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Spectroscopic and photophysical properties of mono- and dithiosubstituted BODIPY dyes

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Graphical abstract

Highlights

- A series of BODIPY dyes, substituted at the 3 and 5 positions with Cl or thioalkyl groups was synthesized
- BODIPY compounds are characterized by strong absorption bands at 500-580 nm, corresponding to $S_0 \rightarrow S_1$ transition

- Emission spectra of BODIPY compounds are mirror images to absorption with maxima at 520-600 nm.
- Substitution of the BODIPY by Cl or S-alkyl induces batochromic shifts in absorption and emission for 50-60 nm and higher Φ_f (0.1-0.7).

Estimated singlet excited state lifetimes ($\tau = 2-6$ ns) reveal that k_R and non k_{NR} do not vary with changes in solvent polarity/polarizability

Abstract

A series of BODIPY (4,4-difluoro-4-bora-3a,4a-diaza-s-indacene) dyes, substituted at the 3 and 5 positions was synthesized and their spectral and photophysical properties were investigated in solvents of different polarity and polarizability. All compounds are characterized by strong absorption bands at 500-580 nm, corresponding to $S_0 \rightarrow S_1$ transition, the typical for the BODIPY chromophore. Emission spectra are mirror images to absorption with maxima at 520-600 nm. Substitution of the BODIPY chromophore by Cl or thioalkyl substituents induces batochromic shifts in both absorption and emission spectra for 50-60 nm and induces higher quantum yields of fluorescence ($\Phi_f = 0.1-0.7$). The findings were rationalized by TD-DFT computations. The dyes exhibit weak solvatochromic properties which could not be correlated to solvent polarizability, contrary to majority of BODIPY derivatives. Furthermore, estimated singlet excited state lifetimes ($\tau = 2-6$ ns) reveal that radiative and non-radiative rate constants for deactivation from S1 do not vary with changes in solvent polarity/polarizability. However, the highest values of Φ_f and τ are generally found in solvents of high polarizability. Presented spectroscopic and photophysical study is important for the use of dyes as chemodosimeters for thiols and cystein, as well as for the rational design of new molecular probes.

Key words: BODIPY; fluorescence spectroscopy; solvatochromism

1. Introduction

Derivatives of 4,4-difluoro-4-bora-3a,4a-diaza-s-indacene,[¹] better known as BODIPY dyes, have become popular fluorophores in life sciences, often used in the design of molecular probes, or in fluorescent microscopy for staining different intracellular organelles.^[2] The outstanding properties of BODIPY dyes include good thermal and photochemical stability, good solubility in many organic solvents, excitation/emission spectra in the visible region and narrow emission bandwidths with high peak intensities, high fluorescence quantum yields (Φ_f) and molar absorption coefficients ($\epsilon > 50\ 000\ M^{-1}\ cm^{-1}$), and usually negligible quantum yields of intersystem crossing (ISC) and triplet-state formation.^[3] In recent years, an increasing number of reports has focused on the syntheses and functionalization reactions of BODIPY providing plethora of new molecules dyes, a with tunable spectroscopic/photophysical properties, which was a subject of several review articles.^[4] However, a pursuit for even better dyes with different properties suitable for various applications is not over. It is particularly important to develop different BODIPY analogues with emission wavelengths tunable from 500 nm to over 700 nm, which can be used as fluorescence FRET pairs with applications in chemistry and biology. One approach to differently substituted BODIPY derivatives include substitution of chlorine on the BODIPY core, which can be facilitated by nucleophiles, [5] or in Pd-catalyzed arylations. [6]Furthermore, Jiao et al. recently introduced a better method for the chlorination⁷] and bromination of BODIPY derivatives.^[8] However, recent synthetic advances allowed for the nucleophilic substitution on the BODIPY without chlorine substitution, [9] as well as direct C-H arylation reactions, [10] significantly shortening the synthetic pathways towards new dyes.

