RATIONAL DESIGN OF TWO PHOTON ABSORBING BODIPY DYES

A THESIS

SUBMITTED TO THE DEPARTMENT OF CHEMISTRY

AND THE INSTITUTE OF ENGINEERING AND SCIENCES

OF BİLKENT UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF SCIENCE

By

BİLAL KILIÇ

August 2010

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis of the degree of Master of Science.

…….

Prof. Dr. Engin U. Akkaya (Principal Advisor)

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis of the degree of Master of Science.

…….

Assist. Prof. Dr. Dönüş Tuncel

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis of the degree of Master of Science.

…….

Assoc. Prof. Dr. Zeynel Sefereoğlu

Approved for the Institute of Engineering and Science:

…….

Prof. Dr. Levent Onural

Director of the Institute of Engineering and Science

ABSTRACT

RATIONAL DESIGN OF TWO PHOTON ABSORBING BODIPY DYES

Bilal Kılıç

M.S. in Chemistry

Supervisor: Prof. Dr. Engin U. Akkaya

August, 2010

Two photon absorption is a nonlinear process which is of particular interest in various applications such as optical data storage, fluorescence imaging, O_2 sensing and photodynamic therapy. These applications have created a strong demand for new dyes which have high two photon absorption cross section. In the two- photon absorption process there is an interaction of the two photons which are simultaneously absorbed by materials. For this purpose, we have designed and synthesized a novel class of distyryl-substituted boradiazaindacene (BODIPY) dyes which absorb two one photon in the green or two photons in the near IR regions of the (electromagnetic) spectrum and have D-A-D structure. As expected, as the strength of the donor groups which were introduced to the 3,5 position of the BODIPY core increase, absorption and emission maxima of the BODIPY dyes are shifted in the near IR regions of the spectrum. Furthermore, GM values increase due to the enhancement donor strength of the terminal groups. In summary, we have successfully synthesized a novel class of BODIPY derivatives which have large TPA cross section values.

Keywords: Boradiazaindacene, two photon absorption, two photon absorption cross section, GM values.

ÖZET

İKİ FOTON SOĞURAN BODİPY TÜREVLERİNİN RASYONEL DİZAYNI

Bilal Kılıç

Kimya Bölümü, Yüksek Lisans

Tez Yöneticisi: Prof. Dr. Engin U. Akkaya

Ağustos, 2010

İki foton soğurma doğrusal olmayan bir süreçtir ve optik veri saklama, floresans etiketleme ve fotodinamik terapi gibi uygulamalar için dikkate değer bir önem taşımaktadır. Bu uygulamalar, yüksek iki foton soğurma katsayısına sahip olan yeni maddelere büyük bir rağbet oluşturmuştur. İki foton soğurma sürecinde, her iki fotonda söz konusu olan madde tarafından aynı anda soğurulur ve maddenin soğurma gücü, ışığın yoğunluğunun karesi ile orantılıdır. Bu amaçla elektromanyetik spektrumun yeşil ve yakın kızıl ötesi bölgesinde iki foton soğuran ve elektron verici-elektron alıcı-elektron verici (D-A-D) yapısına sahip iki stiril grubu içeren yeni bir seri boradiazaindasen(BODIPY) boyalarını tasarladık ve sentezledik. Beklendiği üzere, BODIPY iskeletinin 3 ve 5 pozisyonlarına eklenen elektron verici grupların kuvveti arttıkça, BODIPY türevlerinin soğurma ve emisyon maksimumları elektromanyetik spektrumun yakın kırmızı ötesi bölgesine kaydı. Ayrıca, terminal elektron verici grupların kuvvetlerinin artışına bağlı olarak GM değerleride artış gösterdi. Sonuç olarak, yüksek iki foton soğurma katsayılarına sahip yeni bir seri boradiazaindasen (BODIPY) boyalarını başarılı bir şekilde sentezledik.

Anahtar Kelimeler: Boradiazaindasen, iki foton soğurması, iki foton soğurma katsayısı, GM değerleri.

Dedicated to my family

ACKNOWLEDGEMENT

I would like to express my deepest appreciation to my supervisor Prof. Dr. Engin U. Akkaya, whose encouragement, infinite patience, guidance and unremitting support from the initial to the final level of this research. I am also heartily thankful to him for teaching us how to become a good mentor. Without his guidance and persistent help this thesis would not have been possible. I will never forget his support throughout my life.

I owe a special thank to Dr. Ö. Altan Bozdemir for his support, guidance as well as his unlimited knowledge and experience that i benefited from greatly. Dr. Bozdemir, it has been an honor to work with you

I also owe a special thank to Yusuf Çakmak and Ruslan Guliyev for their support during the course of this research.

My gratitude also goes to our group members H.Eser İden, Safacan Kölemen, Merve Türkşanlı, Fazlı Sözmen , Dr. Cihan Gündüz, Ziya Köstereli, Sencer Selçuk, Onur Büyükçakır, Barboros Reis, Yiğit Altay, Gizem Çeltek, Sündüz Erbaş Çakmak, Fatma Pir, Şeyma Öztürk, Gülcihan Gülseren, Tuğrul Nalbantoğlu, Tuba Yaşar, Nisa Yeşilgül, Hande Boyacı, Seda Demirel, Ahmet Bekdemir, Muhammed Büyüktemiz, Tuğba Özdemir and rest of the SCL (Supramolecular Chemistry Laboratory) members. You are the heart and soul of the SCL

I would like to thank to Mr. Yaochuan Wang for acquiring TPA data and to Dr Bülend Ortaç for the pictures of TPA process.

I would like to thank to TÜBİTAK (The Scientific and Technological Research Council of Turkey) for financial support.

On a different note, many people have been a part of my graduate education and I am highly grateful to all of them.

Finally, the most special thanks go to my family for their love, support and understanding. Without their support none of this would have been possible.

LIST OF ABBREVIATIONS

TPA :	Two photon absorption
OPA:	One photon absorption
PDT:	Photodynamic Therapy
THF:	Tetrahydrofuran
BODIPY:	Boradiazaindacene
GM:	Göppert-Mayer
TPEF:	Two photon excited fluorescence
WLC:	White light continuum method
ICT:	Intermolecular charge transfer
TPA-PDT:	Two photon absorption-photodynamic therapy
OPL:	Optical power limiting
UV:	ultraviolet
TLC:	Thin layer chromatography
TFA:	Trifluroaceticacid
DDQ :	Dicholoro dicyano quinone

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1. Two Photon Absorption

Two photon absorption phenomenon was first introduced by Maria Göppert-Mayer in 1931. She predicted that two photons could be simultaneously absorbed by the same atom or molecule[1]. After 30 years, Kaiser and Garrett confirmed her prediction experimentally. They illuminated a crystal of CaF_2 containing Eu^{+2} ions and obtained experimental evidence for the TPA phenomenon[2].

