Fluorescent Molecular Devices

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The Chemistry of Fluorescent Bodipy Dyes: Versatility Unsurpassed**

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Bodipy · dyes/pigments · energy transfer · fluorescent probes · luminescence

In memory of Charles Mioskowski

The world of organic luminophores has been confined for a long time to fairly standard biological labeling applications and to certain analytical tests. Recently, however, the field has undergone a major change of direction, driven by the dual needs to develop novel organic electronic materials and to fuel the rapidly emerging nanotechnologies. Among the many diverse fluorescent molecules, the Bodipy family, first developed as luminescent tags and laser dyes, has become a cornerstone for these new applications. The near future looks extremely bright for "porphyrin's little sister".

1. Introduction

Despite existing for almost a century, fluorescent dyes continue to attract the attention of scientists from an ever-expanding multidisciplinary arena. Recent developments in the field of personal diagnostics and in the area of organic electroluminescent devices have boosted interest in the development of next-generation emissive dyes. Countless classes of highly fluorescent organic compounds are now known, but the difluoro-boraindacene family (4,4-difluoro-4-borata-3a-azonia-4a-aza-*s*-indacene, abbreviated hereafter as F-Bodipy) has gained recognition as being one of the more versatile fluorophores and this dye has steadily increased in popularity over the past two decades. The first member of this class of compound was reported by Treibs and Kreuzer in 1968,[1] although relatively little attention was given to the discovery until the end of the 1980s.[2] Then, the potential use of this dye for biological labeling was recognized[3] and several new Bodipy[4]-based dyes were designed and indeed commercialized for biological labeling. As a consequence, Bodipy came to be known to the biochemist and biologist as a photostable substitute for fluorescein, and the number of papers and patents started to escalate in the mid 1990s (Figure 1). The use of Bodipy as an effective biological label has been complemented by its known propensity to function as a tunable laser dye.[5] At the beginning of the 21st century, numerous patents were deposited for additional biological labeling purposes, for paint or ink compositions, and for electroluminescent devices. In parallel, more fundamental studies on the chemical reactivity and the photophysical properties of the new dyes began to emerge. This work has brought about a further rise in the number of patents and research publications attesting to the versatility of the Bodipy class of fluorophores; in 2006, some 729 patents and 1074 journal articles were published that described the multifarious applications of Bodipy-based dyes.[6] The excellent thermal and photochemical stability, high fluorescence quantum yield, negligible triplet-state formation, intense

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[**] Bodipy, deriving from *borondipyrromethene*, denotes dipyrromethenboron difluoride, 4,4-difluoro-4-borata-3a-azonia-4a-aza-s-indacene.

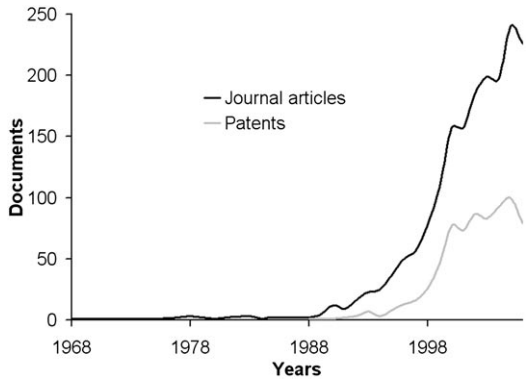

Figure 1. Annual number of scientific publications describing Bodipy fluorophores (source: CAS).

absorption profile, good solubility, and chemical robustness have all added to the general attractiveness of these materials.

2. Synthetic Considerations

The complexation of a dipyrromethene unit to a boron trifluoride salt can lead to formation of a dipyrromethene-boron difluoride structure, which can be considered as being an example of a "rigidified" monomethine cyanine dye (Figure 2). The greatly restricted flexibility leads to unusually

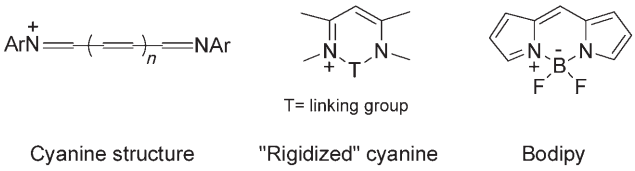

Figure 2. Basic types of cyanine structure.

high fluorescence yields from the dipyrromethene-boron framework. Conjugation of the π-electrons runs along the organic backbone and can be extended by condensation of suitable groups onto the periphery or by the attachment of conjugated units to one or both pyrrole fragments.

This type of structure is commonly described as being a boradiazaindacene by analogy with the all-carbon tricyclic ring, and the numbering of any substituents follows rules set up for the carbon polycycle (Figure 3). By analogy with

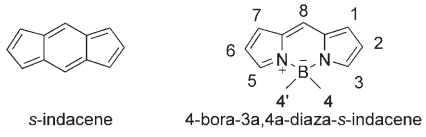

Figure 3. Numbering scheme used for the Bodipy framework derived from indacene.

porphyrinic systems, the 8-position is often referred to as being the *meso* site. The recent development of non-fluorinated Bodipy dyes led to the introduction of a supplementary term for the Bodipy abbreviation that is specific with respect to the nature of the 4,4′-substituents: F for fluoro; C for carbocycle, E for ethynyl, and O for oxygen. The absorption- and fluorescence-spectroscopic properties of members of the Bodipy family are highly influenced by the extent of electron delocalization around the central cyanine framework and, in a modest way, by the donor and acceptor characteristics of the pyrrole substituents. It is, in fact, quite rare for Bodipy dyes to lack alkyl substituents at the pyrrole groups.

2.1. Basic Procedure

Construction of the starting dipyrromethene unit is based on the well-known pyrrole condensation reaction, developed originally for the synthesis of certain types of porphyrin. A highly electrophilic carbonyl compound (for example, acid anhydride, acyl chloride, or aldehyde) is used to form the methene bridge between two pyrrole units. The latter are usually substituted at one of the positions adjacent to the nitrogen atom to avoid polymerization and/or porphyrin formation. An excess of a non-substituted pyrrole is needed to obtain satisfactory yields of the corresponding naked dipyrromethene.[7,8] Such synthetic procedures rapidly lead to the isolation of symmetric F-Bodipy dyes after complexation of $BF_3{\cdot}OEt_2$ in the presence of a base, such as a tertiary amine,[5,9] as shown in Scheme 1.

Using this synthetic method, numerous Bodipy units have been built from readily available pyrroles, with the synthetic effort being focused on varying the nature of substituents located at the 8-position.[10–12] This strategy has allowed the connection of selective groups directly onto the Bodipy fluorophore without drastic change of their optical properties. Such approaches do not perturb the geometry of the

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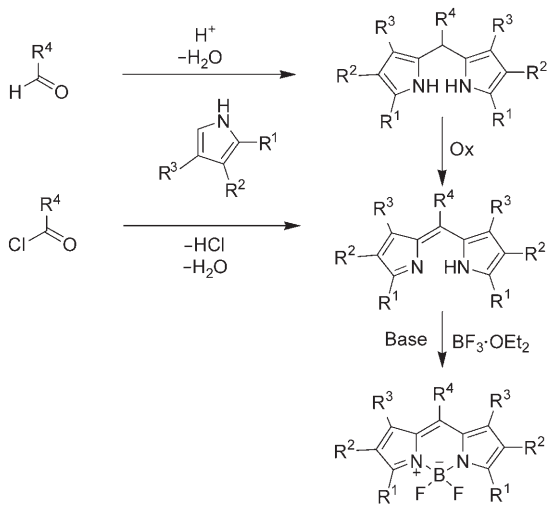
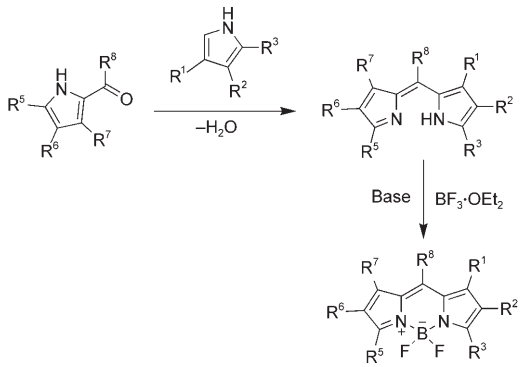
Anthony Harriman was at the Royal Institution (UK) for 14 years, where he was Dewar Research Fellow and Assistant Director of the Davy–Faraday Research Laboratory. He moved to the University of Texas at Austin in 1988 to become Director of the Center for Fast Kinetics Research (CFKR). He then went to the Department of Chemistry at the University of Newcastle (1999). His research interests include aspects of biophysics, especially electronic interactions in DNA. His work is moving towards the emerging field of molecular photoelectronics. He has published more than 350 research articles.



Scheme 1. Outline of a typical synthesis of symmetric F-Bodipy dyes. The base removes HF formed in the final step.

chromophore, they tend to avoid problems arising from steric hindrance, and have little tendency to modify the electron density on the Bodipy unit. A key point is that pyrrole substituents restrict rotation of aromatic groups attached at the 8-position and the resultant orthogonal geometry serves to minimize electronic coupling between the dye and the *meso* substituent. Many interesting chemical sensors have been formulated in this way (see Section 4), which continues to be the most popular route to functionalized Bodipy dyes.

Asymmetric Bodipy dyes are usually obtained by condensation of a carbonyl-containing pyrrole with a pyrrole molecule that is not substituted at the 2-position. Many Bodipy-based biological labels[3,4] are prepared by this particular method (Scheme 2). An active carboxylate group



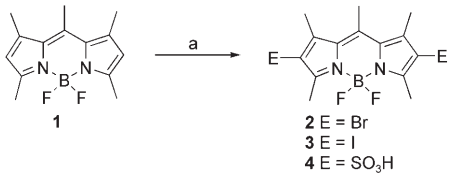
Scheme 2. General outline for the synthesis of asymmetric F-Bodipy dyes.

can be introduced at the 8-position by following a similar procedure. This synthetic route is useful for the preparation of reasonably large batches of dyestuff, although it tends to be expensive in terms of solvent wastage. Purification is best carried out by column chromatography followed by recrystallization. In general, these materials separate well on a chromatography column and can be purified to a high degree.

2.2. Chemistry on the Bodipy Core

2.2.1 Electrophilic Substitution

Treibs and Kreuzer[1] first realized that F-Bodipy dyes which are free of substituents at the 2,6-positions readily undergo electrophilic substitution reactions in the presence of chlorosulfonic acid. This high level of reactivity was exploited later by Boyer and co-workers as a means by which to synthesize water-soluble analogues.[13] Other electrophiles can be introduced in much the same way, thereby providing a facile route to the isolation of F-Bodipy dyes bearing bromine[14] or iodine groups[15] that are then available for further synthetic modification (Scheme 3). It should be noted

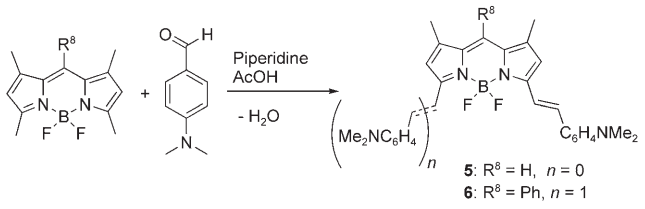


Scheme 3. General procedure leading to electrophilic substitution at the F-Bodipy unit. a) Electrophile in anhydrous solvent.

that this approach leaves the B–F bonds unscathed; the substitution reactions occur exclusively at the 2,6-positions, and is therefore a valuable route to selective substitution.

2.2.2 Active Methyl Groups

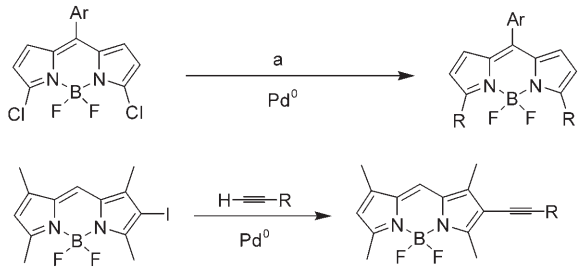
An F-Bodipy core bearing methyl groups at the 3,5-positions can be subjected to chemical modifications on the methyl carbon atoms owing to their strong nucleophilic character. These methyl groups can be deprotonated under mild conditions. The resultant intermediates will readily add to an electron-rich aromatic aldehyde, thereby generating a styryl group (Scheme 4).[3,16,17] This synthetic procedure has been used to extend the degree of π-electron conjugation and has the effect of introducing a pronounced bathochromic shift to both absorption and fluorescence spectral maxima. Furthermore, the intermediary carbenium ion can be oxidized in situ, leading to the corresponding 3-formyl derivative in quite respectable yield.[17]



Scheme 4. Introduction of styryl groups by addition–elimination steps with an adventitious aldehyde. Ac = acetyl.