Moreover, Jiao et al. also described transition-metal-free regioselective C-H/S-H crosscoupling of BODIPY with thiols.[¹¹]

Different substituents at the BODIPY positions 3 and 5 provided new dyes whose photophysical properties have been investigated.^[12] These dyes mostly exhibit fluorosolvatochromic properties that were related to polarizability of solvent.^[12] However, a striking difference in the spectral and photophysical properties was observed between mono-^{[13}] and bis-anilino-substituted BODIPY dyes,^{[14}] and rationalized in view of the typical properties of polymethine dyes.^{[13,14,15}] On the other hand, solvatochromic properties of certain dyes could not be explained by solvent polarizability and multiple-parameter approach introduced by Catalan was used.^[16] Here we report a systematic study of spectroscopic and photophysical properties for 5 BODIPY dyes that bear different subsitution at the 3 and 5 positions (Figure 1). Two dyes are symmetrically substituted (Cl2 and S2), two are monosubstituted (H-Cl and H-S) and one is asymmetrically substituted (S-Cl). Our spectroscopic investigation is initiated due to recent applications of Cl-substituted BODIPY dyes or carbaldehydes as chemosensors for cysteine, [¹⁷] or glutathione. [¹⁸] Therefore, we disclose a thorough spectroscopic and photophysical investigation of S-substituted BODIPY dyes in comparison to Cl-substituted dyes. Synthesis of S-substituted BODIPY dyes has been reported, [19] as well as some preliminary investigation of their photophysical properties. [20]However, a thorough photophysical investigation and comparison between the Cl- and Ssubsitited dyes has hitherto not been disclosed.



Figure 1. BODIPY derivatives

2. Materials and Methods

2.1.General

¹H and ¹³C NMR spectra were recorded at 300, or 600 MHz (75 MHz and 150 MHz) at 25 °C using TMS as a reference and chemical shifts were reported in ppm. ¹³C NMR spectra were recorded by APT or complete (COM) techniques. HRMS were obtained on a MALDI TOF/TOF instrument. Chemicals were purchased from the usual commercial sources and were used as received. Silica gel (0.05–0.2 mm) was used for chromatographic purifications. Solvents for chromatographic separations were used as delivered from the supplier (p.a. or HPLC grade) or purified by distillation (CH₂Cl₂). Dry CH₂Cl₂ was obtained after standing of commercial product over anhydrous MgSO₄ overnight, then filtered and stored over 4Å molecular sieves. Dry THF was obtained by distillation from Na, and stored over Na. Synthetic procedure and characterization of known intermediates and known BODIPY compounds Cl2, H-Cl, S-Cl and S2 is reported in the Supporting Information.

2.2. Synthesis of 4,4-Difluoro-8-(4-methylphenyl)-3-(2-ethoxy-2-oxoethyl)thio-4-bora-3a,4a-diaza-s-indacene (H-S)

BODIPY compound **H-Cl** (20 mg, 0.063 mmol) was dissolved in CH₃CN (10 mL). To the solution ethyl mercaptoacetate (8 μ L, 0.069 mmol) and triethylamine (TEA, 10 μ L, 0.069 mmol) were added. The reaction mixture was stirred at rt 4 h. When the reaction was completed, H₂O (20 mL) was added and an extraction with CH₂Cl₂ (2× 20 mL) was carried out. The extracts were dried over anhydrous Na₂SO₄, filtered, and the solvent was removed on a rotary evaporator. The residue was chromatographed on a column of silica gel using CH₂Cl₂ as eluent to afford the pure product (10 mg, 40%).