In the two-photon absorption, two photons are simultaneously absorbed by the same species and this molecule reaches the exited state. The strength of the absorption of the chromophore in the two photon absorption phenomenon depends on the light intensity. In other words, the probability of the transition for the absorption of the two photons which are identical is proportional to the square of the light intensity. On the other hand, one photon absorption is a linear optical process since it is related linearly on the intensity of light. This is the main difference between one and two-photon absorption.[3]

Generally speaking, the half of the energy (or twice the wavelength) of the corresponding one photon provides the access to a given excited state. In the

TPA process, there is no need for an intermediate state to populate before arriving at the final state. (S_1). Instead of this intermediate state, the electron is excited to a '' virtual state '' which can be defined as a superposition of states. Furthermore, it is not an eigenstate of the atom. The virtual state occurs just while the molecules absorb the first photon. These states are labeled in Figure 1.

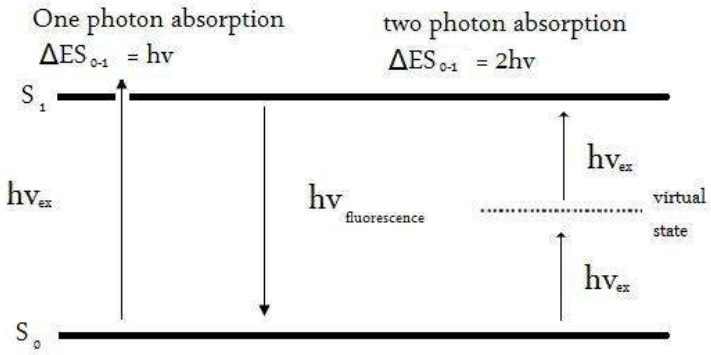


Figure 1: Energy level diagram for the OPA and TPA.

From this energy diagram it can be understood that the two photons are absorbed successively. However, TPA is as a result of simultaneous absorption of the photons. That is the reason why there is not any intermediate state in the figure 1.There is only a virtual state. Therefore, the chromophore has to absorb two photons simultaneously. Consequently, the TPA process becomes responsive to the instantaneous optical density. To increase the probability of the simultaneous absorption of the two photons high peak intensities, generally 10^{20} to 10^{30} photons/(cm^2.s) are requirements for TPA. Another issue in the TPA is the selection rule for light absorption. Because of the fact that the selection rules are different for OPA and TPA, the chromophores reach different excited states with different modes. Therefore, TPA spectroscopy is known as a complementary part in investigating the exited states of the chromophore[4]. Conversely, regardless of one or two photon absorption, they emit from the same excited state[5].

Two photon absorption is the nonlinear process which means transmittance of the material changes as a function of light intensity and it is of particular interest for various applications such as optical data storage[6], fluorescence imaging[7], O_2 sensing[8], photodynamic therapy[9], upconverting lasing[10,11], microfibracation[12,13], optical power limiting[14], two photon microscopy[15] and two photon induced biological caging studies[16].

These applications exploit the important features of TPA which is to access the highly energetic excited states by using comparatively low energy photons and quadratic dependence of the absorption process. Owing to the quadratic dependence of the TPA process, spatial selectivity is obtained by using focused beam.

In these several applications, especially in the two photon fluorescence microscopy and photodynamic therapy the aim is to achieve excitations wavelengths on the order of 0.65-1.0 μm because of the fact that light between these excitation wavelengths can penetrate deeper into the biological tissues than visible light and beyond roughly 1000 nm water begins to absorb light[17].

The use of two photon absorption especially in the visible region of the spectrum in the optical power limiting has a big importance for the protection of the eyes[18]. TPA could also play an important role in the photodynamic therapy[19]. Until today a large number of studies about photosensitizers which benefit from the conventional one photon absorption phenomenon (OPA) have been published in the literature. However, very few studies have been dedicated to develop photosensitizer which absorbs two photon simultaneously.[20] Another application area of the TPA is microfabrication which utilizes two photon absorption mechanisms has attracted attention recently[21].

In recent years, owing to these various applications, the design of two photon absorbing chromophores has gained much attention and there has been a growing interest in developing such two photon absorbing materials which have high two photon absorption cross sections. Among these materials boradiazaindacenes commonly known as BODIPY dyes have particularly

attracted considerable attention due to their high photostability and significant two photon absorption cross section.[22]

1.1.1. Two photon absorption cross section

According to the Lambert-Beer Law, the absorption of light is related to the properties of the material through that light travels. The Lambert-Beer Law states that the transmission, *T*, of the light through a substance depends logarithmically on the product of the absorption coefficient of the substance, α, and the path length, l, the light travels through the substance. The absorption coefficient can be described as

$$T = I / I_0 = e^{-\alpha l} = e^{-\sigma l \varepsilon} \quad (1)$$

Sequentially, I and I_0 are the intensity of the incident light and transmitted light. In the TPA the absorption coefficient α becomes the two photon absorption cross section β. It is important to note that people can confuse about the Greek letter β which is used in nonlinear optics because it is occasionally used to denote the second order polarizability. To denote molecular TPA cross section the letters δ and σ are also mostly used. A beam of light is attenuated by TPA and this attenuation is described in the following equation:

$$\partial I / \partial z = -N\alpha_2 I^2 = -N \delta F I \quad (2)$$

In this equation I is the intensity, α_2 is a molecular coefficient for two photon absorption, N is the number of molecules per unit volume, and z is the distance into the medium.

Two photon absorption cross section δ is mostly denoted in the units of Göppert-Mayer (GM), where 1 GM is 10^{-50} cm^4.s.photons^{-1}. Considering the fact that the units consist cm^4s, it is obvious that it arises from the product of the two areas (each photon in cm^2) and a time when the two photons are simultaneously absorbed by the same molecule.

$$\delta_{max} = \frac{2\pi h v^2 L^4}{\varepsilon_0^2 n^2 c^2} \left[\frac{1}{\Gamma}\right] S_{fg} \quad ; \qquad (3)$$

$$S_{fg} = \left[\sum_i (\mu_{gi}\, \mu_{if})/ (E_{gi}-hv)\right]^2$$

In these equations the energy gap between the ground state and an intermediate state is denoted by $E_{gi.}$ The letter Γ is used to denote the half-width at half-maximum of the TPA band in energy units. The enhancement of the optical field in the medium is demonstrated with the letter L. This letter L is equal to $(n^2+2)/3$ where n is the refractive index. The amplitude of the transition dipole moment is denoted by $\mu_{kl.}$ This transition dipole moment is stimulated by the electric field of a light wave. Its frequency fits to the energy difference between the states which are k and l[23].