2.2.3 Metal-Catalyzed Cross-Coupling

The presence of a halogen atom, either directly on the Bodipy core or attached to an aryl ring, facilitates further extension of the conjugation length and the building of more sophisticated structures through the use of palladium-catalyzed coupling reactions.[18] A halogen atom can be introduced onto the F-Bodipy core by way of a suitably substituted pyrrole,[19] with chlorinated dipyrromethene precursors,[20] or by electrophilic substitution onto the Bodipy unit.[12] Various types of coupling reactions, such as Sonogashira, Heck, Stille, or Suzuki, have been used to introduce ethyne, ethene, and aryl groups onto the F-Bodipy framework (Scheme 5). Again, it should be noted that the B–F bonds remain inert during such cross-coupling reactions.

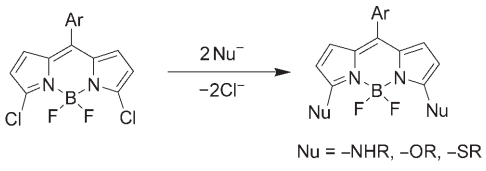


Scheme 5. Examples of palladium-catalyzed cross-coupling reactions on the F-Bodipy core. a) Reagents: $SnPh_4$ (R = Ph), or $ClC_6H_4B(OH)_2$ (R = *p*-ClC_6H_4), or styrene (R = CHCHPh), or phenylacetylene (R = C≡CPh).

The rational design of F-Bodipy dyes starting from 4-iodobenzoylchloride[21] leads to fluorescent materials that can be easily connected to certain aryl or heteroaryl groups through similar palladium(0)-catalyzed procedures. This method is preferred for assembling multicomponent molecular systems capable of intramolecular energy and/or electron transfer (see Section 3.1).

2.2.4 Nucleophilic Substitution of Leaving Groups

The presence of good leaving groups, such as chlorine atoms at the 3,5-positions of an F-Bodipy dye, allows the facile introduction of amino or alkoxy groups at these sites by nucleophilic substitution (Scheme 6).[22] A thiomethyl group at the 8-position is also an effective leaving group in the presence of an amine.[23]



Scheme 6. Selected example of nucleophilic substitution at the 3,5-position of an F-Bodipy dye.

2.3 Extending the Degree of π-Electron Conjugation

Obtaining F-Bodipy dyes exhibiting fluorescence in the far-red or near-IR regions of the spectrum requires the presence of an extended delocalization pathway. Several strategies are available by which to build this type of Bodipy dye. The most direct method is to synthesize pyrrole derivatives bearing phenyl, vinyl, or thiophene groups at the 3-position (Figure 4).[24,25]

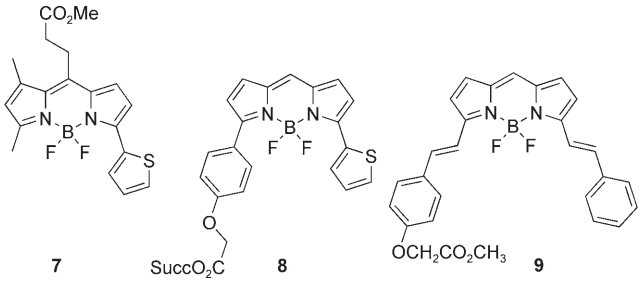


Figure 4. Examples of F-Bodipy dyes with extended π systems.

Derivatives with an additional benzene ring fused to the pyrrole group are well known and can be used as the basis of an alternative strategy for the introduction of a bathochromic shift (Figure 5), but it should be noted that isoindoles are not

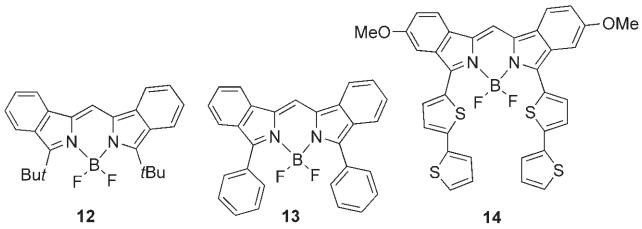
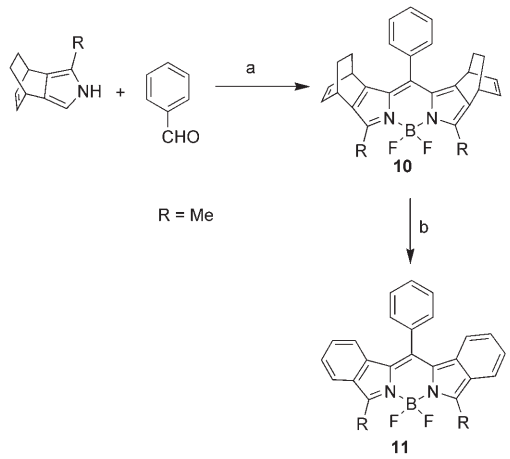


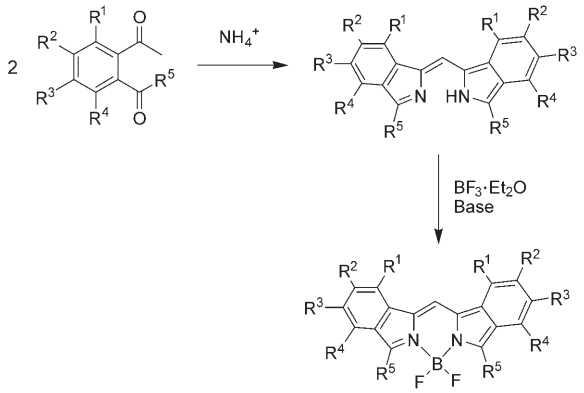
Figure 5. F-Bodipy dyes with a bis(isoindole)methene core.

suitable for the strategy described in Scheme 1. However, Urano et al. showed[26a] that the isoindole framework could be unmasked by a retro-Diels–Alder reaction (Scheme 7). This procedure provides an indirect route to functionalized F-Bodipy dyes starting from isoindole fragments.

Related dyes can be obtained by condensation of *ortho*-diacetophenone with an ammonium salt, followed by boron complexation (Scheme 8).[27] A different strategy employed to produce long-wavelength absorbing Bodipy-based dyes is to chemically modify the Bodipy framework (Figure 5). One such way to extend π-electron delocalization is by formation of a styryl group at the 3-position of the Bodipy unit by reaction of a methyl group with an active aldehyde in basic media. Conversely, a Wittig-type reaction can be carried out on a suitable aldehyde.[13] This latter strategy has been used recently with considerable success to generate a new class of ratiometric fluorescence sensors (see Section 4).



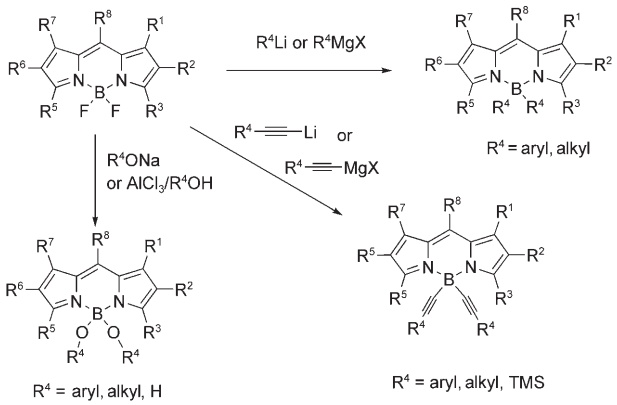
Scheme 7. Retro-Diels–Alder reaction used to extend the conjugation for an F-Bodipy dye. Conditions: a) trifluoroacetic acid, 4,5-dichloro-3,6-dioxo-1,2-benzenedinitrile (DDQ), iPr$_2$NEt, $BF_3{\cdot}OEt_2$ in CH_2Cl_2; b) 220 °C, 30 min.



Scheme 8. Synthesis of bis(isoindole)metheneboron derivatives from two equivalents of *ortho*-diacetylbenzene. See ref. [27] for details.

2.4. Modifications at the Boron Center

Few attempts had been reported that set out to substitute the fluorine atoms of an F-Bodipy dye until very recently, when Murase et al. registered a patent[28] reporting the replacement of the fluorine atoms with aryl groups. In this case, phenylmagnesium chloride was used to carry out the replacement. The organometallic approach has been further developed by Ulrich, Ziessel, and co-workers[29] and used to introduce aryl,[30] ethynylaryl,[31] and ethynyl[32] subunits in place of the usual fluorine atoms. These developments provided access to a library of highly stable C-Bodipy and E-Bodipy dyes and opened the way to the preparation of new diads and cascade-type dyes. Depending on the nature of the substrate, organolithium or Grignard reagents were used to efficiently substitute the fluorine atoms (Scheme 9). The properties and photophysical behavior of these new dyes will be discussed in Section 3. It should be stressed, however, that this simple strategy of carrying out substitution reactions at



Scheme 9. Selected methods for modification at the boron center. TMS = trimethylsilyl.

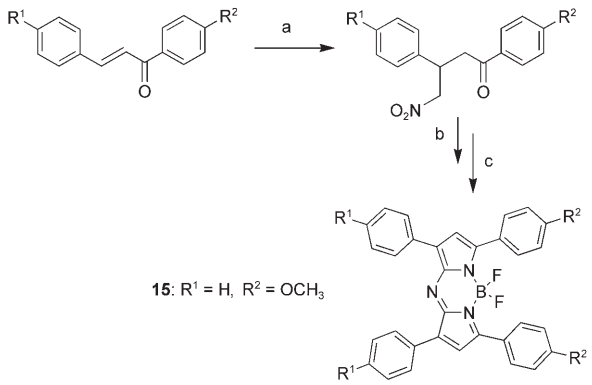
the boron center has led to a dramatic increase in the versatility of Bodipy dyes. In particular, it is now possible to synthesize sophisticated arrays in which different types of appended groups are positioned at the *meso* and boron sites. This approach allows the isolation of molecular triads, tetrads, and so on that were hitherto unimaginable.

The first reported example of an O-Bodipy dye involved displacement of the fluorine atoms with *o*-phenoxy groups located at the 3,5-positions in the presence of BBr_3.[33] Hiroyuki et al. referred to fluorine displacement using sodium alkoxides (Scheme 9) or thiolates in a patent.[34] This procedure was used recently to finetune the reduction potentials of fluorescent sensors for nitric oxide detection.[35] It is also of note that the fluorine atoms can be rather easily replaced with hydroxy groups in the presence of a strong Lewis acid.[36]

2.5. Related Structures

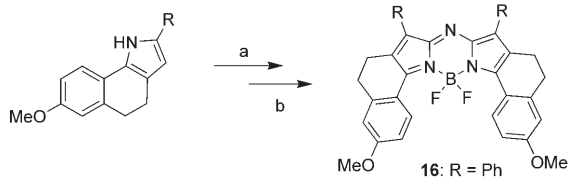
Very recently, interest has been increased in the 4-bora-3a,4a,8-triazaindacene dyes (commonly referred to as azabodipy dyes) owing to their efficient fluorescence in the far-red and near-IR regions of the spectrum. The nitrogen lone pair at the 8-position appears to contribute to the orbital levels of the actual cyanine framework, reducing the HOMO–LUMO energy gap relative to F-Bodipy dyes bearing similar substituents. Electrochemical measurements and molecular-orbital calculations could confirm this effect, which is responsible for the red-shifted absorption and emission maxima. To obtain azabodipy dyes, the main synthetic effort has been directed towards isolation of the azadipyrromethene precursor, with the boron center being coordinated to fluorine atoms in the usual way. This type of structure was first reported by Boyer and Morgan[37] who obtained the azadipyrromethene precursor by condensation of hydroxylamine with 1-oxopropionitrile[38] followed by $BF_3{\cdot}OEt_2$ complexation. The necessary research to obtain symmetric and asymmetric azabodipy dyes was conducted primarily by the groups of O'Shea and Carreira, motivated by the potential applications as biological labels, as sensitizers for photodynamic therapy,[39] and as luminescent proton sensors.[40]

O'Shea's method is based on the addition of nitromethane to a chalcone, followed by condensation with an ammonium salt (Scheme 10).[41] In contrast, Carreira and Zhao's restrict-



Scheme 10. Synthesis of an azabodipy dye. Conditions: a) CH_3NO_2, $HNEt_2$, MeOH, Δ; b) NH_4OAc (Ac = acetyl); c) $BF_3{\cdot}OEt_2$, Hünig's base, RT.

ed azabodipy dyes were obtained by reaction of a 2,4-diarylpyrrole with $NaNO_2$ in an acetic acid/anhydride mixture (Scheme 11).[42] In both cases, the F-azabodipy dye is obtained by complexation of $BF_3{\cdot}OEt_2$ in the presence of Hünig's base (*N*,*N*-diisopropylethylamine).