violet crystals; mp 142-143 °C; ¹H NMR (CDCl₃, 300 MHz): δ = 7.79 (s, 1H), 7.42 (d, 2H, *J* = 8.0 Hz), 7.31 (d, 2H, *J* = 7.9 Hz), 6.95 (d, 1H, *J* = 4.2 Hz), 6.80 (d, 1H, *J* = 4.2 Hz), 6.57 (d, 1H, *J* = 4.5 Hz), 6.48 (dd, 1H, *J* = 1.9, 2.1 Hz), 4.24 (q, 2H, *J* = 7.2, Hz,), 2.46 (s, 3H), 1.29 (t, 3H, *J* = 7.2 Hz) ppm; ¹³C NMR (CDCl₃, 150 MHz, COM): δ = 168.3 (s), 157.7 (s), 143.0 (s), 141.0 (d), 140.9 (s), 136.7 (s), 134.2 (s), 132.3 (d), 130.9 (s), 130.5 (d), 129.1 (d), 128.8 (d), 118.0 (d), 117.4 (d), 62.2 (t), 34.7 (t), 21.4 (q), 14.1 (q) ppm; HRMS (MALDI-TOF/TOF) calculated for C₂₀H₁₉BF₂N₂O₂S 400.1228; found 400.1217.

2.3. UV-vis and fluorescence spectroscopy

UV-vis spectra were recorded on a PG T80/T80+, or a Varian Cary 100 Bio spectrophotometer at rt. Fluorescence measurements were performed on an Agilent Cary Eclipse fluorometer by use of slits corresponding to the bandpass of 2.5 nm for the excitation and 5.0 nm for the emission. The samples were excited at 480, 490 and 500 nm, and for **S-H**, **S-Cl** and **S2** also at 520 nm. The emission was detected in the range of 490-800 nm. Solvents for photophysical measurements were of HPLC or spectroscopic grade purity. Fluorescence quantum yields were determined by use of rhodamine B in CH₃OH ($\Phi_f = 0.66$) as a reference.[²¹] Quantum yields Φ_f were calculated according to Eq. S1 in the SI. One fluorescence measurement was performed by exciting sample at three or four different

wavelengths, and the average value was calculated. Prior to the measurements, the solutions were purged with Ar for 15 min. The measurement was performed at rt (25 $^{\circ}$ C).

2.4. Time-resolved fluorescence

Time-resolved florescence measurements were performed on a LP980 Edinburgh Instruments spectrometer. For the excitation the second harmonic of a Qsmart Q450 Quantel YAG laser was used. The energy of the laser pulse at 543 nm was set to <5 mJ and it was adjusted prior to each measurement not to saturate the detector. The pulse duration was 7 ns. Absorbances at the excitation wavelength were set to < 0.1. The solutions were purged for 15 min with Ar prior to the measurements. The decays were analyzed by fitting to sums of exponentials (Eq. S2 in the SI) using Gaussian-weighted non-linear least-squares fitting based on Marquardt-Levenberg minimization implemented in the software package from Edinburgh Instruments. The fitting parameters (decay times and pre-exponential factors) were determined by minimizing the reduced chi-square χ^2 and graphical methods were used to judge the quality of the fit that included plots of the weighted residuals *vs*. channel number. For each sample, three decays were measured at three emission wavelengths, and the average value is reported.

2.5. Computational methods

The DFT computations were performed using the Gaussian 09 program package.[²²] All stationary point of BODIPY derivatives **Cl2**, **S-Cl** and **S2** depicted in Fig. 5 were optimized using the B3LYP functional,[²³] together with the 6-31G(d,p) basis set [²⁴] in the gas phase. The UV-vis absorption spectra in CH₃CN were simulated using Time-Dependent density functional theory (TD-DFT) [²⁵] employing CAM-B3LYP/6-31G(d,p) [²⁶] and the conductor-like polarizable continuum model (CPCM) [²⁷] by single point calculations on the ground state optimized geometries.

3. Results and discussion

3.1. Synthesis

Synthetic procedure for the preparation of BODIPY dyes is based on the standard procedure for the preparation of the BODIPY core substituted with chlorines, [²⁸] which can be substituted by nucleophiles.[5] However, contrary to previous report,[²⁸] chlorination of dipyrromethane afforded a mixture of mono- and bis-chloro substituted molecules which were not separated, but they were transformed to a mixture of BODIPY derivatives **H-Cl** and **Cl2** (Scheme 1), which are more stable so it was easier to separate them. Note that chlorination of BODIPY, as reported by Jiao et al. provides chlorinated derivatives in higher yields.[7] Nevertheless, nucleophilic substitution of **H-Cl** and **Cl2** with ethyl 2-mercaptoacetate afforded dyes **H-S, SCl** and **S2** in good yields.