1.1.2. Measurements Techniques for Two photon Absorption

There are various techniques by which we can measure two photon absorption cross section. The most common techniques are two photon excited fluorescence (TPEF) and ‘’z-scan.’’ Other techniques such as white-light continuum method and fs-WLC (white-light continuum method) are rarely used and give less information about TPA. In the TPEF experiments a pulsed laser, generally about 100 fs, is used, even though the accuracy of the two photon absorption cross section which is obtained from TPEF experiment does not depend on the pulse width[24]. Since TPEF experiment is performed with a dilute solution, a very small amount of material is needed.

There are two restrictions of this technique. The first one is; the TPEF cannot be performed in spectral region with one-photon absorption and this limitation is a common problem for all techniques which are used for the determination of the substantial two photon absorption cross section. The second one is the material must have a photoluminescence feature and can be handled by measuring the secondary photochemical process, like the generation of the luminescence from singlet oxygen which is generated by an energy transfer from the triplet excited state of the material which is achieved by TPA.

When the TPA-cross section values obtained from TPEF experiments are compared with the values obtained from z-scan experiments, one can see that the TPA cross section values are somewhat magnified[25].

It is important to note that the occurred error in the determination of the two photon absorption cross section are commonly more than 10 %, even if the experiments are carefully performed at the best condition[26].

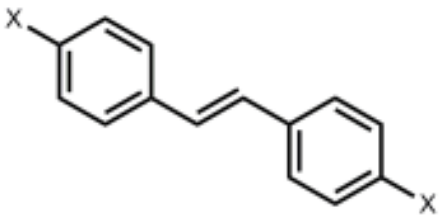
1.1.3. Design of the two photon absorbing chromophores

In 1963, the experiment of the two photon absorption of the organic dyes was firstly performed[27]. In the ensuing years, it was realized that there is relevance between the structure and TPA properties. Developments in the application areas of the two photon absorption such as bioimaging, photodynamic therapy, optical power limiting, etc. give rise to a great demand for the new two photon absorbing chromophores which have high TPA cross section. Many research groups have attempted to design novel and more responsive two photon absorbing chromophores in recent years[28-31].

1.1.3.1 Terminal Groups

From the viewpoint of the designing of a perfect molecular structure for a two photon absorbing chromophore which has high two photon absorption cross section, there are number of molecular features that influence the value of the two photon absorption cross section[32]. The presence of an electron donating group and an electron withdrawing group is needed to have an ideal molecular structure in order to obtain a high value two photon cross section. In this situation ICT (intermolecular charge transfer) has an important role in the presence of these electron donor and withdrawing groups. Namely, ICT is a triggering force[33, 34].

Marder et al. published a work on the structure-property relationship in 1997. They compared the trans-stilbene (**1**) with a derivative of trans-stilbene (**2**) which contains terminal donor groups. Their work puts emphasis on the effect of the terminal group which influences the two photon absorption cross section[35].



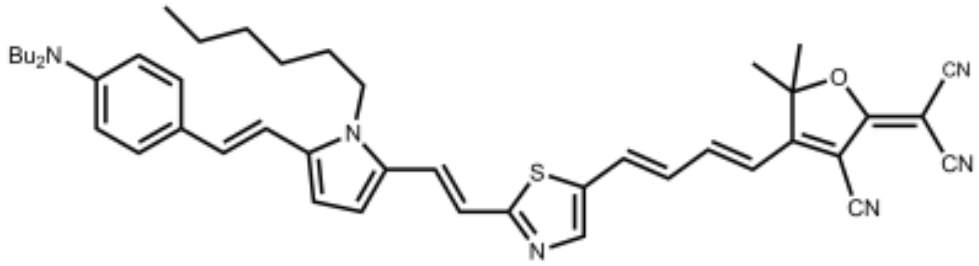
1, X :H
2, X: NBu_2
3, X: NPh_2

Figure 2 : Derivatives of trans-stilbene

The compound **1** has a two photon absorption cross section (δ_{max}) of 12 GM at 514 nm, while the two photon absorption cross section δ_{max} of the

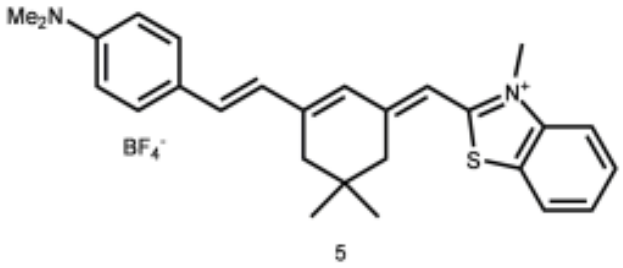
compound **2** is 110 GM at 620 nm. One can see that two photon absorption value of the compound **2** is increased nearly 10 times by changing of substituent H with NBu_2. An additional enhancement was obtained for the compound **3** with a substituent NPh_2[36]. Compound **3** has δ_{max} 340 GM at 680 nm. These results suggest a design method of new two photon absorbing chromophors containing two donor or acceptor terminal groups which are linked with a π-conjugated bridge[37]. Several research groups attempted to develop novel centrosymmetric chromophores owing to the consequence that centrosymmetric charge transfer gives rise to the high value of two photon absorption cross section.

Prasad et al. worked on the dipolar chromophores with π-bridge which have D- π-A structure. In recent years, a small number of studies on the dipolar chromophores with high TPA cross section have been published. For instance, compound **4**[29] and **5**[36] have significantly high TPA cross section values. The two photon absorption cross section δ_{max} of the compound **4** is 1200 GM at 1440 nm while the compound **5** exhibits a TPA cross section δ_{max} value 730 GM at 1250 nm.



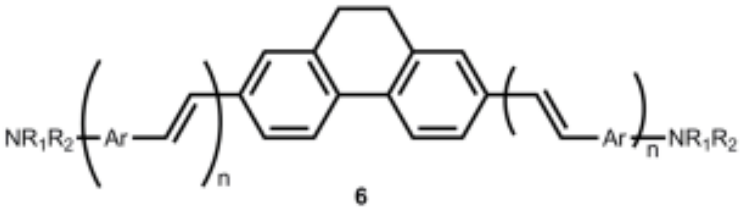
4

Figure 3 : Structure of the compound **4**



5

Figure 4 : Structure of the compound **5**



6

Figure 5: Structure of the compound **6**

However, dipolar chromophores exhibit mostly lower TPA cross section value than centrosymmetric chromophores which have the same complexity and size.

Blanchard-Desce et al. designed and prepared push-push functionalized molecules. Namely, the molecules have bis-donor terminal groups. One of them is compound **6**.