Scheme 11. Alternative synthesis of a restricted azabodipy dye. Conditions: a) HOAc, Ac_2O, $NaNO_2$ b) $BF_3{\cdot}OEt_2$, Hünig's base, RT.

3. Optical Properties: Energy Transfer

One of the features of Bodipy dyes is that it is possible to easily modify their molecular backbone, which provides further opportunities to vary their optical properties and to provide recognition sites for a variety of analytes. These dyes have sharp bands in the absorption spectra (half-widths typically being around 25–35 nm), large molar absorption coefficients (typically being in the region of 40000 to 110000 $M^{-1}cm^{-1}$), high fluorescence quantum yields (normally between 60 and 90%), reasonably long excited singlet-state lifetimes (these being around 1 to 10 ns), excellent chemical and photochemical stability in both solution and solid states, and versatile charge-transfer properties. The good solubility of these dyes in most common solvents (excluding water) should also be noted. In general, Bodipy dyes are resistant towards aggregation in solution. The absorption spectra recorded in solution or plastic films exhibit intense transitions that correspond to the S_0–S_1 process, together with clear vibrational fine structure, and a more modest set of transitions owing to absorption from S_0 to S_2 states. Both transitions usually show vibrational fine structure ranging from 1200 to 1400 cm^{-1} typical of the molecular C=C framework of the Bodipy core. When excited into either S_1 or S_2 states, strong fluorescence is observed from the S_1 state, which shows good mirror symmetry with the lowest-energy absorption band. No fluorescence has been observed from the S_2 state and it appears that internal conversion is quantitative. For selected spectroscopic data, see Table 1.

Under most experimental conditions, the fluorescence decay profiles are well described by monoexponential kinetics. In general, the radiative rate constants (ca. $10^8\,s^{-1}$) are quite high, owing to the strong absorption transitions, whilst the rate constants (ca. $10^6\,s^{-1}$) for intersystem crossing to the triplet state are relatively unimportant. The radiative rates calculated from the Strickler–Berg expression remain in excellent agreement with the experimental values. The excited triplet state can be detected by laser flash photolysis techniques, and has a lifetime on the order of several μs in the absence of molecular oxygen. There is only one report of low-temperature phosphorescence from a simple Bodipy dye,[43] for which the process required promotion of intersystem crossing by the external heavy-atom effect. Interestingly, triplet emission is also observed for a Bodipy dye equipped with an ancillary ruthenium(II) poly(pyridine) complex,[44] which functions as a triplet sensitizer. In both cases, phosphorescence is found around 780 nm, which indicates a rather low-lying triplet state.

3.1. Cassettes

A common problem found with organic dyes is that the Stokes' shift is too small for optimum use in flow cytometry and fluorescence microscopy. Synthetic strategies have been developed to circumvent this problem by covalent attachment of an ancillary light absorber to the Bodipy core to form a cassette. The intention is to channel all the photons absorbed by the secondary chromophore, which is usually an aromatic polycycle, to the Bodipy emitter. In this way, there is a large disparity in excitation and emission wavelengths and the full benefits of the Bodipy emitter are retained.[19,45] Some prototypic examples of such dual chromophore dyes are given in Figures 6 and 7.[46,47] An important feature of these systems is that the two chromophores remain electronically isolated because of the orthogonal arrangement around the connecting linkage. The rate of energy transfer depends on the structure of the dual-dye system and decreases with increasing center-to-center separation in line with a dipole–dipole transfer mechanism. The overall energy-transfer efficiency exceeds 90%, even in the most extended system.[45] Significantly faster energy transfer is found when the anthracene donor is attached to the long axis of the F-Bodipy acceptor, as in **18**, than if the donor is coupled to the short axis, as in **17**.[19]

Some new dual chromophore dyes are given in Figure 7. In each case, the aromatic polycycle, either pyrene, perylene, or a mixture of both, is attached to the boron atom. Whereas

Table 1: Spectroscopic data for selected Bodipy dyes.

Compound	Solvent	λ_{abs}/nm ($\varepsilon/\times10^4$ M^{-1} cm^{-1})	λ_{em}/nm	Φ/%	τ/ns	*E*/ V vs SCE	
						$B/B^{\bullet-}$	$B^{\bullet+}/B$
1[13]	EtOH	493 (7.9)	519	99	–	–	–
7[24]	$CHCl_3$/MeOH	546	564	19	–	–	–
8[24]	$CHCl_3$/MeOH	588	617	40	–	–	–
9[24]	$CHCl_3$/MeOH	637	652	48	–	–	–
10[26]	Hexane	529	544	90	5.96	−1.57	+0.67
11[26]	Hexane	599	605	91	5.71	−1.53	+0.33
12[27]	CH_2Cl_2	571	597	–	–	–	–
13[27]	MeOH	634 (10.8)	658	92	–	–	–
14[27]	MeOH	766 (6.5)	831	–	–	–	–
15[41]	$CHCl_3$	688 (8.5)	715	36	–	–	–
16[42]	CH_3CN	740 (1.6)	752	28	–	–	–
17[19]	$CHCl_3$	569	594	75	3.7	–	–
18[19]	$CHCl_3$	517	532	39	2.1	–	–
19[45]	CH_2Cl_2	528 (8.3)	544	90	7.0	−1.19	+1.02
20[45]	CH_2Cl_2	526 (6.0)	544	60	5.0	−1.32	+0.99
21[45]	CH_2Cl_2	532 (4.3)	545	68	4.3	−1.35	+0.99
22[46]	CH_2Cl_2	516 (7.5)	552	80	5.7	−1.74	+0.78
23[46]	CH_2Cl_2	526 (4.6)	562	19	2.0	−1.76	+0.78
24[31]	CH_2Cl_2	517 (7.8)	537	90	9.5	−1.58	+0.87
25[31]	CH_2Cl_2	516 (7.3)	537	94	6.2	−1.52	+0.89
		371 (9.5)	537	90			
26[47]	CH_2Cl_2	516 (6.3)	535	94	7.6	−1.47	+0.86
		464 (9.7)	535	93			
27[47]	CH_2Cl_2	516 (6.5)	535	95	6.2	−1.50	+0.87
		466 (4.7)		95			
		372 (5.1)		90			
28[51]	CH_2Cl_2	536 (6.7)	544	1	<1	−1.27	+1.13
29[51]	CH_2Cl_2	529 (7.15)	542	1	1.3	−1.32	+1.02
30[51]	CH_2Cl_2	524 (6.8)	540	72	10.6	−1.32	+1.02
32[52]	CH_3CN	503	514	69		−1.42	+1.62
33[54]	Et_2O	498	509/615[a]	1.2/5[a]	0.01/3.5[a]	–	–
34[54]	Et_2O	498	510/613[a]	0.4/5[a]	0.015/3.6[a]	–	–
35[55]	CH_2Cl_2	718 (7.25)	784	29	0.8	–	–
36[57]	MeOH	534 (11.0)	542	2	–	–	–
38[58]	CH_2Cl_2	667 (8.8)	702	56	6.5	–	–
39[58]	CH_2Cl_2	720 (9.0)	754	33	7.2	–	–
40[62]	CH_3CN	498	509	3	–	–	–
41[62]	CH_3CN	499	528	0.5	–	–	–
44[68]	Hexane	623	631	92	4.9	–	–
45[69]	$CHCl_3$	504	515	–	–	–	–
47[72]	$CHCl_3$	572	585	1.0	3.8	–	–
48[73]	Et_2O	594 (9.8)	638	83	3.8	–	–
50[75]	CH_3CN	529	565	0.6	–	–	–
52[77]	Et_2O	501	510	32	1.8	–	–
56[82]	H_2O/DMSO[b]	496 (7.3)	505	0.1	–	–	–
57[82]	H_2O/DMSO[b]	498 (5.2)	507	40	–	–	–
58[85]	H_2O[c]	499	509	0.3	–	–	–
59[86]	CH_3CN	600	656	12	–	–	–
60[90]	CH_3CN	498 (1.2)	516	39	–	–	–
61[91]	CH_2Cl_2	529 (7.2)	548	87	5.3	−1.14	+1.11
63[100,102]	CH_3CN	491 (8.1)	501	95	5.2	−1.18	+1.22
64[100,102]	CH_3CN	514 (7.9)	531	87	5.6	−1.29	+1.02
65[100,102]	CH_3CN	521 (6.8)	557	41	3.9	−1.24	+1.01
66[105]	CH_2Cl_2	525 (6.20)	538	50	7.3	–	–
67[106]	CH_2Cl_2	510 (3.25)	539	25	5.1	–	–

[a] The low energy absorption and emission band correspond to a photoinduced charge transfer transition. [b] Phosphate buffer. [c] Tris HCl buffer.

the absorption spectral profiles contain important contributions from each of the subunits, fluorescence occurs exclusively from the Bodipy fragment.[47] Intramolecular excitation energy transfer is extremely efficient in each case, even though spectral overlap integrals for the pyrene-based system are modest. Although sterically congested, molecular dynam-

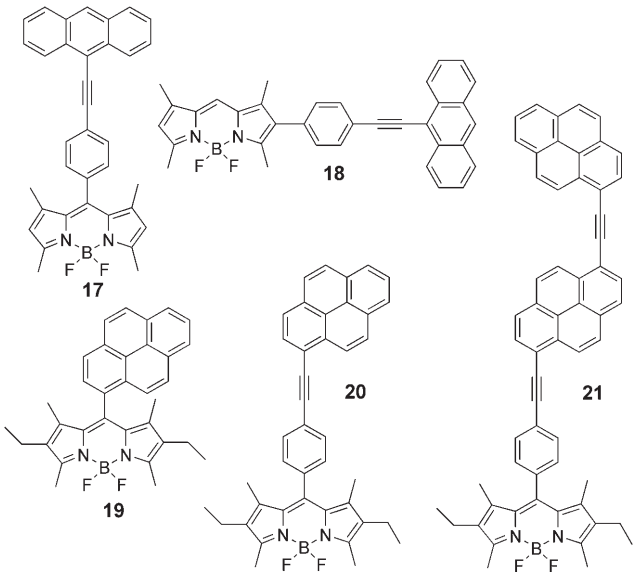


Figure 6. Selected examples of F-Bodipy dyes grafted with anthracene or pyrene residues as ancillary light absorbers.

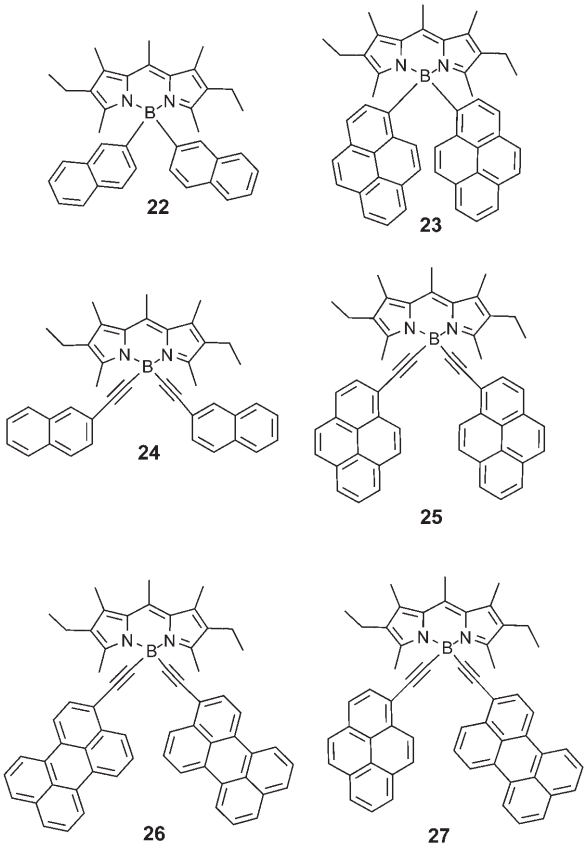


Figure 7. Selected examples of C-Bodipy and E-Bodipy dyes equipped with naphthalene, pyrene or perylene moieties.

ics simulations indicate that the polycycles are in dynamic motion and this fact prevents meaningful computation of the orientation factors for Förster-type energy transfer. These new dyes, especially the mixed polycycle system, greatly extend the range of excitation wavelengths that can be used for fluorescence microscopy.

