophore interactions may contribute to the unusual for other polydimethylsiloxanes structuralization of **5**, which can be distinctly visualized by the fluorescence microscopy.

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References

1 G. Lukinavičius, L. Reymond, K. Umezawa, O. Sallin, E. D'Este, F. Göttfert, H. Ta, S. W. Hell, Y. Urano and K. Johnsson, *J. Am. Chem. Soc.*, 2016, **138**, 9365.
2 Q. Zheng, M. F. Juette, S. Jockusch, M. R. Wasserman, Z. Zhou, R. B. Altman and S. C. Blanchard, *Chem. Soc. Rev.*, 2014, **43**, 1044.
3 V. I. Martynov, A. A. Pakhomov, N. V. Popova, I. E. Deyev and A. G. Petrenko, *Acta Naturae*, 2016, **8**, 33.
4 N. Boens, V. Leen and W. Dehaen, *Chem. Soc. Rev.*, 2012, **41**, 1130.
5 A. Bessette and G. S. Hanan, *Chem. Soc. Rev.*, 2014, **43**, 3342.
6 J. Chen, W. Zhong, Y. Tang, Z. Wu, Y. Li, P. Yi and J. Jiang, *Macromolecules*, 2015, **48**, 3500.
7 M. E. Pérez-Ojeda, V. Martín, A. Costela, I. García-Moreno, I. J. Arroyo Córdoba and E. Peña-Cabrera, *Appl. Phys. B*, 2012, **106**, 911.
8 H. Lu, J. Mack, Y. Yang and Z. Shen, *Chem. Soc. Rev.*, 2014, **43**, 4778.
9 A. Loudet and K. Burgess, *Chem. Rev.*, 2007, **107**, 4891.
10 T. V. Ovchinnikova, A. V. Pshezhetsky, A. B. Tuzikov and N. V. Bovin, *Mendeleev Commun.*, 2015, **25**, 422.
11 E. V. Ilnitskaya, Yu. N. Kononevich, A. M. Muzafarov, S. A. Rzhevskiy, I. A. Shadrin, E. V. Babaev, V. I. Martynov and A. A. Pakhomov, *Russ. J. Bioorg. Chem.*, 2015, **41**, 451 (*Bioorg. Khim.*, 2015, **41**, 505).
12 I. A. Boldyrev, X. Zhai, M. M. Momsen, H. L. Brockman, R. E. Brown and J. G. Molotkovsky, *J. Lipid Res.*, 2007, **48**, 1518.
13 F. Ciardelli, G. Ruggeri and A. Pucci, *Chem. Soc. Rev.*, 2013, **42**, 857.
14 A. C. Grimsdale, K. L. Chan, R. E. Martin, P. G. Jokisz and A. B. Holmes, *Chem. Rev.*, 2009, **109**, 897.
15 S. H. Alamudi, R. Satapathy, J. Kim, D. Su, H. Ren, R. Das, L. Hu, E. Alvarado-Martínez, J. Y. Lee, C. Hoppmann, E. Peña-Cabrera, H.-H. Ha, H.-S. Park, L. Wang and Y.-T. Chang, *Nat. Commun.*, 2016, **7**, 11964.
16 A. A. Anisimov, A. V. Zaytsev, V. A. Ol'shevskaya, M. I. Buzin, V. G. Vasil'ev, K. L. Boldyrev, O. I. Shchegolikhina, V. N. Kalinin and A. M. Muzafarov, *Mendeleev Commun.*, 2016, **26**, 524.
17 M. Liras, M. Pintado-Sierra, F. Amat-Guerri and R. Sastre, *J. Mater. Chem.*, 2011, **21**, 12803.
18 H. Rathnayake, J. Binion, A. McKee, D. J. Scardino and N. I. Hammer, *Nanoscale*, 2012, **4**, 4631.
19 C. Peters, A. Billich, M. Ghobrial, K. Högenauer, T. Ullrich and P. Nussbaumer, *J. Org. Chem.*, 2007, **72**, 1842.
20 M. Okamoto, S. Kobayashi, H. Ikeuchi, S. Yamada, K. Yamanouchi, K. Nagasawa, S. Maekawa, T. Kato and I. Shimizu, *Steroids*, 2012, **77**, 845.
21 A. Leydet, H. El Hachemi, B. Boyer, G. Lamaty, J. P. Roque, D. Schols, R. Snoeck, G. Andrei, S. Ikeda, J. Neyts, D. Reymen, J. Este, M. Witvrouw and E. De Clercq, *J. Med. Chem.*, 1996, **39**, 1626.
22 A. A. Pakhomov, Yu. N. Kononevich, A. A. Korlyukov, V. I. Martynov and A. M. Muzafarov, *Mendeleev Commun.*, 2016, **26**, 196.
23 A. A. Pakhomov, Y. N. Kononevich, M. V. Stukalova, E. A. Svidchenko, N. M. Surin, G. V. Cherkaev, O. I. Shchegolikhina, V. I. Martynov and A. M. Muzafarov, *Tetrahedron Lett.*, 2016, **57**, 979.
24 G. M. Sheldrick, *Acta Crystallogr., Sect. A*, 2015, **71**, 3.
25 O. V. Dolomanov, L. J. Bourhis, R. J. Gildea, J. A. K. Howard and H. Puschmann, *J. Appl. Crystallogr.*, 2009, **42**, 339.
26 G. M. Sheldrick, *Acta Crystallogr., Sect. C*, 2015, **71**, 3.
27 T. A. Pryakhina, D. I. Shragin, T. V. Strelkova, V. M. Kotov, M. I. Buzin, N. V. Demchenko and A. M. Muzafarov, *Russ. Chem. Bull., Int. Ed.*, 2014, **63**, 1416 (*Izv. Akad. Nauk, Ser. Khim.*, 2014, 1416).

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