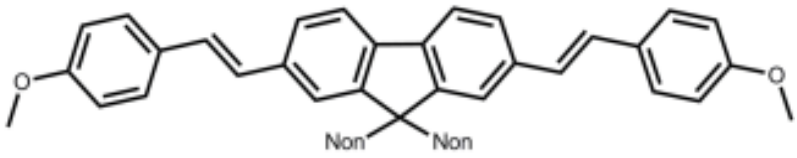
Based on their earlier work, they used the dihydrophenanthrene moiety and the di-(n-alkyl)amino substituent in order to obtain a chromophore which has an elongated π-system and shows high two photon absorption cross section in the near-IR region of the spectrum[38]. In recent years, it has been reported that chromophores which contain two terminal donor group or two terminal acceptors can have two photon absorption features[39] and high two photon absorption cross section values[40]. This result is related to the intramolecular charge transfer. This charge transfer takes place between the core and the terminal groups of the chromophore. Hence, over the past decade, almost all

research groups have attempted to increase this charge transfer either by designing promising structures such as D-A-D or D-A-A-D[37] or by extending the π-system[41].

The choice of terminal groups is also an important factor in the development of the novel two photon absorbing chromophores. Actually, it depends on the type of chromophore. It can be either donor or acceptor group.

There are a great number of terminal donor groups, but the alkyl and diaryl amino groups are typically used. Nitrogen based donor groups (-NR_2) are mostly more effective than their counterparts which are based on oxygen.

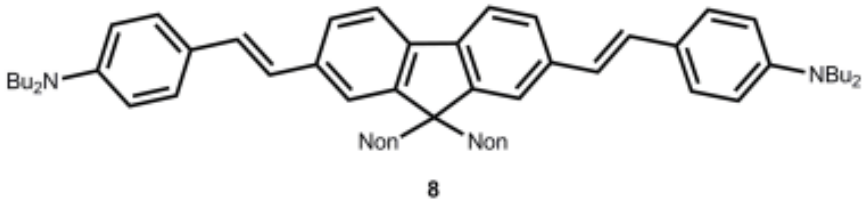
For instance compound **7** exhibits higher two photon absorption cross section than compound **8**.



7

Figure 6 : Structure of the compound **7**

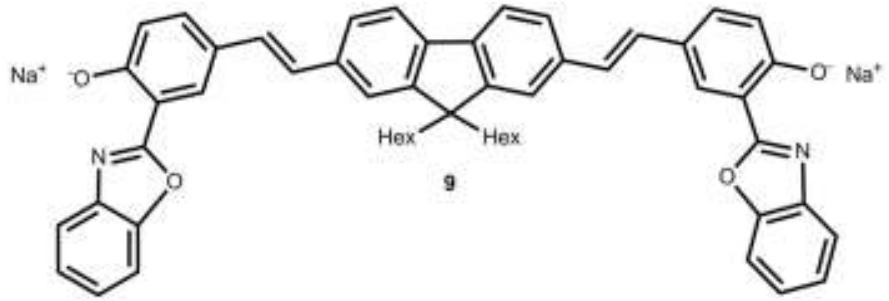
Compound **7** exhibits a two photon absorption cross section of 110 GM at 705 nm while compound **8** has high value of two photon absorption cross section, 1300 GM[42].



8

Figure 7 : Structure of the compound **8**

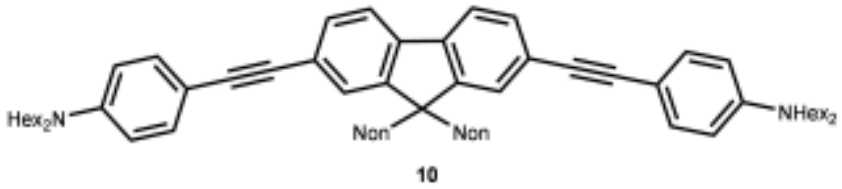
Jen and coworkers have recently published a work on two photon absorbing chromophores. In this work, they reported a choromophore which is shown in the Figure 9. which has higher TPA cross section compare to the compound **7** and **8** owing to the fact that the funtional group fenoxides are strong electron donating group.This chromophore, compound **9**, has a TPA cross section of 4100 GM at 740 nm. One can see that the choice of the terminal electron donating group is of high importance in terms of having significant two photon absorption cross section value.



9

Figure 8 : Structure of the compound **9**

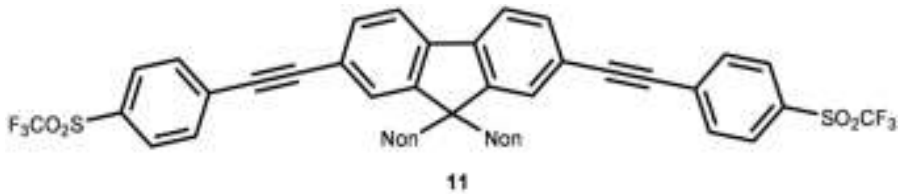
A-D-A or A-π-A are the other structures that can be used in order to obtain high TPA cross section value. Many research groups have studied these structures which have at the ends of the molecule electron withdrawing groups. However, the recent publications have showed that the structures that have electron donating groups at the ends of the molecule show comparatively higher TPA cross section values than the molecules that at their ends electron withdrawing groups at either terminus[45].



10

Figure 9 : Structure of the compound **10**

Compound **10** has a TPA cross section of 1200 GM at 705 nm. It contains two nitrogen based terminal electron donating groups (-$NHex_2$). Hence, it exhibits significantly high TPA cross section value whereas the compound **11** shows relatively low TPA cross section value owing to the presence of terminal electron withdrawing groups.



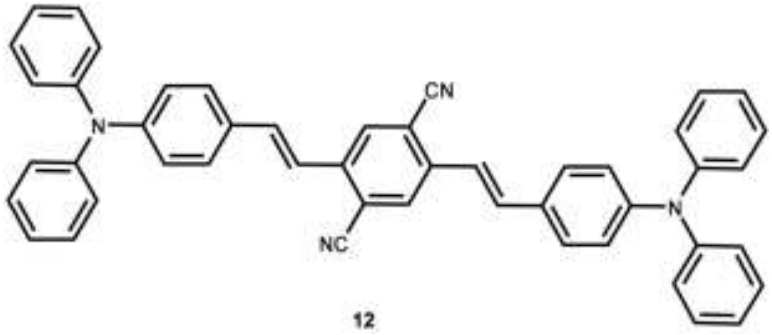
11

Figure 10: Structure of the compound **11**

The TPA cross section value of the compound **11** is 83 GM at 705 nm. By comparing these two compounds, it can be concluded that the molecule that

contains terminal electron donor groups is more efficient than the structure that includes terminal electron withdrawing groups.

M. Albota et al. also worked on these subjects and determined that the TPA cross section value of the molecules that contain terminal electron withdrawing groups is lower than molecules which have terminal electron donating groups. They designed and synthesized the compound **12** so that they obtained donor-acceptor-donor structure.