The new dual-chromophore dyes display extremely fast intramolecular energy transfer from the polycycles to the Bodipy residue. Similar behavior has been noted before for polycycles attached to the indacene core and the rates appear comparable for the different systems.[46,47] The ease of synthesis and, in particular the ability to isolate asymmetrical derivatives, is a clear advantage of the boron-substituted dyes. There is no reason why the synthesis cannot be extended to include other polycyclic substituents nor why cross-functionalized dyes, having additional substituents covalently linked at the indacene backbone, cannot be prepared. An interesting feature of these E-Bodipy dyes is that the substituent does not affect the photophysical properties of the Bodipy unit; which is in marked contrast to the corresponding F-Bodipy dyes, in which the absorption and fluorescence spectral profiles can be tuned over a wide range. The ethynyl substituent merely functions as an ancillary light harvester for near-UV photons. In this respect, the asymmetric derivative **27** is the most attractive dye, as it collects photons across most of the accessible spectral range. This compound fluoresces strongly when dispersed in polymeric media and acts as a highly efficient solar concentrator. It also provides a large virtual Stokes' shift, displaying several clear absorption peaks that are useful as markers for chemical sensors. The fluorescence quantum yield is independent of temperature and excitation wavelength and relatively insensitive to changes in the polarity of the surrounding medium.[47]

Intramolecular excitation energy transfer appears to be consistent with the Förster dipole–dipole mechanism, at least for the perylene-based chromophore. It is possible that the rate of energy transfer is augmented by Dexter-type through-bond interactions, given the short separation and conjugated ethynylene linker. This linker is an effective bridge for electron-exchange processes. The ability to tunnel through the central boron atom is an unknown entity, however, and it has not been necessary to invoke the Dexter mechanism in our work.[47]

The final point of interest concerns the possibility of setting up a cascade effect in the asymmetric derivative **27**. In such a scenario, photons absorbed by the pyrene unit can be transferred directly to the Bodipy S_2 state, in accordance with model calculations, or to the perylene unit. This unit is perfectly placed to act as an energy acceptor. Calculations, using suitable reference compounds,[47] predict that the Förster-type energy transfer from pyrene to perylene could compete with direct transfer to the dye but this result has not been confirmed experimentally.

In certain cases, it has been shown that Dexter-type electron exchange can compete with Förster-type energy transfer provided the reacting units maintain quite strong electronic communication.[48–50] For any given system, the actual mechanism for intramolecular energy transfer will depend on the nature of the reactants, their mutual separation distance, the surrounding environment and the type of linkage. That both Dexter and Förster mechanisms operate is an added bonus and suggests that new diads might be designed that display very fast energy transfer.

3.2. Electron-Transfer Reactions

Photoinduced electron transfer (PET) is a well-known mechanism through which the fluorescence of a fluorophore is quenched in a polar environment at ambient temperature. A common strategy is to incorporate either an amino donor (such as a tertiary amine) or a nitro acceptor (for example, a nitroaromatic residue) close to the Bodipy dye such that electron transfer can compete with fluorescence (Figure 8).

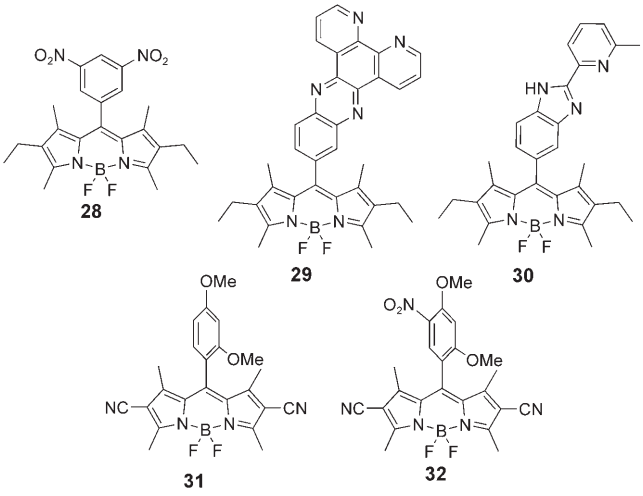


Figure 8. Examples of donor–acceptor diads based on F-Bodipy.

This approach can be used to design fluorescent probes, and in particular pH indicators. The thermodynamics of the system have to be poised such that efficient electron transfer occurs in the "off" state, thereby ensuring minimal fluorescence. Coordination of the proton or metal ion to the quencher raises the relevant reduction potential to such a level that fluorescence is restored. Thus, the "on" state displays the fluorescence properties inherent to the Bodipy nucleus.

Several studies have described photoinduced electron transfer from the Bodipy unit to nitro or phenazine fragments[51] or from a dimethoxybenzene donor to the Bodipy unit.[52] Replacing phenazine with an indole fragment decreases the thermodynamic driving force for light-induced electron transfer to the extent that the characteristic fluorescence signal is restored. Interestingly, the dicyano derivative **32** is subject to extensive fluorescence quenching. Addition of a nitronium ion, however, restores the fluorescence as a consequence of nitration of the phenyl ring, which decreases significantly the electron-donating ability of the phenyl ring. These fluorescence probes might find application in biological samples submitted to nitric oxide (NO) stress.

3.3. Intramolecular Charge Transfer

Photoinduced charge transfer (PCT) is closely related to PET but usually the π system responsible for the emission (Bodipy) and the anilino donor are held orthogonal to one another, which minimizes electronic coupling. Of course, an orthogonal geometry is not a requirement for light-induced charge transfer, but it certainly helps to slow down the rate of charge recombination, thereby allowing fluorescence to take place with reasonable efficacy. Normally, for such systems the bands in the absorption spectra are fairly narrow and characteristic of an unperturbed Bodipy dye. However, the fluorescence spectra are strongly dependent on the polarity of the solvent. The fluorescence yields are quenched in polar solvents but not in non-polar media and, in some cases, dual emission is observed, for example, for compound **33** (Figure 9).[53] The change in dipole moment resulting from PCT

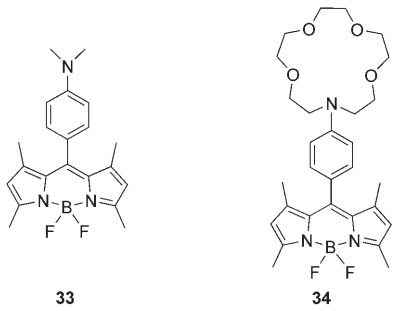


Figure 9. Examples of prototypic Bodipy-based dyes that exhibit charge-transfer fluorescence.

induces a large Stokes' shift, the magnitude of which depends on the environment around the fluorophore. It can be anticipated that a cation, or a proton, in close interaction with the electron-rich donor will drastically change the efficiency of PCT and, consequently, modulate the fluorescence yield and/or spectral properties. A particularly interesting case arises when a coordinated cation switches off the fluorescence that accompanies charge recombination and restores the typical Bodipy-like fluorescence. A variety of PCT sensors have been built from macrocyclic chelates and display severe on–off fluorescence changes on cation binding. Some of these materials include Bodipy labels modified in the 8-position with tertiary amines or azareceptors (Figure 9).[54]

3.4. Near-IR Emitters and Singlet Oxygen Sensitizers

Several different approaches are available that shift the emission wavelength of the Bodipy-based fluorophore towards lower energy. A relatively facile method involves extending the degree of π conjugation running through the central core (Figure 10). For example, distyrylboradiazaindacenes have been prepared from the corresponding 3,5-dimethyl derivatives and the resulting dyes show pronounced charge-transfer character, with much reduced fluorescence quantum yields in polar solvents.[55] Water-soluble dyes were subsequently obtained by functionalization with oligo(ethyleneglycol) residues. These latter materials show good permeability into intact biological cells and tumor-targeting

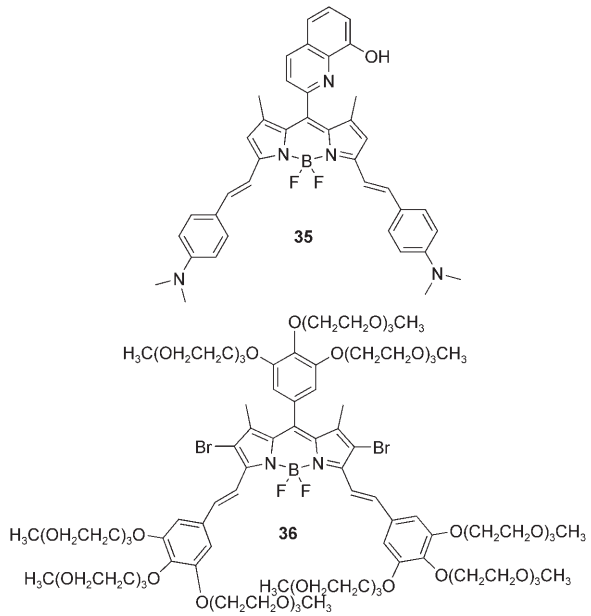


Figure 10. Selected examples of distyryl containing F-Bodipy dyes.

characteristics that make them interesting candidates for sensitizers in photodynamic therapy.[56]

The valuable light-absorbing properties are offset, however, by the very poor triplet yields inherent to Bodipy-based dyes. This problem can be overcome to some extent by attaching heavy atoms, such as iodine, directly to the Bodipy nucleus of **37** (Figure 11), thereby favoring intersystem crossing to the triplet state. The fluorescence efficiency drops from 70% to 2% compared to the reference dye which lacks iodine groups. Under aerobic conditions, $^1O_2$ is generated with modest efficiency on illumination and cellular toxicity has been reported.[57]

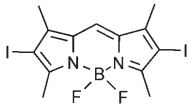


Figure 11. An efficient singlet oxygen generator based on an F-Bodipy dye.

Tailoring the nature of the central unit to give a rigid, bis(isoindolo) core offers further potential for the construction of a large set of dyes emitting in the near-IR region (Figure 12). In particular, substitution at the 3,5-positions of F-Bodipy with anisole or ethylthiophene residues substantially increases the extent of π-electron conjugation and pushes the absorption maximum to 673 and 727 nm, respectively. In accord with the exponential energy-gap law, there is a decrease in the fluorescence quantum yield, from 49 to 20%, as the emission maximum moves towards lower energy. The strategy of conducting chemistry at the boron center using ethynylaryl Grignard reagents opens up the route to produce the Cascatelle-type dyes for which the virtual Stokes' shift exceeds 13000 cm^{-1}.[58] (Cascatelle is the French term for a small cascade.)

A novel approach to the design of Bodipy-based dyes that emit at long wavelength involves equipping the chromophore with an empty coordination site able to complex transition-metal ions. The intention is to benefit from the heavy-atom effect to favor population of a low-lying triplet excited state that can phosphoresce[44] (Figure 13). In both cases shown in Figure 13, very weak emission from the Bodipy triplet is observed at low temperature and lies within the 770 to 800 nm range.[59] This achievement is quite remarkable considering that phosphorescence from Bodipy dyes is very rarely seen.[43] The actual mechanism for population of the Bodipy triplet state depends on the nature of the compound and on the excitation wavelength. Several potential energy-transfer steps are available, including triplet–triplet energy transfer from the metal complex to the dye.

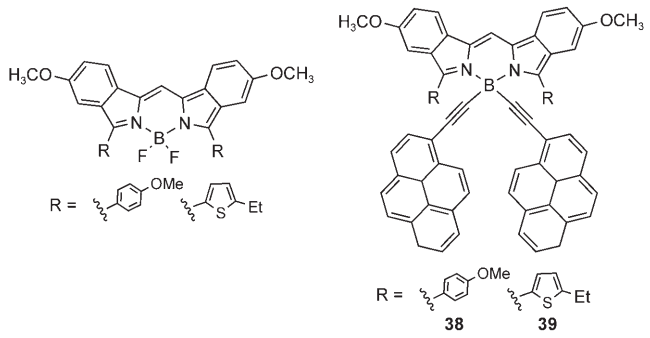


Figure 12. Examples of bis(isoindolo) Bodipy dyes.