Scheme 1. Synthesis of BODIPY derivatives (ΔT - heating).

3.2. Spectroscopic and photophysical properties

Absorption and fluorescence spectra for the set of 5 BODIPY dyes were measured in eight solvents characterized by different polarity and polarizability. Table 1 compiles spectroscopic properties of the dyes. Absorption spectra are characterized by the typical BODIPY sharp band with a maximum at 500-579 nm due to the 0-0 $S_0 \rightarrow S_1$ transition, a shoulder at higher

energy side due to 0-1 vibrational band of the same transition, and a weaker broad band at 300-400 nm, populating higher excited states. The half width of the intense absorption band (fwhm_{abs}) is small 700-900 cm⁻¹, regardless of substituents, contrary to the pronounced effects observed for amino substituted BODIPY dyes that exhibit much larger fwhm_{abs}.^[13,14] Emission spectra are small Stokes-shifted mirror images of the intense absorption bands with maxima at 510-590 nm. The substitution of the BODIPY moiety with Cl, or more pronounced with thiol groups, shifts both absorption and fluorescence spectra batochromically. Figure 2 shows absorption and fluorescence spectra of the dyes in cyclohexane, and Fig. S1 in acetonitrile (CH₃CN). In cyclohexane, a difference in the maximum of absorption between H-Cl and S2 is 55 nm, similar to the difference in fluorescence spectra of 59 nm. Such a trend hardly changes with the solvent polarity. Thus, similar differences of 56 nm in the absorption and 66 nm in fluorescence spectra were observed and between H-Cl and S2 in CH₃CN. The origin of the batochromic shifts is in a significant electron density on the Cl and S atoms in HOMO and LUMO orbitals (vide infra), giving rise to a higher degree of electron delocalization. In addition to batochromic shifts, substitution of the BODIPY moiety gives rise to higher fluorescence quantum yields (Φ_f). The highest Φ_f was measured for S2, S-Cl and Cl2 molecules, whereas H-Cl and HS are generally less fluorescent (Table 1).



Figure 2. Absorption (left) and fluorescence spectra (right) of BODIPY dyes in cyclohexane.

Comp	Solvent	λ_{abs} / nm_a	fhwm _{abs} /cm ^{-1 b}	λ_{em} / nm ^c	Stokes / cm ^{-1 d}	$\Phi_{\mathrm{f}}~^{\mathrm{e}}$
Cl2	Cvclohex.	514	724	524	371	0.24±0.03
	toluene	515	790	529	514	0.69±0.01
						$0.63[^{20}]$
	CH ₂ Cl ₂	512	803	524	447	0.42±0.05
	EtOAc	509	775	521	452	0.42±0.02
	THF	511	769	523	449	0.47±0.01
						$0.37[^{20}]$
	DMSO	512	879	527	556	0.087 ± 0.0
						01
	CH ₃ CN	508	819	519	417	0.41±0.01
	CH ₃ OH	508	819	520	454	0.38±0.01
H-Cl	Cyclohex.	505	784	518	497	0.10±0.02
	toluene	508	856	522	528	0.27±0.01
	CH ₂ Cl ₂	512	803	518	226	0.14±0.01
	EtOAc	502	877	516	540	0.13±0.01
	THF	504	869	517	499	0.16±0.01
	DMSO	505	904	521	608	0.080 ± 0.0
	-					01
	CH ₃ CN	500	884	514	545	0.11 ± 0.01
	CH ₃ OH	501	842	515	543	0.11 ± 0.01
H-S	Cyclohex.	533	778	546	447	0.07 ± 0.01
	toluene	535	805	553	608	0.18 ± 0.01
	CH ₂ Cl ₂	532	817	547	515	0.09±0.01
	EtOAc	530	824	546	553	0.078 ± 0.0
	ТНЕ	532	851	5/19	582	0.083 ± 0.0
	1111	552	0.51	515	562	02
	DMSO	535	912	553	608	0.130±0.0
						03
	CH ₃ CN	528	830	545	591	0.08 ± 0.01
	CH ₃ OH	528	830	542	489	0.064 ± 0.0
						02
S-Cl	Cyclohex.	541	684	553	401	0.20 ± 0.02
	toluene	544	746	557	429	0.52 ± 0.01
	CH ₂ Cl ₂	540	757	553	435	0.30 ± 0.03
	EtOAc	537	799	552	506	0.36 ± 0.03
	THF	540	793	555	501	0.28 ± 0.01
	DMSO	542	892	560	593	0.33±0.02
	CH ₃ CN	535	842	551	543	0.25±0.01
	CH ₃ OH	535	805	550	510	0.26±0.02
S2	Cyclohex.	569	884	583	422	0.65 ± 0.05
	toluene	572	768	588	476	0.75±0.01
	CH_2Cl_2	567	812	582	456	0.50 ± 0.05