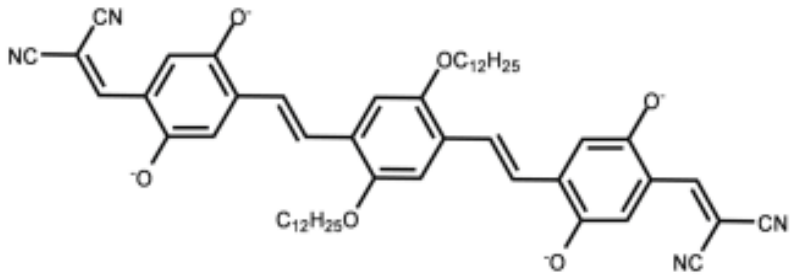


12

Figure 11 : Structure of the compound **12**

Cyano groups on the central ring are the acceptor groups and the triphenylamino groups are electron donating groups. This compound has a TPA cross section value of 950 GM at 625 nm.

They also synthesized the compound **13** in order to create acceptor-donor-acceptor (A-D-A) structure and to reverse the charge transfer by attaching the alkoxy groups to the rings of the molecule and adding terminal electron withdrawing groups.



13

Figure 12: Structure of the compound **13**

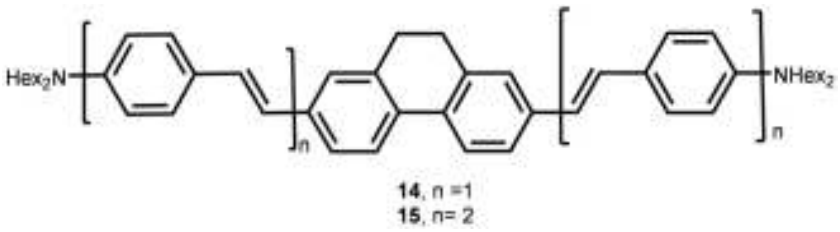
Compound **13** has a TPA cross section value of 570.4 GM at 666 nm. One can see that the effect of the terminal groups on the magnitude of the TPA cross section. Consequently, the compound **13** has lower TPA cross section value than compound **12**.

When a number of strong electron donor groups, a number of electron withdrawing groups and π-bridges come together, it gives rise to dipolar, quadrupolar or octupolar structures.

The most widely used electron acceptor groups are cyano[37], nitro[43], sulfonyl[44], triflyl[45], aldehyde[46] and arylcarbonyl[47]. Moreover, π-deficient heterocyclics are also used as electron withdrawing groups[51]. As electron donor groups, dialkyl and diaryl amino groups are widely used owing to their strong electron donating features[37].

1.1.3.2 The extent of the π system

The extent of the π system is important for the two photon absorption cross section, since it gives rise to the states which have extended charge separation[37, 48]. By extending the π system, the transition dipole moments $\mu_{ig,}$ and $\mu_{if.}$ increase and an enhancement in the TPA cross section value is obtained. The effect of the the extension of the π system on the TPA cross section value is showed below with two examples.



14, n =1
15, n= 2

Figure 13 : Structures of the compound **14** and **15**

The compound **15** has two more stilbene groups compared to the compound **14**. The TPA cross section value of the compound **15** is almost two times higher than the TPA cross section value of the compound **14**. The TPA cross section value of the compound **15** is 3300 GM at 740 nm while the compound **14** has the TPA cross section value of 1700 GM at 740 nm[40].

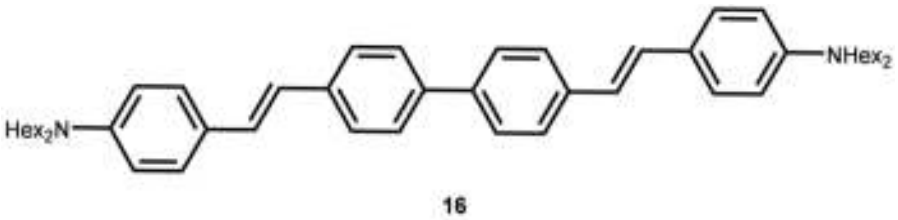
This effect has also been observed on the porphyrin derivatives. Anderson and coworkers have investigated this effect on the conjugated porphyrin dimers and its monomer in the near region. They have demonstrated that all of the conjugated dimers of the porphyrin have more than a few hundred

times higher TPA cross section value than its corresponding porphyrin monomer[49].

1.1.3.3 The conformation of chromophores

In increasing the effectiveness of the ICT coplanarity has a critical role. Hence, it is important for a high TPA cross section value. Lee et al. have investigated such effect on the TPA cross section[50]. Prasad and co-workers have also studied this effect. They have argued that their results arise from the planarity of the bridge in their molecules and improvement of the conjugation across the molecules. Actually, the result was the reduction of the TPA cross section. They have postulated that this occurs due to the reduction of the conjugation between electron donor and electron acceptor group which is aroused by a group whose rotation increases[51]. The effect of the conformation on the two photon absorption cross section was also theoretically proved[52]. The difference between the TPA cross section value of the compound **8** and compound **16** demonstrates how the conformation of the molecules affects the TPA cross section value of the chromophores.

The compound **16**[45] has a TPA cross section value of 1000 GM at 730 nm while the compound **8** has a TPA cross section value of 1300 GM at 740 nm.



16

Figure 14 : Structure of the compound **16**

The reason for this difference of between TPA cross section values is the different bridges of the molecules. That is to say, the compound **16** has a biphenyl bridge which is not rigid; on the other hand, the compound **8** has a rigid 9, 9-dinonylfluorene as a bridge. As a consequence, the conformation of the compound **8** becomes fixed.

1.1.4 Applications of the two photon absorption

Two photon absorption technique is widely used in various application areas owing to its certain advantages such as focusing to a small focal volume, less photochemical damage in biological tissue and spatial resolution.[53]

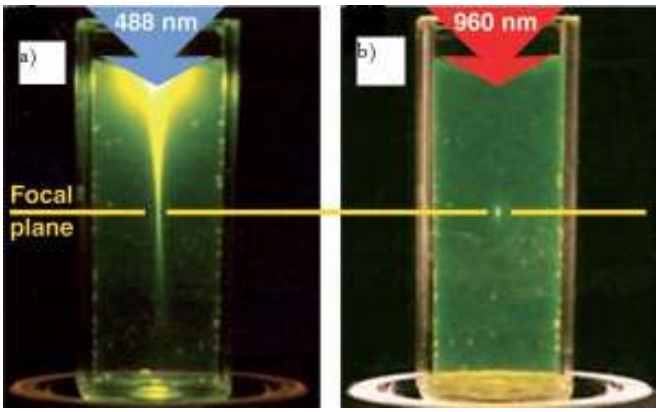


Figure 15 : a) Excitation by focused light (OPA) , b) TPE by focused light[63]**.** Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

1.1.4.1 Photodynamic Therapy

Photodynamic therapy (PDT) has gained plenty of attention because of the fact that it has emerged in recent years as a novel and one of the most promising treatment modalities for malignant and non-malignant diseases.