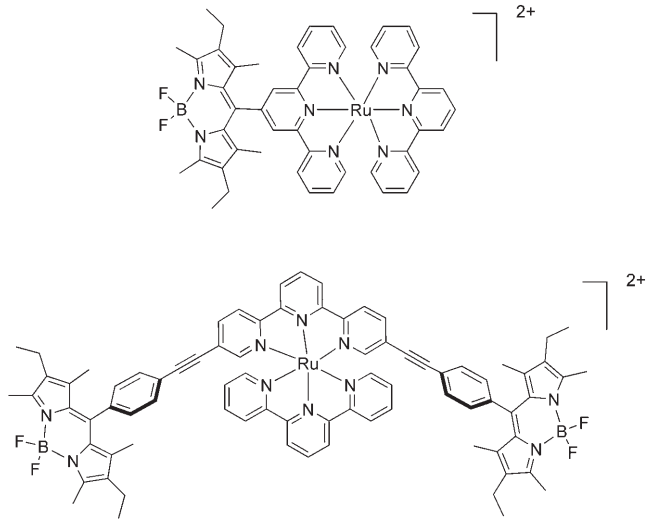


Figure 13. Examples of F-Bodipy dyes grafted with ancillary ruthenium(II) poly(pyridine) complexes that function as triplet sensitisers.

Near-IR luminescence in the region of 900 to 1600 nm was obtained by complexing a Bodipy core with Yb, Nd, or Er units (Figure 14). Irradiation into the S_1 state localized on the Bodipy center causes energy transfer that populates excited states on the lanthanide ion. The efficiency for this energy-transfer step depends markedly on the relative positioning of the energy levels involved.[60]

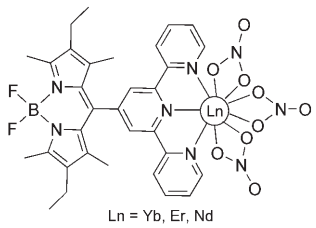


Figure 14. An example of a Bodipy-based diad that shows sensitized emission from the lanthanide cation in the near infrared region.

3.5. Bodipy Dyes Bearing Ancillary Radical Centers

The synthesis of dual probes constructed from a fluorescent module, notably a Bodipy dye, and a covalently bound radical leads to combined sensors that can be detected by fluorescence, NMR, and ESR spectroscopic methods.[61] In these hybrid systems, the paramagnetic radical (e.g., a stable nitroxide free radical) quenches fluorescence from the Bodipy-based dye by one of several mechanisms, but fluorescence is restored when the nitroxide is reduced to the corresponding hydroxylamine. The most important application of these systems is the detection of oxyradicals in situ. Thus, any oxyradical will react with the nitroxide precursor to form the more stable nitroxide radical. This reaction is accompanied by a decrease in fluorescence from the accompanying Bodipy dye, as long as the radical center resides reasonably close to the dye. Examples of known spin carriers of this type are shown in Figure 15.[62] These Bodipy–radical hybrids can also interact with cations or electrons and are considered to be good candidates for Boolean logic-gate applications.

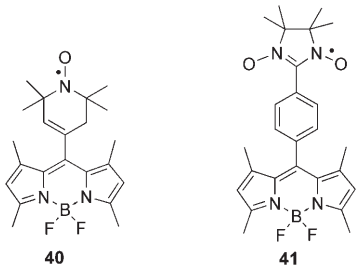


Figure 15. Examples of F-Bodipy dyes bearing ancillary spin carriers.

Magnetic properties can be influenced by external stimuli and, in particular, the use of photons can give key information on the control of molecular spin. Coupling spin alignment to photoinduced electron- or energy-transfer processes is an emerging research target. For example, linking a Bodipy dye, which functions as a light-activated electron acceptor, to an photoactive anthracene moiety, which also acts as the electron donor, and to a verdazyl π radical provides a unique opportunity to generate a spin-polarized quartet induced by an ion-pair state (**42**, Figure 16).[63]

A local electrical field has been used to influence the rate constants for photoinduced electron transfer and subsequent charge recombination of the resultant ion pair in multicomponent prototypes bearing Bodipy units (**43**). In such molecular architectures, state switching is controlled by fast optical pulses and offers many interesting possibilities to develop electronic devices that function at the molecular scale.[64]

4. Chemical Sensors

The development of efficient sensors that operate by fluorescence modulation is of great interest in analytical chemistry and for the clinical, medical, and environmental sciences.[65] The key feature of all such applications is that the trapping of an analyte at some pre-designed site, such as a cavity inside a macrocycle or a hydrophobic patch, causes a pronounced change in the fluorescence properties of the sensor. Recognition of the analyte in this manner can increase or decrease fluorescence but, in general, a better analytical procedure is when the presence of the analyte causes the appearance of fluorescence. In many cases, improved sensi-

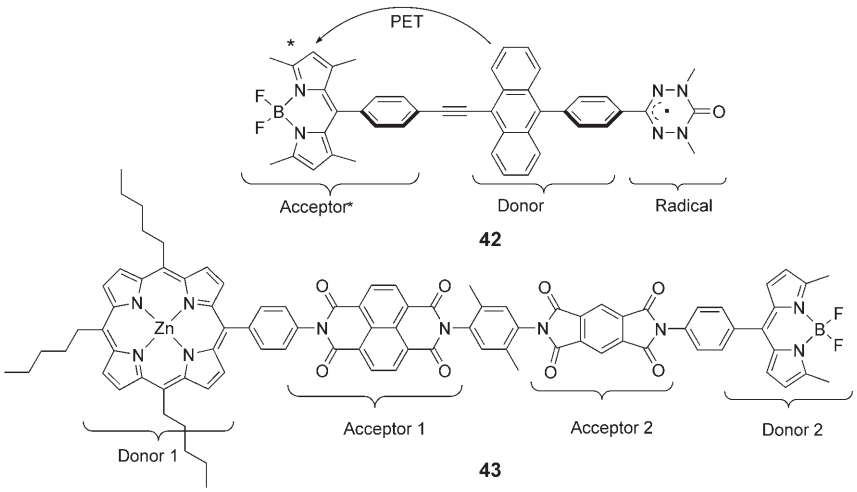


Figure 16. Examples of multicomponent donor–acceptor molecules based on F-Bodipy.

tivity can be obtained when the sensing event perturbs a charge-transfer excited state or interrupts intramolecular electron transfer.[66] Daub and Rurack[67] were the first to show the high potential for Bodipy dyes in this field, and their original research has been followed by countless examples of Bodipy-based fluorescent molecular sensors. A brief summary of the field is given in Sections 4.1–4.5.

4.1. pH Sensors

There is a very comprehensive range of fluorescent dyes that can be used as pH indicators and as chemical sensors for protons present in organic media. Their mode of operation is apparent from close examination of compound **33** (Figure 9). The availability of a strong electron donor close to the Bodipy chromophore ensures that efficient intramolecular charge transfer from the dimethylamino nitrogen atom to the excited singlet state of the Bodipy dye occurs upon illumination with visible light. The normal Bodipy fluorescence is extinguished in favor of charge-recombination fluorescence. The nitrogen donor can be protonated at low pH value or upon addition of acid to an organic solvent, so that light-induced electron transfer is curtailed. This protonation results in the restoration of normal Bodipy fluorescence.[67] By changing the nature of the donor, or by systematic alteration of its reduction potential, the pH range over which fluorescence modulation occurs can be tuned. The wavelength range can be varied by careful choice of the Bodipy dye, as exemplified for the near-IR emitter **44** (Figure 17).[68] Related systems are also known;

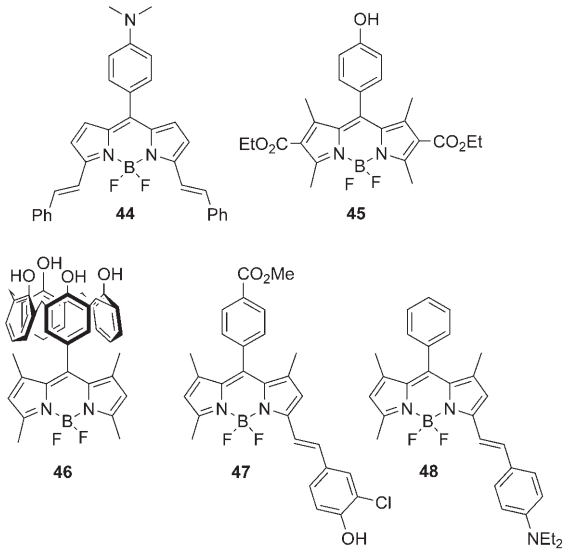


Figure 17. Selected examples of F-Bodipy dyes functionalized with secondary groups that undergo pH-induced transitions.

for example, compound **45** bears a phenolic residue that is deprotonated at high pH value. The thermodynamic driving force for light-induced electron transfer from the phenol to the Bodipy dye is strongly dependent of the state of protonation of the phenol, thereby allowing pH measurements to be made in alkaline solution.[69] Other molecular architectures coupling different phenolic functions to a generic Bodipy core serve to extend the workable pH range. Related structures have calixarene, **46**,[70] or naphthol[71] groups attached to the Bodipy *meso* position. Again, building a styryl connection at the 3-position offers an easy route to produce systems working at long wavelength and able to monitor at high pH value, as illustrated by **47**,[72] or in the presence of acid, as found for **48** (Figure 17).[73] Similar systems can be envisioned that operate as chemical sensors for simple cations in solution (see Sections 4.2–4.4).

4.2. Crown-Ether-Based Sensors

The preferred strategy for using fluorescent dyes to monitor cations employs a functionalized macrocycle to trap the target ion, with the selectivity being set by the size and coordination sphere offered by the macrocycle. To switch off an intramolecular charge-transfer process, upon substrate recognition, it is normal practice to incorporate a suitable nitrogen donor group into the macrocyclic structure but sufficiently close to the Bodipy core to facilitate light-induced electron transfer. Compound **34** (Figure 9) is typical of this class of chemical sensor. Thus, cations accommodated within the crown-ether void coordinate to the nitrogen lone pair, raising its reduction potential and thereby eliminating the thermodynamic driving force for intramolecular electron transfer to the singlet-excited state of the Bodipy dye. The result, of course, is the reappearance of normal Bodipy fluorescence. Only those cations included into the macrocycle restore fluorescence, and by calibration of the system using fluorescence-spectroscopic titrations, the concentration of cation is easily measured from relative changes in fluorescence yield. Improvements can be obtained using time-resolved fluorescence spectroscopy to record emission lifetimes, as the free and bound species usually give quite disparate decay rates. By changing the nature and/or site of attachment of the macrocycle, it becomes possible to design suitable chemical sensors for most simple cations.[74] Considerable versatility is possible in this field and some highly unusual macrocyclic structures have been reported, such as compound **49**[75] which is used for detecting potassium cations, and compound **50**, which offers good potential for detecting sodium cations[76] (Figure 18).

The use of sulfur-containing macrocycles or open-chain systems extends detection to transition metals and mercury salts. For example, a Bodipy dye bearing an aminotetrathio-[15]crown-5 at the *meso* position **51** (Figure 19) has proved to be a good sensor for mercury(II) salts.[77] Size contraction, leading to compound **52**,[78] or ring opening, as in **53**,[79] have led to the development of efficient sensors for iron(III) or copper(I) salts, even in living cells (Figure 19). Association of two Bodipy dyes possessing quite disparate optical properties and a crown ether provides an elegant way to obtain sensitive ratiometric fluorescent chemosensors for mercury(II), as **54**[80] (Figure 19) or for silver(I).[81]

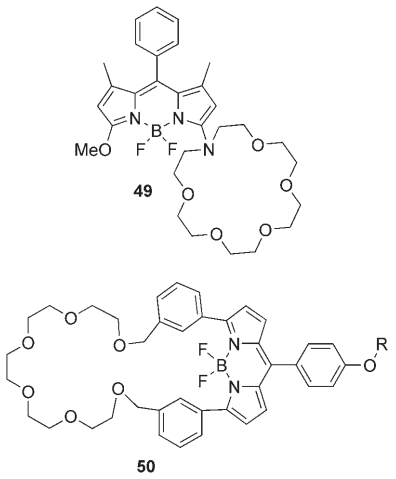


Figure 18. Examples of F-Bodipy dyes bearing appended macrocycles able to bind adventitious cations.

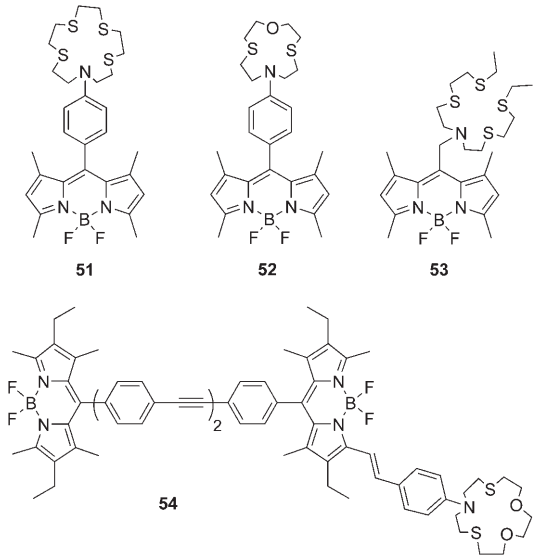
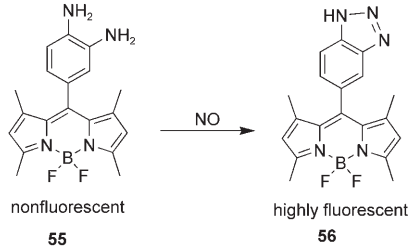


Figure 19. Selected examples of F-Bodipy dyes functionalized with sulfur-based chelating sites.