Table 1. Spectral and photophysical properties of BODIPY derivatives.

EtOAc	566	814	582	486	0.63 ± 0.03
THF	569	806	588	568	0.62 ± 0.01
DMSO	573	897	592	560	0.50 ± 0.05
CH ₃ CN	564	791	580	489	0.66 ± 0.01
CH ₃ OH	564	824	580	489	0.61 ± 0.02

^a Maximum in absorption spectrum. ^b Half width of the absorption band, fhwm_{abs}.^c Maximum in emission spectrum. ^d Stokes shift. ^e Quantum yield of fluorescence measured by use of Rhodamine B in CH₃OH as a reference ($\Phi_f = 0.66$).[²¹] The Reported values represent average from at least three measurements, and the error is maximal deviation.

Increase of solvent polarity generally induces small blue shifts in the absorption and batochromic shifts in the emission spectra for all dyes. Normalized absorption and emission spectra for S-Cl and S2 are shown in Figs 3 and 4 (for other molecules see Figs S2-S4 in the SI). However, dependence of the maxima in absorption, emission, or Stokes shifts could not be well correlated to polarity parameter $f(\varepsilon)$, polarizability $f(n^2)$, Lippert $(f(\varepsilon) - f(n^2))$, E_T(30) (for correlations see figs S5-S8 in the SI). Albeit somewhat better correlation was found for the dependence of the Stokes shift on the Lippert parameter for S2 (r = 0.76) and E_T(30) for Cl2 (r = 0.85), general lack of the correlation suggests that Cl and thiol substituted BODIPY dyes, particularly those which are asymmetrically substituted, do not exhibit an increase of dipole moment between S₀ and S₁. Therefore, there is no dependence on fluorosolvatochromic properties on the Lippert parameter or $E_T(30)$. A blue shift in the absorption spectra upon increase of solvent polarity actually suggests a larger dipole moment in S₀ then in S₁. As for the dependence of the solvatochromicity on the solvent polarizability $f(n^2)$, fitting gave poor correlations, with the notable exceptions for the dependence of v_{abs} and v_{em} for H-Cl (r = 0.75 and 0.74, respectively). These findings indicate that the Wan der Waals and excitonic interactions with polarizable solvent are masked with solvent-solute specific interactions, resulting in no clear dependence of the maxima in absorption or emission on $f(n^2)$. Such a solvatochromic behavior has been documented for asymmetrically substituted BODIPY,^[13]

but it contrasts majority of symmetrically substituted BODIPY dyes such as phenoxy-[¹²] and anilino-derivatives [¹⁴] whose solvatochromic properties depend on the polarizability of solvent.