PDT is a targeted, tissue specific and light activated treatment modality which is used in certain fields such as oncology, dermatology, ophthalmology and cardiology[54,55]. Furthermore, PDT is particularly appealing in atherosclerotic illnesses such as coronary artery diseases[56]. In the PDT the light is used at the appropriate wavelength to activate photosensitizer to its triplet state which is accumulated in affected or tumor tissue. The energy of triplet state of the photosensitizer can be effectively transferred to molecular oxygen and this transfer of the energy gives rise to generation of singlet oxygen[57]. This cytotoxic singlet oxygen causes direct chemical damage to the malignant tissues and to atherosclerotic plaque. To be effective in the PDT, the combination of action between light and drug must give rise to targeted delivery of cytotoxic effect[58]. Singlet oxygen production is an important issue for the PDT and it requires a sufficiently high energy of the triplet state of the sensitizer. The main disadvantage of one photon PDT is the requirement of excitation with visible light and it is far from the efficient optical window of mammalian tissues which limits deeper penetration. Deeper penetration has been achieved by using near IR light[59]. In the table 1, the penetration depth of the light based on the wavelength is showed.

Tissue	Wavelength/ nm							
	600	650	700	750	800	850	900	1064
Human Retinoblastoma	2.9	3.8	4.0	4.0	4.1	4.2	4.3	5.1
Porcine Brain	1.8	2.4	2.9	3.0	3.3	3.5	3.7	4.0
Human Hand	1.9	2.0	2.6	2.7	3.0	3.0	3.0	
Melanotic melanoma		0.28	0.34	0.41	0.50	0.56	0.64	1.4

Table 1 : Penetration Depths (mm) at several wavelengths[60]

The most recent method is TPA to overcome such disadvantages. By using two photon PDT, photosensitizer is excited at a focal volume and deeper penetration is obtained at the longer wavelength. Moreover, the damage of the nearby tissues is prevented During the PDT treatment, biological tissues can scatter the light which is also a main problem and is overcome by using two photon PDT. Namely, PDT may become more effective by using TPA chromophores

Over the past two decades, two photon PDT has been studied by several research groups, but these studies on two photon PDT have not gained much interest due to the fact that the photosensitizers had relatively low TPA cross section(< 50 GM). On the other hand, numerous photosensitizers which have high TPA cross section value have been recently published[61, 62].

For instance, K. Ogawa et al have reported a photosensitizer which shows significant TPA cross section value under two photon excitation. They performed TPA-PDT experiment and showed that Hela cancer cells were successfully killed[63].

As a conclusion, TPA-PDT provides spatially selective treatment for the malignant and non-malignant tissues. During this treatment modality, the light penetrates relatively deeper into the tissues.

1.1.4.2 Optical Data Storage and Microfabrication

TPA technique is widely used to develop for various applications because of its numerous advantages. Among its application areas, optical data storage has a big importance owing to the fact that TPA allows a substantial enhancement in the date storage in a three- dimensional medium. CDs and DVDs are commonly used as optical data storage equipments. To read and write the data, one photon excitation is used and it proceeds on a two dimensional surface[64].

Microfabrication is another class of potential application of TPA. Three dimensional microstructures are widely produced by using TPA technique.

The polymerization of acrylates which induced by TPA can be given as an example for the microfabrication. It is believed that this polymerization is proceeded by the electron transfer from the excited state of the two photon absorbing chromophore to the monomer of the acrylate[12]. Most widely used photoinitiators have relatively low TPA cross section value[65]. However, in recent years, a number of chromophores which are noticeably efficient TPA initiators have been reported[66, 67].

1.1.4.3 Two photon microscopy

Two photon microscopy is one of the important application areas of the TPA technique. It is a novel imaging technique and was first introduced by a German scientist Winfried Denk. To obtain high resolution, three dimensional images of biological tissues or samples in biological medium, two photon microscopy is used because of the fact that at a longer wavelength, less scattering occurs compared to the shorter wavelengths.[68].

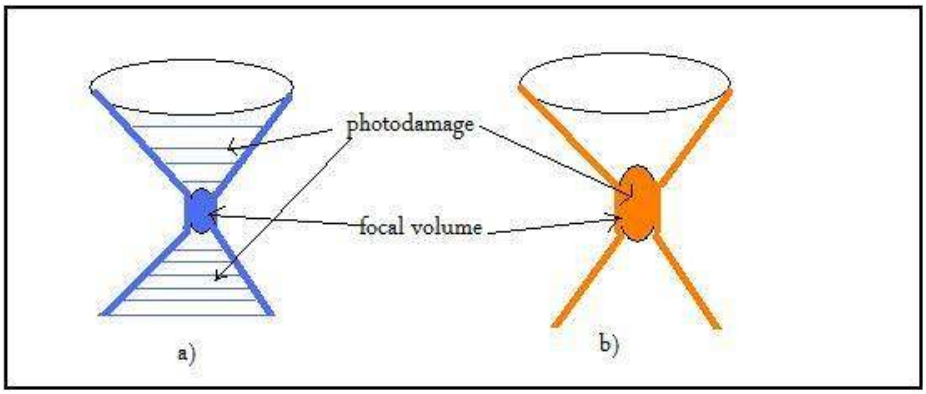


Figure 16 : a) Photodamage during the 1PFM and b) 2PFM

1.1.4.4 Optical Power Limiting

The advantages of the TPA, especially spatial features, are not particularly utilized by some of the applications of the TPA. In the optical power limiting the only thing which is used by materials as a feature of the chromophore is nonlinear transmittance. Namely, the absorption of the chromophore depends on the intensity of the incident light, so that the chromophore becomes transparent to the light when the intensity of the light is low. On the other hand, it becomes nontransparent to the light which is intense[69].

Optical power limiting is also used in optical telecommunications in order to get rid of the sudden intensity increase. OPL is utilized in order to protect human eyes and optical sensors from the intense laser pulses as well[70]. The current most widely used OPL materials are fullerenes[71], metal-organic compounds[72], porphyrines[73] and phtalocyanines[74].

1.2. BODIPY® Chemistry

1.2.1. Fundamental properties of BODIPY Dyes

Bodipy dyes, which are also called as 4, 4-difluoro-4-bora-3a, 4a-diaza-s-indacene (henceforth abbreviated as BODIPY) dyes. Borondiazaindacenes and borondipyrrins are used to denominate these dyes, as well[75]. Treibs and Kreuz who are the discoverers of the BODIPY class of dyes, introduced first these compounds in 1968[76]. Over the past three decades, BODIPY dyes have gained great attention because of the fact that BODIPY dyes have good photophysical and photochemical features, and they have various potential application areas which are continuously growing[77]. Therefore, many research groups have focused their attention on the development of these dyes and attempted to synthesize new derivatives of these BODIPY dyes with structural modification. Their emission and absorption wavelengths can be altered by modifying their structure, as well. The research groups, which work on the BODIPY dyes in order to develop novel derivatives of these dyes, are Akkaya research group, Ziessel research group, Boens research group, Burgess research group, Rurack research group and Nagano research group.