4.3. Anilino-Based Recognition Sites

Some particularly interesting chemical sensors have been constructed by attaching aniline derivatives to F-Bodipy. Thus, Nagano et al.[82] and Zhang and co-workers[83] have observed regeneration of Bodipy fluorescence after reaction of the aromatic amine residue with both NO and NO_2^- (Scheme 12).[84]. The detection of NO in situ has many obvious biomedical implications and is a challenging topic, and these particular sensors hold considerable potential.

Anilino derivatives equipped with flexible coordination arms can be used to recognize certain transition metals. For example, compounds **57**[85] and **58**[86] (Figure 20), can be used to detect zinc(II) and cadmium(II) ions, respectively, in intact biological cells.[87] Alcohol or ester functions seem more suitable for detection of lead(II) or copper(II) salts.[88] In many of these cases, several mechanisms contribute towards



Scheme 12. A Bodipy-based chemical sensor for the detection of NO.

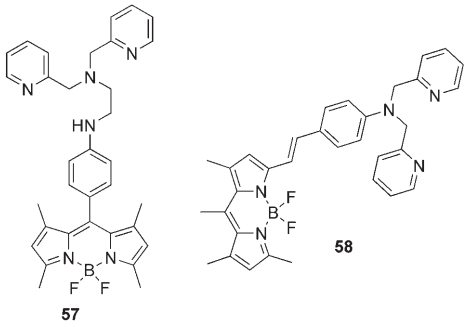


Figure 20. Selected examples of F-Bodipy dyes equipped with secondary anilino functions.

fluorescence modulation and it is not possible to give an unambiguous description of the underlying chemistry. The Bodipy dye is a good candidate for use in such systems because of its high versatility.

4.4. Pyridine-Based Chemical Sensors

When a pyridine or an oligopyridine,[89] such as 2,2′-bipyridine **59**[90] or 2,2′:6′,2″-terpyridine **60** (Figure 21)[91] replaces aniline in the chemical sensors shown in Figure 20, there is no inherent quenching of the Bodipy fluorescence, as these units are not electrochemically active at normal potentials. In many cases, however, cation coordination to the unbound nitrogen atoms induces intramolecular charge transfer, with concomitant quenching of the Bodipy fluorescence. Such behavior occurs when zinc cations are added to a

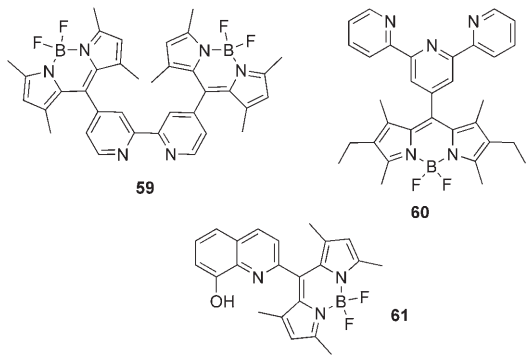


Figure 21. Examples of F-Bodipy dyes functionalized with oligo-(pyridine) residues suitable for coordination of added cations.

solution of the terpyridine-based reagent **60**[91] (Figure 21); absorption and fluorescence spectral profiles are dominated by contributions from the Bodipy unit. Zinc cations bind to the vacant terpy ligand to form both 1:1 and 1:2 (cation/ligand) complexes, as seen from X-ray structural data, NMR spectroscopy, and spectrophotometric titrations. Attachment of the cations is accompanied by a substantial decrease in fluorescence from the bodipy chromophore owing to intramolecular electron transfer across the orthogonal structure. At low temperature, nuclear tunneling occurs and the rate of electron transfer has essentially no activation barrier. However, activated electron transfer is seen at higher temperatures and allows calculation of the corresponding reorganization energy and electronic coupling matrix element. In both cases, charge recombination is faster than charge separation.[43] The corresponding hydroxyquinoline-based Bodipy dye **61** (Figure 21) acts as an efficient fluorescence-based sensor for mercury(II)[92] and for copper(II) ions[93] in solution.

4.5. Related Systems

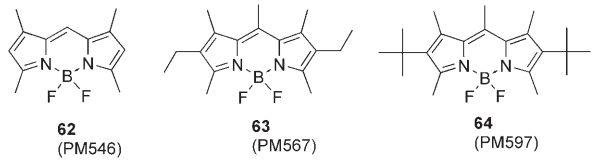
A great number of other Bodipy-based fluorescence sensors have been reported. Notable among these reagents is an optically active binaphthol derivative that offers chiral discrimination.[94] Also noteworthy is the Bodipy dye equipped with an aryl boronic acid residue that can be used to detect fructose.[95] The high DNA affinity of the Bodipy–pyrene couple was revealed by fluorescence quenching upon intercalation into the duplex.[96] A limited amount of anion detection has been described using free **59** (Figure 21) or its corresponding zinc complex, respectively, for fluoride ions[97] and phosphate.[98]

5. Luminescent Devices

5.1. Electroluminescent Devices

An interesting feature of most Bodipy dyes, in common with porphyrins and several other classes of fluorescent dyes, is that the main structural framework undergoes reversible oxidation and reduction processes at accessible potentials.[89] This feature has resulted in Bodipy being used as both an oxidative and reductive sensitizer, as outlined briefly in Section 4. Furthermore, the various types of substituent attached at any of the available sites can also partake in electrochemical reactions so as to produce electroluminescent materials for use in organic light-emitting diodes (OLEDs). Indeed, functionalized Bodipy dyes have been used for electrogenerated chemiluminescence (ECL) by alternating the applied potential so as to form the radical cation and anion in rapid sequence. Many different dyes have been tested in this way, leading to correlations between electrode activity and molecular structure.[67] In general, dyes with a lower degree of substitution show higher fluorescence efficiency while the lack of electron-donating substituents in positions 2, 6, and 8 cause a decrease in the stability of the radical ions, leading to irreversible electrochemical processes (Figure 22). This instability gave rise to poor ECL behavior, in addition to formation of a film on the electrode. Appropriate substitution with donating groups provides for moderately intense ECL signals that correlate well with the respective fluorescence efficiencies in solution.[99] Doping of poly(*N*-vinylcarbazole), a well-known hole-transporting material, with an appropriate Bodipy dye can be used to produce electroluminescence over an unusually wide range of colors.[100]

Bright green emission is observed when **60** (Figure 21) is incorporated as the dopant (< 1 %) in a double-layer OLED using a metal-based, electron-transporting matrix (Alq_3). Within this device, complete quenching of emission from Alq_3 occurs because of efficient energy transfer to the Bodipy unit. This latter component, despite being present at low concentration, is responsible for the observed emission. The vacant terpyridine site aids solubility in the matrix and decreases the aggregation ability of the dye.[101]



62 (PM546) **63** (PM567) **64** (PM597)

Figure 22. The positioning of alkyl groups on the periphery of an F-Bodipy dye (numbers in brackets refer to the laser dye name).[102]

The Bodipy unit in **60** acts merely as an exciton trap and its value stems from it being a strong emitter in the green region. Other types of Bodipy-based dyes have been developed to function as both light emitter and hole-transfer agent. To conceive highly efficient OLEDs, with good stability during long-term operation, it has proved necessary to replace all the alkyl substituents with condensed arene rings (Figure 23). These arene rings help to extend the conjugation of the π system. As a result, the emission wavelength is shifted to the red region but the quantum yield remains fairly high. The hole-transport properties are provided by the appended aryl amine, with both symmetric and asymmetric derivatives being available.[103]

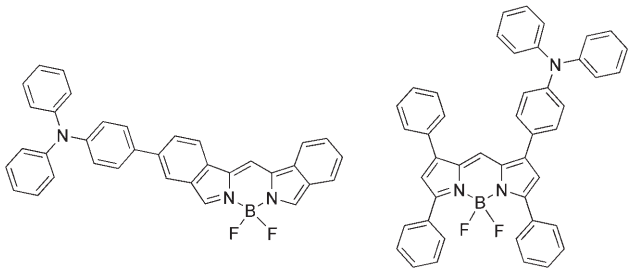


Figure 23. Selected examples of F-Bodipy dyes having condensed phenylene rings (left) to improve the optical properties and being equipped with secondary units (right) to improve hole transport.

5.2. Mesomorphic Materials

The rational design of segmented Bodipy dyes that possess useful chemical, optical, electrochemical, or biological functionalities and are able to self-assemble into predictable and tunable supramolecular assemblies such as micelles, liposomes, microcapsules, dendrimers, gels, and liquid crystals is a rapidly expanding research area. There is a need to identify new materials that are easily manufactured in large quantities and that possess valuable properties in terms of color and stability. In this respect, attention has turned towards soft materials, such as liquid crystals, and robust organogels, and considerable effort has gone into the systematic modification of the Bodipy architecture to enable its incorporation into such supramolecular assemblies.[104,105] Entangled three-dimensional networks of fibers entrapping solvent molecules have been produced by grafting paraffin chains onto preorganized platforms carrying amido functions (Figure 24). Balancing the molar ratio of paraffin chains and

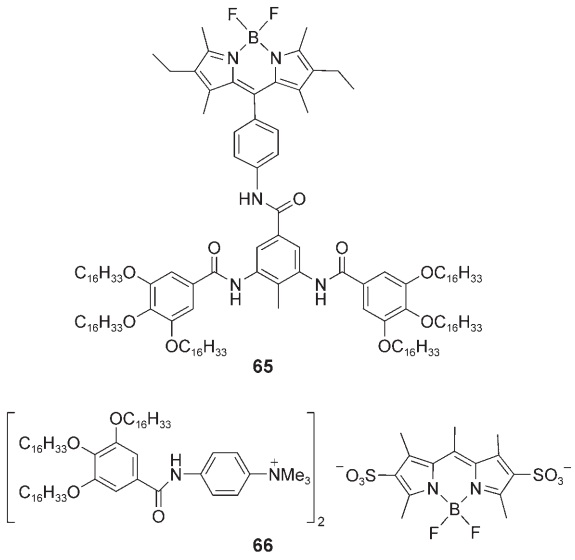


Figure 24. Self-assembly of functionalized Bodipy dyes into columnar liquid crystals.

the rigid aromatic core provides columnar mesophases, the symmetry of which depends strongly on weak intermolecular interactions.[105] The ionic self-assembled adducts shown in Figure 24 are known to generate columnar liquid-crystalline materials and thin films that are stable over a wide temperature range. The flexibility introduced by the ready exchange of ionic components and the use of highly fluorescent templates, such as sulfonated Bodipy dyes, allows the emergent mesomorphic textures to be monitored by fluorescence microscopy without the need for crossed polarizers.[106]

6. Biological Labeling

A considerable volume of work involving Bodipy fluorophores has focused on their use as labeling reagents for biological materials. The favorable photophysical properties inherent to this family of dyes, including large absorption coefficients, high fluorescence quantum yields, relative insensitivity to changes in polarity and pH value,[107] narrow emission profiles, nanosecond excited-state lifetimes, large range of colors, and improved photostability relative to fluorescein, make for a commercially attractive product.[108] With the exception of recent developments in the use of Cascatelle dyes,[29] most of labeling studies have involved the use of commercial materials bearing an anchor with which to attach the dye to the biological host. Little chemistry has been developed on the boradiazaindacene core for this purpose since the pioneering work of Haughland, Kang, Pagano, and co-workers.[3,109] These important applications of Bodipy dyes falls outside the scope of this Minireview but merit their own compilation.