Solvatochromic properties in absorption and emission spectra, and the Stokes shifts were fitted also to multiparameter Catalán equation (Eq. 1), which includes solvent acidity (SA), basicity (SB), polarizability (SP) and dipolarity (SdP).[²⁹] Estimated fitting parameters can be found in the SI (Table S1). Contrary to previously demonstrated applicability of the Catalán approach for the estimation of spectral properties of BODIPY dyes,[^{16,30}] the best correlation was found for the dependence of the Stokes shift for Cl2 (r = 0.85), and v_{abs} and v_{em} for S-Cl (r = 0.89 and 0.88) and S2 (r = 0.95 and 0.96), whereas for the other dyes the Catalán approach is not applicable. Furthermore, for S2 for which the best correlation was observed we investigated which parameters significantly affect the v_{abs} and v_{em} and found out that none of the parameters can be excluded. Fitting to SP and SdP only (two independent parameters), gave poor correlations with r \approx 0.1, whereas including SA or SB (three independent parameters) increased the quality of the fit with the correlation of r \approx 0.5. Consequently, the set of investigated BODIPY derivatives shows mild and not specific solvatochromic properties.

$$y = y_0 + a_{SA}SA + b_{SB}SB + c_{SP}SP + d_{SdP}SdP$$
(Eq. 1)



Figure 3. Absorption spectra of S-Cl (left) and S2 (right) in different solvents.



Figure 4. Emission spectra of S-Cl (left) and S2 (right) in different solvents.

Singlet excited state lifetimes for BODIPY derivatives were measured on a laser flash photolysis (LFP) setup ($\lambda_{ex} = 534$ nm), giving only approximate lifetime values (τ , Table 2, for some representative decays see Figs S9-S11 in the SI). However, these approximate values together with $\Phi_{\rm f}$ allowed for the approximation of rate constant for radiative (k_R) and nonradiative deactivation from S_1 (k_{NR}). Note a general trend that all BODIPY derivatives exhibit the highest values of Φ_f and τ in highly polarizable solvents such as CH₂Cl₂ or toluene. Such a behavior has been reported for different BODIPY dyes.[3,12,13,14,15,20] The estimated values of $k_{\rm R}$ are (3-6)×10⁷ s⁻¹ for **H-S**, (6-12)×10⁷ for **S-Cl** and $\approx 10^8$ s⁻¹ for **S2**, and similarly to $k_{\rm NR}$, they do not vary much with changes in solvent polarity/polarizability. On the hand, it is interesting to note that $k_{\rm NR}$ exhibits almost an order of magnitude lower values for more fluorescent S2 BODIPY compared to less fluorescent derivatives H-S, or S-Cl, indicating that $k_{\rm NR}$ has a more profound effect on $\Phi_{\rm f}$ then $k_{\rm R}$. A significant effect of BODIPY molecular structure on $k_{\rm NR}$ and $\Phi_{\rm f}$ has been reported, particularly in the examples for the N-substituted dyes which undergo photoinduced charge transfer.^{[12,13,14}] However, for the BODIPY derivatives investigated herein, charge transfer is not plausible, as reflected by weak solvatochromic properties.

Comp.	Solvent	τ / ns ^a	$k_{\rm R}/10^7 {\rm ~s^{-1}}^{\rm b}$	$k_{\rm NR}/10^7 {\rm \ s^{-1} \ c}$
H-S	Cyclohex.	2.3±1	3.0	40
	toluene	2.9±0.3	6.2	28
	CH_2Cl_2	2.1±0.8	4.3	43
	EtOAc	3.0±0.5	2.6	31
	THF	2.2±0.5	3.7	42
	DMSO	2.1±0.6	6.2	41
	CH ₃ CN	2.9±1	2.8	32
	CH ₃ OH	2.5±0.5	2.5	37
S-Cl	Cyclohex.	3.3±0.5	6.0	24
	toluene	3.8±0.3	14	13
	CH_2Cl_2	3.5±0.2	8.6	20
	EtOAc	2.9±0.5	12	22
	THF	2.4±0.3	12	30
	DMSO	3.3±0.4	10	20
	CH ₃ CN	3.4±0.3	7.4	22
	CH ₃ OH	2.8±0.3	9.3	26
S2	Cyclohex.	5.3±0.3	12	6.6
	toluene	5.8±0.4	13	4.3
	CH ₂ Cl ₂	6.1±0.5	8.2	8.2
	EtOAc	5.9±0.5	11	6.3
	THF	5.6±0.4	11	6.8
	DMSO	5.3±0.3	9.4	9.4
	CH ₃ CN	5.8±0.4	11	5.9
	CH ₃ OH	5.8±0.3	10	6.7

Table 2. Photophysical properties of BODIPY compounds.