Among the most important features of the BODIPY dyes, there are their strong absorption in the UV (ultraviolet) region of the spectrum and their emission with high quantum yields. In addition to having high quantum yields, their fluorescence peaks are sharp and they have high extinction coefficient.

Another important characteristic of these molecules is their insensitivity to the polarity of the solvent and pH. It shows that the BODIPY dyes are stable to the environmental conditions, in other words, their features do not change by altering the solvent in which the dye is solvated.

Beside these various excellent properties, there are some drawbacks of the BODIPY dyes. For instance, their emission maxima are at below 600 nm

where the biological tissues are not transparent. Another drawback is the solubility of these dyes in water. Only a few BODIPY dyes are soluble in water. Hence, some modifications[78] are carried out in order to obtain soluble derivatives of BODIPY dyes which will give rise to more efficient chromophores for imaging of living cells.

The IUPAC numbering system of the BODIPY is showed in the Figure 17.

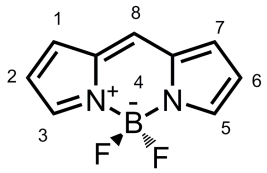


Figure 17: Structure and Numbering System of the BODIPY core

1.2.2. Application areas of BODIPY Dyes

Owing to their various characteristics of BODIPY dyes, they are potentially useful in many areas such as photodynamic therapy[79], dye sensitized solar cell[80], molecular logic gates[81], ion sensing[82] and light harvesting system (Figure 18).

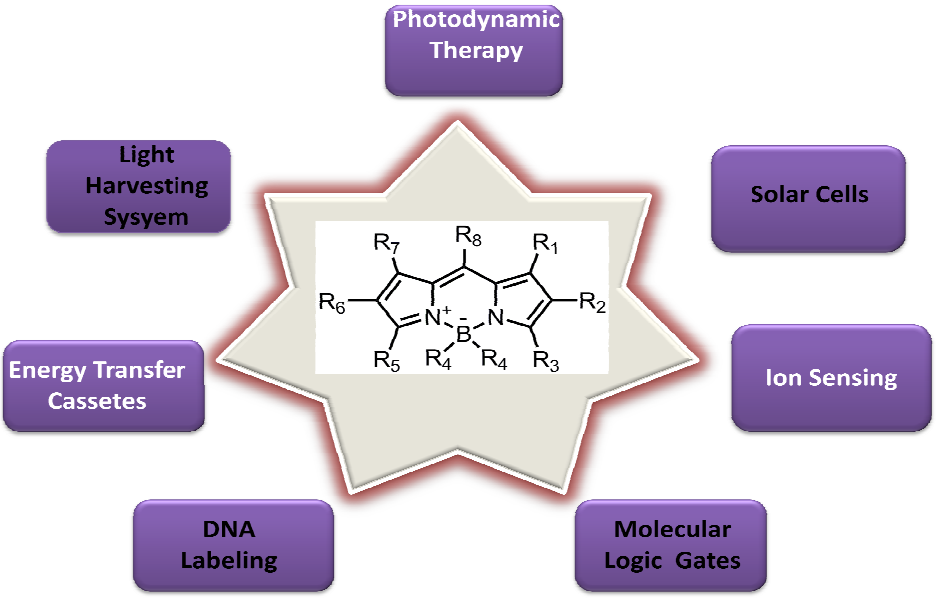


Figure 18 : Application areas of BODIPY Dyes

The R_1 , R_3, R_5 and R_7 on the BODIPY which is showed in the Figure 18 are the extension of the delocalisation and/ or other funtional groups. R_4 provides an increase in the Stokes' shift.

From the viewpoint of the environmental and biological issues, the chemosensors have a great importance. Hence, many research groups attempted to design new chemosensors. Our research group has reported a number of chemosensors in recent years[83-85]. (Compound **17, 18, 19**)

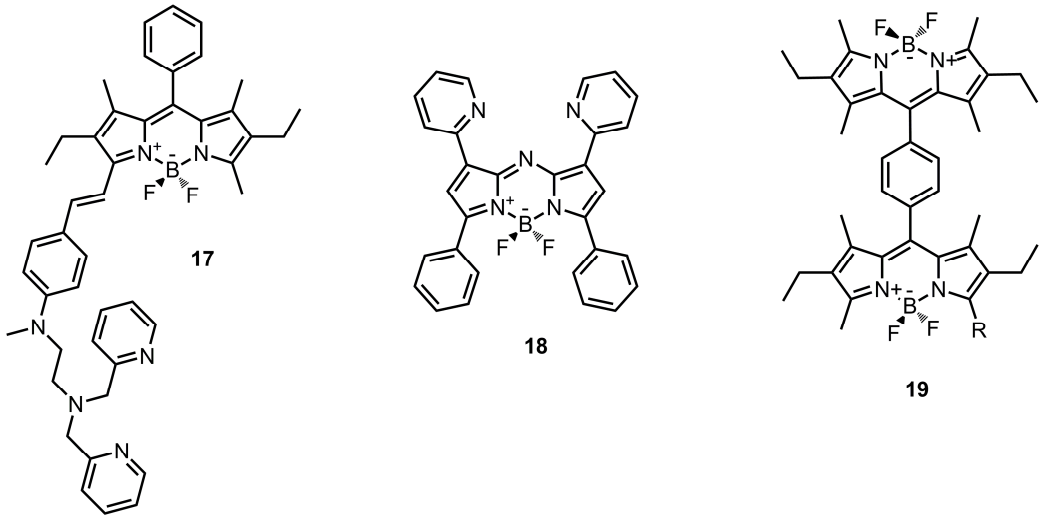


Figure 19 : BODIPY - based Chemosensors

Another potential application area of the BODIPY dyes is photodynamic therapy (PDT) which is a noninvasive treatment modality for various malignant and non-malignant diseases. The efficiency of the singlet oxygen generation and high absorption coefficient of the photosensitizer are the requirements for PDT and BODIPY dyes offset these requirements. Among the requirements, solubility of the photosensitizer in water has a paramount importance. Akkaya et al. have recently reported a BODIPY-based photosensitizer which fulfills these requirements[86].

1.2.3 BODIPY Dyes in the TPA Application

After the discovery of the TPA phenomena by Maria Göppert-Mayer in 1931[1], a great number of chromophores have been developed and introduced. However, many of these chromophores have some disadvantages such as low TPA cross section value, photostability of the chromophores, etc.