7. Concluding Remarks

With regard to the design of fluorescent labels for analysis in situ, Bodipy dyes offer many significant advances over other dyes. Indeed, tagging a Bodipy dye to a speciality antibody should provide biological labels of unparalleled sensitivity and selectivity. The high fluorescence yield also ensures that these dyes have important applications in analytical science, OLEDs, solar concentrators, and as registers in molecular electronics. Part of the success of Bodipy-based dyes relates to the extremely low triplet yields. This feature serves to minimize the formation of singlet molecular oxygen and thereby to prevent photodegradation of the dye. The triplet state can be generated by way of sensitization[44] or through charge recombination in certain donor–acceptor diads.[110] By equipping the Bodipy dye with suitable ancillary binding sites, a tremendous range of chemical sensors can be realized that take advantage of the ability to functionalize most sites on the dye superstructure. In reality, the recent discovery that the fluorine atoms can be replaced by organic moieties, thereby expanding the range of derivatives and facilitating the attachment of multiple chromophores, should be recognized as a major accomplishment in this field.[111] A simple illustration of this point can be made by considering the Bodipy–terpyridine conjugate, compound **60** (see Figure 21) having the chelate attached to the *meso* position. Linear coordination structures are found upon addition of appropriate cations to **60**. Replacing the fluorine atoms with terpyridine units, however, leads to the formation of more complex supramolecular structures that might include networks.[112]

The way is now open to incorporate Bodipy-based dyes into all manner of interesting molecular-scale devices. For example, logic gates[113] and photochromic switches[114] are known, and Bodipy-based units are often used as input/output signalers in optoelectronic devices.[115] An intriguing aspect of this approach is how the attachment affects the properties of the Bodipy dye. It has already been stressed that conjugates of the type Bodipy–terpyridine can be built into supramolecular structures, including polymers, but unusual properties can also result from the various Bodipy–pyrene diads. These

properties arise because of the quite disparate solvation demands of the two units. Pyrene is often involved in π stacking as a means by which to minimize surface contact with the surroundings and recent studies have shown that the diads are prone to solvatophobic effects. Such behavior perturbs the photophysical properties of the Bodipy core but also, in extreme cases, can induce self-association.[112] In other cases, the Bodipy dye has been built into organogels or included in plastic films, where its resistance to high temperatures facilitates processing.

It seems inevitable that a far greater variety of Bodipy-based diads, triads, and so on will be forthcoming in the near future and that these materials will find applications in optoelectronic devices. In addition to light-induced electron transfer, Bodipy can function as a chromophore in light-harvesting systems and this research area seems set to undergo rapid expansion. The important point in this case concerns the high photostability of the dyes since light collectors and solar concentrators are subject to fatigue and photocorrosion. Such problems might be offset by the low rate of intersystem crossing in Bodipy and by the facile attachment of ancillary groups. It might be stressed that any practical organic-based system for solar energy conversion and storage needs to be fitted with a light harvester and Bodipy might well be the answer.

Finally, we have referred specifically to the versatility of Bodipy dyes which is related to their synthetic adaptability. It is now possible to produce derivatives having attachments placed at the *meso*, pyrrole, or boron sites, with each having advantages. The *meso* site favors orthogonal geometries for attached aromatic residues which can minimize electronic coupling. The pyrrole site allows coplanar geometries that maximize electronic communication between the subunits, and the boron center provides for free rotation. Thus, the same appendage can exert different properties according to its site of attachment. The ability to construct asymmetric dyes by attaching different substituents at the boron center adds to the variety of compounds that can be made. Altering the overall electronic charge is easy. The photophysical properties of the Bodipy core are relatively insensitive to changes in temperature or environment whilst the electrochemical properties are straightforward to interpret. The net result is a universal fluorescent dye awaiting further interesting applications.[116]

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[1] A. Treibs, F.-H. Kreuzer, *Justus Liebigs Ann. Chem.* **1968**, *718*, 208 – 223.
[2] H. Falk, O. Hofer, H. Lehner, *Monatsh. Chem.* **1974**, *105*, 169 – 178; E. VosdeWael, J. A. Pardoen, J. A. Vankoeveringe, J. Lugtenburg, *Recl. Trav. Chim. Pays-Bas* **1977**, *96*, 306 – 309; H. J. Wories, J. H. Koek, G. Lodder, J. Lugtenburg, R. Fokkens, O. Driessen, G. R. Mohn, *Recl. Trav. Chim. Pays-Bas* **1985**, *104*, 288 – 291.
[3] R. P. Haughland, H. C. Kang, US Patent US4774339, **1988**; F. J. Monsma, A. C. Barton, H. C. Kang, D. L. Brassard, R. P. Haughland, D. R. Sibley, *J. Neurochem.* **1989**, *52*, 1641 – 1644.
[4] Registered trademark of Molecular Probes; http://probes.invitrogen.com.
[5] M. Shah, K. Thangraj, M. L. Soong, L. Wolford, J. H. Boyer, I. R. Politzer, T. G. Pavlopoulos, *Heteroat. Chem.* **1990**, *1*, 389 – 399.
[6] Source: CAS SciFinder.
[7] B. J. Littler, M. A. Miller, C.-H. Hung, R. W. Wagner, D. F. O'Shea, P. D. Boyle, J. S. Lindsey, *J. Org. Chem.* **1999**, *64*, 1391 – 1396.
[8] M. Baruah, W. Qin, N. Basaric, W. M. De Borggraeve, N. Boens, *J. Org. Chem.* **2005**, *70*, 4152 – 4157.
[9] A. Burghart, H. Kim, M. B. Welch, L. H. Thorensen, J. Reibenspies, K. Burgess, *J. Org. Chem.* **1999**, *64*, 7813 – 7819.
[10] H. C. Kang, R. P. Haughland, US Patent 5187288, **1993**.
[11] G. Ulrich, R. Ziessel, *J. Org. Chem.* **2004**, *69*, 2070 – 2083.
[12] L. R. Morgan, J. H. Boyer, US Patent 5446157, **1993**.
[13] J. H. Boyer, A. M. Haag, G. Sathyamoorthi, M. L. Soong, K. Thangaraj, *Heteroat. Chem.* **1993**, *4*, 39 – 49.
[14] T. Yogo, Y. Urano, Y. Ishitsuka, F. Maniwa, T. Nagano, *J. Am. Chem. Soc.* **2005**, *127*, 12162 – 12163.
[15] K. Rurack, M. Kollmannsberger, J. Daub, *New J. Chem.* **2001**, *25*, 289.
[16] N. Saki, T. Dinc, E. U. Akkaya, *Tetrahedron* **2006**, *62*, 2721 – 2725.
[17] G. Sathyamoorthi, L. T. Wolford, A. M. Haag, J. H. Boyer, *Heteroat. Chem.* **1994**, *5*, 245 – 249.
[18] E. Negishi, *Handbook of Organopalladium Chemistry for Organic Synthesis*, Wiley, New York, **2002**.
[19] C.-W. Wan, A. Burghart, J. Chen, F. Bergström, L. B.-A. Johansson, M. F. Wolford, T. G. Kim, M. R. Topp, R. M. Hochstrasser, K. Burgess, *Chem. Eur. J.* **2003**, *9*, 4430 – 4431.
[20] T. Rohand, W. Qin, N. Boens, W. Dehaen, *Eur. J. Org. Chem.* **2006**, 4658 – 4663.
[21] F. Li, S. I. Yang, Y. Ciringh, J. Seth, C. H. Martin III, D. L. Singh, D. Kim, R. R. Birge, D. F. Bocian, D. Holten, J. S. Lindsey, *J. Am. Chem. Soc.* **1998**, *120*, 10001 – 10017.
[22] W. Qin, T. Rohand, M. Baruah, A. Stefan, M. van der Auweraer, W. Dehaen, N. Boens, *Chem. Phys. Lett.* **2006**, *420*, 562 – 568; T. Rohand, M. Baruah, W. Qin, N. Boens, W. Dehaen, *Chem. Commun.* **2006**, 266 – 268; M. Baruah, W. Qin, R. A. L. Vallée, D. Beljonne, T. Rohand, W. Dehaen, N. Boens, *Org. Lett.* **2005**, *7*, 4377 – 4380.
[23] T. V. Goud, A. Tutar, J.-F. Biellmann, *Tetrahedron* **2006**, *62*, 5084 – 5091.
[24] H. C. Kang, R. P. Haughland, US Patent 5451663, **1993**.
[25] L. H. Thoresen, H. Kim, M. B. Welch, A. Burghart, K. Burgess, *Synlett* **1998**, 1276 – 1278; J. Chen, A. Burghart, A. Derecskei-Kovacs, K. Burgess, *J. Org. Chem.* **2000**, *65*, 2900 – 2906.
[26] a) M. Wada, S. Ito, H. Uno, T. Murashima, N. Ono, T. Urano, Y. Urano, *Tetrahedron Lett.* **2001**, *42*, 6711 – 6713; b) Z. Shen, H. Rohr, K. Rurack, H. Uno, M. Spieles, B. Schulz, G. Reck, N. Ono, *Chem. Eur. J.* **2004**, *10*, 4853 – 4871.
[27] H. C. Kang, R. P. Haughland, US Patent 5433896, **1995**; Y. Wu, D. H. Klaubert, H. C. Kang, Y-Z. Zhang, US Patent 6005113, **1999**.
[28] S. Murase, T. Tominaga, A. Kohama, Eur. Pat. 1253151a, **2002**.
[29] G. Ulrich, C. Goze, M. Guardigli, A. Roda, R. Ziessel, *Angew. Chem.* **2005**, *117*, 3760 – 3764; *Angew. Chem. Int. Ed.* **2005**, *44*, 3694 – 3398.
[30] C. Goze, G. Ulrich, L. J. Mallon, B. D. Allen, A. Harriman, R. Ziessel, *J. Am. Chem. Soc.* **2006**, *128*, 10231 – 10239.
[31] C. Goze, G. Ulrich, R. Ziessel, *J. Org. Chem.* **2007**, *72*, 313 – 322.