^a Estimated lifetime measured by LFP spectrometer.

^b Radiative rate constant for deactivation from S₁.

^c Nonradiative rate constant for deactivation from S₁.

3.3. Molecular modeling

To rationalize spectral and photophysical observations, computations were performed for molecules Cl2, S-Cl and S2. Figure 5 shows the optimized structures and orbital distributions. The HOMO is delocalized over both pyrrole rings as π -bonding orbitals, while the LUMO expands all over the BODIPY moiety as π *-antibonding orbital. Note that both HOMO and LUMO have electron density on the S and Cl atoms, contributing to the increased electron delocalization and observed red-shifts in absorption and fluorescence spectra compared to non-substituted dyes. Furthermore, promotion of an electron from HOMO to LUMO increases

electron density on the *meso*-phenyl ring. However, excitation does not lead to a significant change in dipole moment, which was reflected in modest fluorosolvatochromic properties that do not depend on the Lippert or $E_T(30)$ parameters.





Figure 5. Optimized geometry for BODIPY derivatives **Cl2**, **S-Cl** and **S2** at B3LYP/6-31G (d, p) level of theory, and the corresponding HOMO and LUMO orbitals.

Calculated energies of HOMO and LUMO are compiled in Table 3. The substitution of Cl by thiols causes a small increase in the energy level of the HOMO and a slight increase in the energy level of the LUMO, thus decreasing the energy gap between these frontier orbitals from 2.94 eV to 2.74 eV for S-Cl and 2.6 eV for S2 in good agreement with the measured UV-vis spectra (Fig. 3, for computed spectra see Fig S12 in the SI). The experimentally observed absorption maxima at 508 nm for Cl2, 535 nm for S-Cl and 564 nm for S2 nm originate mainly from the HOMO \rightarrow LUMO transitions, and they are comparable to computed maxima at 427 nm, 449nm, and 479nm, respectively.

Table 3.Calculated energy levels (in eV) of the HOMO, LUMO and energy gap (ΔE) at B3LYP/6-31G(d,p) level of theory.

Ehomo	$E_{ m LUMO}$	ΔE^{a}

Comp.	-5.871936	-2.931072	2.94
S-Cl	-5.433744	-2.687632	2.74
S2	-5.07416	-2.473296	2.60

^a $\Delta E = E_{LUMO} - E_{HOMO}$

4. Conclusion

A series of BODIPY dyes, symmetrically or asymmetrically substituted at the 3 and 5 positions was synthesized. Photophysical properties of the dyes were investigated in solvents of different polarity and polarizability. In contrast to majority of BODIPY derivatives, here presented dyes exhibit weak solvatochromic properties that cannot be correlated to solvent polarizability. Substitution of the BODIPY chromophore by Cl or thioalkyl substituents induces batochromic shifts in both absorption and emission spectra for 50-60 nm and induces higher quantum yields of fluorescence. Thus, the highest Φ_f was measured for Cl2, S-Cl and S2, whereas H-Cl and H-S are less fluorescent. Similarly to weak solvatochromic properties, Φ_f , singlet excited state lifetimes, k_R and k_{NR} , are insignificantly affected by changes in solvent polarity/polarizability. Nevertheless, the highest values of Φ_f and τ were found in solvents of the highest polarizability. The findings were rationalized by TD-DFT computations. Presented study is important for the use of chloro-substituted BODIPY dyes as chemodosimeters for thiols and cystein, as well as for the rational design of new dyes.

Conflict of interest

The authors declare no conflict of interest.

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