[32] C. Goze, G. Ulrich, R. Ziessel, *Org. Lett.* **2006**, *8*, 4445 – 4448.
[33] H. Kim, A. Burghart, M. B. Welch, J. Reibenspies, K. Burgess, *Chem. Commun.* **1999**, 1889 – 1890.
[34] S. Hiroyuki, K. Yojiro, M. Tsutayoshi, T. Keisuke, JP 11043491, **1999**.
[35] Y. Gabe, T. Ueno, Y. Urano, H. Kojima, T. Nagano, *Anal. Bioanal. Chem.* **2006**, *386*, 621 – 626.
[36] C. Tahtaoui, C. Thomas, F. Rohmer, P. Klotz, G. Duportail, Y. Mély, D. Bonnet, M. Hibert, *J. Org. Chem.* **2007**, *72*, 269 – 272.
[37] L. R. Morgan, J. H. Boyer, US Patent 5446157, **1993**.
[38] H. Stetter, H. Kuhlmann, G. Lorentz, *Org. Synth.* **1979**, *59*, 53 – 55.
[39] E. Carreira, W. Zhao, PCT Patent WO 2006/058448, **2006**.
[40] A. Gorman, J. Killoran, C. O'Shea, T. Kenna, W. M. Gallagher, D. F. O'Shea, *J. Am. Chem. Soc.* **2004**, *126*, 10619 – 10631; M. J. Hall, S. O. McDonnell, J. Killoran, D. F. O'Shea, *J. Org. Chem.* **2005**, 70, 5571 – 5578; S. O. McDonnell, M. J. Hall, L. T. Allen, A. Byrne, W. M. Gallagher, D. F. O'Shea, *J. Am. Chem. Soc.* **2005**, *127*, 16360 – 16361; M. J. Hall, L. T. Allen, D. F. O'Shea, *Org. Biomol. Chem.* **2006**, *4*, 776 – 780.
[41] J. Killoran, D. F. O'Shea, *Chem. Commun.* **2006**, 1503 – 1505.
[42] W. Zhao, E. M. Carreira, *Chem. Eur. J.* **2006**, *12*, 7254 – 7263.
[43] A. Harriman, J. P. Rostron, M. Cesario, G. Ulrich, R. Ziessel, *J. Phys. Chem. A* **2006**, *110*, 7994 – 8002.
[44] M. Galletta, F. Puntoriero, S. Campagna, C. Chiorboli, M. Quesada, S. Goeb, R. Ziessel, *J. Phys. Chem. A* **2006**, *110*, 4348 – 4358.
[45] R. Ziessel, C. Goze, G. Ulrich, M. Césario, P. Retailleau, A. Harriman, J. P. Rostron, *Chem. Eur. J.* **2005**, *11*, 7366 – 7378.
[46] C. Goze, G. Ulrich, L. J. Mallon, B. D. Allen, A. Harriman, R. Ziessel, *J. Am. Chem. Soc.* **2006**, *128*, 10231 – 10239.
[47] A. Harriman, G. Izzet, R. Ziessel, *J. Am. Chem. Soc.* **2006**, *128*, 10868 – 10875.
[48] T. G. Kim, J. C. Castro, A. Loudet, J. G.-S. Jiao, R. M. Hochstrasser, K. Burgess, M. R. Topp, *J. Phys. Chem. A* **2006**, *110*, 20 – 27.
[49] T. Förster, *Discuss. Faraday Soc.* **1959**, *27*, 7 – 17.
[50] R. Bandichhor, A. D. Petrescu, A. Vespa, A. B. Kier, F. Schroeder, K. Burgess, *J. Am. Chem. Soc.* **2006**, *128*, 10688 – 10689.
[51] R. Ziessel, L. Bonardi, P. Retailleau, G. Ulrich, *J. Org. Chem.* **2006**, *71*, 3093 – 3102.
[52] T. Ueno, Y. Urano, H. Kojima, T. Nagano, *J. Am. Chem. Soc.* **2006**, *128*, 10640 – 10641.
[53] K. Rurack, M. Kollmannsberger, U. Resch-Genger, J. Daub, *J. Am. Chem. Soc.* **2000**, *122*, 968 – 969.
[54] M. Kollmannsberger, K. Rurack, U. Resch-Genger, J. Daub, *J. Phys. Chem. A* **1998**, *102*, 10211 – 10220.
[55] Z. Dost, S. Atilgan, E. U. Akkaya, *Tetrahedron* **2006**, *62*, 8484 – 8488; Y.-H. Yu, A. B. Descalzo, Z. Shen, H. Röhr, Q. Liu, Y.-W. Wang, M. Spieles, Y.-Z. Li, K. Rurack, X.-Z. You, *Chem. Asian J.* **2006**, *1*, 176 – 187.
[56] S. Atilgan, Z. Ekmekci, A. Lale Dogan, D. Guc, E. U. Akkaya, *Chem. Commun.* **2006**, 4398 – 4400.
[57] T. Yogo, Y. Urano, Y. Ishitsuka, F. Maniwa, T. Nagano, *J. Am. Chem. Soc.* **2005**, *127*, 12162 – 12163.
[58] G. Ulrich, S. Goeb, A. De Nicola, P. Retailleau, R. Ziessel, *Synlett* **2007**, 1517 – 1520.
[59] M. Galletta, S. Campagna, M. Quesada, G. Ulrich, R. Ziessel, *Chem. Commun.* **2005**, 4222 – 4223.
[60] R. F. Ziessel, G. Ulrich, L. Charbonnière, D. Imbert, R. Scopelliti, J.-C. G. Bünzli, *Chem. Eur. J.* **2006**, *12*, 5060 – 5067.
[61] T. Kalai, E. Hideg, J. Jekö, K. Hideg, *Tetrahedron Lett.* **2003**, *44*, 8497 – 8499.
[62] T. Kalai, K. Hideg, *Tetrahedron* **2006**, *62*, 10352 – 10360.
[63] Y. Teki, H. Tamekuni, J. Takeuchi, Y. Miura, *Angew. Chem.* **2006**, *118*, 4782 – 4786; *Angew. Chem. Int. Ed.* **2006**, *45*, 4666 – 4670.
[64] M. P. Debreczeny, W. A. Svec, M. R. Wasielewski, *Science* **1996**, *274*, 584 – 587.
[65] A. P. de Silva, H. Q. N. Gunaratne, T. Gunnlaugsson, A. J. M. Huxley, C. P. Mc Coy, J. T. Rademacher, T. E. Rice, *Chem. Rev.* **1997**, *97*, 1515 – 1566.
[66] B. Valeur, *Molecular Fluorescence*, Wiley-VCH, Weinheim, **2002**; K. Rurack, U. Resch-Genger, *Chem. Soc. Rev.* **2002**, *31*, 116 – 127.
[67] M. Kollmannsberger, T. Gareis, S. Heinl, J. Breu, J. Daub, *Angew. Chem.* **1997**, *109*, 1391 – 1393; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 1333 – 1335.
[68] K. Rurack, M. Kollmannsberger, J. Daub, *New J. Chem.* **2001**, *25*, 289 – 292.
[69] T. Gareis, C. Huber, O. S. Wolfbeis, J. Daub, *Chem. Commun.* **1997**, 1717 – 1718.
[70] C. N. Baki, E. U. Akkaya, *J. Org. Chem.* **2001**, *66*, 1512 – 1513.
[71] M. Baruah, W. Qin, N. Basaric, W. M. De Borggraeve, N. Boens, *J. Org. Chem.* **2005**, *70*, 4152 – 4157.
[72] W. Qin, M. Baruah, W. M. De Borggraeve, N. Boens, *J. Photochem. Photobiol. A* **2006**, *183*, 190 – 197.
[73] K. Rurack, M. Kollmannsberger, J. Daub, *Angew. Chem.* **2001**, *113*, 396 – 399; *Angew. Chem. Int. Ed.* **2001**, *40*, 385 – 387.
[74] M. Kollmannsberger, S. Heinl, T. Werner, C. Huber, A. Boila-Göckel, M. J. P. Leiner, US Patent 6001999, **1999**.
[75] M. Baruah, W. Qin, R. A. L. Vallée, D. Beljonne, T. Rohand, W. Dehaen, N. Boens, *Org. lett.* **2005**, *7*, 4377 – 4380.
[76] K. Yamada, Y. Nomura, D. Citterio, N. Iwasawa, K. Suzuki, *J. Am. Chem. Soc.* **2005**, *127*, 6956 – 6957; V. V. Matin, A. Rothe, Z. Diwu, K. R. Gee, *Bioorg. Med. Chem. Lett.* **2004**, *14*, 5313 – 5316.
[77] K. Rurack, M. Kollmannsberger, U. Resch-Genger, J. Daub, *J. Am. Chem. Soc.* **2000**, *122*, 968 – 969.
[78] J. L. Bricks, A. Kovalchuk, C. Trieflinger, M. Nofz, M. Büsche, A. I. Tolmachev, J. Daub, K. Rurack, *J. Am. Chem. Soc.* **2005**, *127*, 13522 – 13529.
[79] L. Zeng, E. W. Miller, A. Pralle, E. Y. Isacoff, C. J. Chang, *J. Am. Chem. Soc.* **2006**, *128*, 10 – 11.
[80] A. Coskun, E. U. Akkaya, *J. Am. Chem. Soc.* **2006**, *128*, 14474 – 14475.
[81] A. Coskun, E. U. Akkaya, *J. Am. Chem. Soc.* **2005**, *127*, 10464 – 10465.
[82] T. Kabu, Y. Urano, T. Nagano, JP 2003277385A, **2003**; Y. Gabe, Y. Urano, K. Kikuchi, H. Kojima, T. Nagano, *J. Am. Chem.* **2004**, *126*, 3357 – 3367.
[83] X. Zhang, R. Chi, J. Zou, H.-S. Zhang, *Spectrochimica Acta A* **2004**, *60*, 3129 – 3134.
[84] M. Li, H. Wang, X. Zhang, H.-S. Zhang, *Spectrochimica Acta A* **2004**, *60*, 987 – 993.
[85] H. Koutaka, J. Kosuge, N. Fukasaku, T. Hirano, K. Kikuchi, Y. Urano, H. Kojima, T. Nagano, *Chem. Pharm. Bull.* **2004**, *52*, 700 – 703.
[86] X. Peng, J. Du, J. Fan, J. Wang, Y. Wu, J. Zhao, S. Sun, T. Xu, *J. Am. Chem. Soc.* **2007**, *129*, 1500 – 1501.
[87] Y. Wu, X. Peng, B. Guo, J. Fan, Z. Zhang, J. Wang, A. Cui, Y. Gao, *Org. Biomol. Chem.* **2005**, *3*, 1387 – 1392.
[88] X. Qi, E. J. Jun, L. Xu, S.-J. Kim, J. S. J. Hong, Y. J. Yoon, J. Yoon, *J. Org. Chem.* **2006**, *71*, 2881 – 2884.
[89] G. Ulrich, R. Ziessel, *J. Org. Chem.* **2004**, *69*, 2070 – 2083.
[90] A. Coskun, B. T. Baytekin, E. U. Akkaya, *Org. Lett.* **2002**, *4*, 2857 – 2859.
[91] C. Goze, G. Ulrich, L. Charbonnière, M. Cesario, T. Prangé, *Chem. Eur. J.* **2003**, *9*, 3748 – 3755.
[92] S. Y. Moon, N. R. Cha, Y. H. Kim, S.-K. Chang, *J. Org. Chem.* **2004**, *69*, 181 – 183.

[93] Y. Mei, P. A. Bentley, W. Wang, *Tetrahedron Lett.* **2006**, *47*, 2447 – 2449.
[94] G. Beer, K. Rurack, J. Daub, *Chem. Commun.* **2001**, 1138 – 1139.
[95] N. DiCesare, J. R. Lakowicz, *Tetrahedron Lett.* **2001**, *42*, 9105 – 9108.
[96] J. P. Rostron, G. Ulrich, P. Retailleau, A. Harriman, R. Ziessel, *New J. Chem.* **2005**, *29*, 1241 – 1244.
[97] A. Coskun, E. U. Akkaya, *Tetrahedron Lett.* **2004**, *45*, 4947 – 4949.
[98] A. Coskun, B. T. Baytekin, E. U. Akkaya, *Tetrahedron Lett.* **2003**, *44*, 5649 – 5651.
[99] .R. Y. Lai, A. J. Bard, *J. Phys. Chem. B* **2003**, *107*, 5036 – 5042.
[100] J. M. Brom, J. L. Langer, *J. Alloys Compd.* **2002**, *338*, 112 – 115.
[101] A. Hepp, G. Ulrich, R. Schmechel, H. von Seggern, R. Ziessel, *Synth. Met.* **2004**, *146*, 11 – 15.
[102] F. Lopez Arbeloa, J. Banuelos Prieto, V. Martinez Martinez, T. Arbeloa Lopez, I. Lopez Arbeloa, *ChemPhysChem* **2004**, *5*, 1762 – 1771.
[103] Z. R. Owczarczyk, C. T. Brown, V. V. Jarikov, US Patent 2005/0221120, **2005**.
[104] F. Camerel, L. Bonardi, M. Schmutz, R. Ziessel, *J. Am. Chem. Soc.* **2006**, *128*, 4548 – 4549.
[105] F. Camerel, L. Bonardi, G. Ulrich, L. Charbonnière, B. Donnio, C. Bourgogne, D. Guillon, P. Retailleau, R. Ziessel, *Chem. Mater.* **2006**, *18*, 5009 – 5021.
[106] F. Camerel, G. Ulrich, J. Barbera, R. Ziessel, *Chem. Eur. J.* **2007**, *13*, 2189 – 2200.
[107] J. Karolin, L. B.-A. Johansson, L. Strandberg, T. Ny, *J. Am. Chem. Soc.* **1994**, *116*, 7801 – 7806.
[108] *The Handbook: A Guide to Fluorescent Probes and Labeling Technologies*, 10th ed., R. P. Haughland, **2005**, Invitrogen http://www.probes.invitrogen.com.
[109] R. E. Pagano, O. C. Martin, H. C. Kang, R. P. Haughland, *J. Cell Biol.* **1991**, *113*, 1267 – 1279; H.-G. Knaus, T. Moshammer, K. Friedrich, H. C. Kang, R. P. Haughland, H. Glossmann, *Proc. Natl. Acad. Sci. USA* **1992**, *89*, 3586 – 3590.
[110] A. Harriman, L. J. Mallon, G. Ulrich, R. Ziessel, *Phys. Chem. Chem. Phys.* **2007**, *8*, 1207 – 1214.
[111] C. Goze, G. Ulrich, R. Ziessel, *J. Org. Chem.* **2007**, *72*, 313 – 322.
[112] A. Harriman, L. J. Mallon, B. Stewart, G. Ulrich, R. Ziessel, *Eur. J. Org. Chem.* **2007**, 3191 – 3198.
[113] T. A. Golovkova, D. V. Kozlov, D. C. Neckers, *J. Org. Chem.* **2005**, *70*, 5545 – 5549.
[114] V. A. Azov, F. Diederich, Y. Lill, B. Hecht, *Helv. Chim. Acta* **2003**, *86*, 2149 – 2155.
[115] D. Holten, D. F. Bocian, J. S. Lindsey, *Acc. Chem. Res.* **2002**, *35*, 57 – 69.
[116] Note added in proof: The popularity and attractivity of these exceptional dyes is illustrated by two recent and exhaustive reviews dealing with dipyrrines und Bodipy derivatives published during the course of this review: a) T. E. Wood, A. Thompson, *Chem. Rev.* **2007**, *107*, 1831 – 1861; b) A. Loudet, K. Burgess, *Chem. Rev.* **2007**, *107*, 4891 – 4932.