On the other hand, the interest in the designing novel chromophores which have large TPA cross section value has increased rapidly and a number of research groups have attempted to develop new chromophores which exhibit high TPA cross section and high fluorescence quantum yields[87].

Among these chromophores, BODIPY dyes have gained attraction because of their great photophysical and photochemical properties.

BODIPY-based two photon absorbing chromohores (Compound **20, 21, 22**) were synthesized by Xuhong et al.[88]. The goal of their work is to develop novel BODIPY dyes which have D-π-D structure (Figure 20). All of these compounds exhibit red emission. They attached substituents to the 2,6 positions of the BODIPY core in order to obtain long wavelength absorption because of the fact that the therapeutic window for biological tissue is between 650 and 800 nm. By introducing substituents on these positions of the BODIPY core, these BODIPYs become quite symmetric.

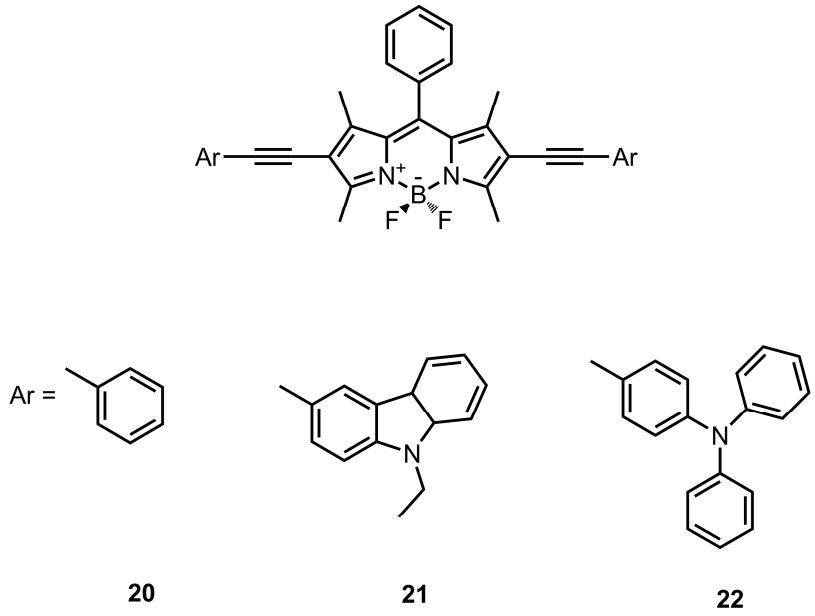
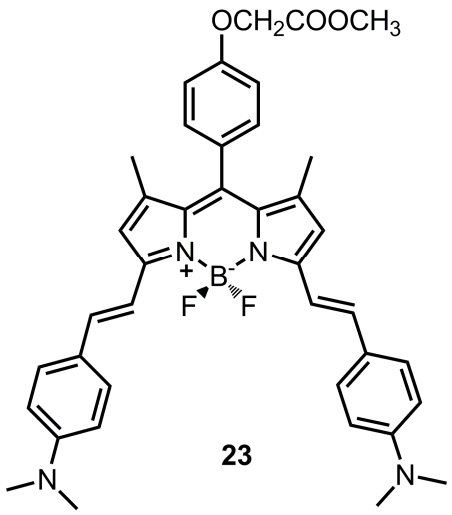


Figure 20 : BODIPY - based two photon absorbing chromophores

In these BODIPY compounds, Aryl-groups, which are triphenylamino and carbazole groups, act as a terminal electron donor group. BODIPY core acts as an electron withdrawing group. Ethynyl group is known as a common π bridge in the design of two photon absorbing chromophores and in these BODIPY dyes ethynyl π bridge is used as a π conjugated spacer.

Compounds **20, 21** and **22** have TPA cross section values of 29 GM, 46 GM and 60 GM respectively. Compound **21** and **22** show two photon absorption maximum at 670 nm and 687 nm successively.

Prasad *et al.* have recently reported on a BODIPY-based near IR two photon absorbing chromophore (Compound **23**) which is shown in Figure 21.

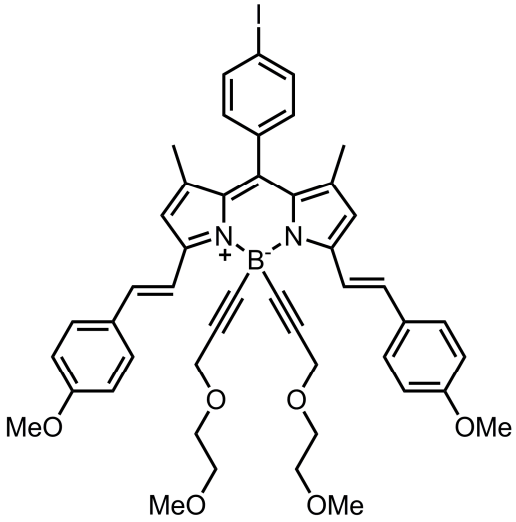


23

Figure 21 : Structure of the compound **23**

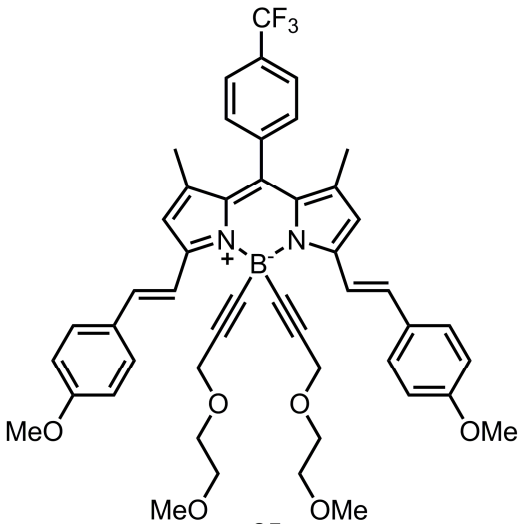
Compound **23** has a TPA cross section value of 110 GM at 1310 nm and D-A-D structure.

Ziessel *et al.* have recently introduced novel two photon absorbing chromophores (Compound **24** and **25**)[89] which are shown in the figures 22 and 23 respectively. They have designed a push-pull-push structure which is a paramount requirement for the TPA spectroscopy[2].



24

Figure 22 : Structure of the compound **24**



25

Figure 23 : Structure of the compound **25**

Compound **24** has a TPA cross section value of 72 GM around 780 nm. Compound **25** exhibits a TPA cross section value of 60 GM around 780 nm. The presence of the strong elecetron donating and electron withdrawing groups on the BODIPY core give rise to the intramolecular charge transfer which increases TPA cross section value substantially.

Andraud et al. developed two novel BODIPY-based two photon absorbing chromophores (Compound **26** and **27**)[90].

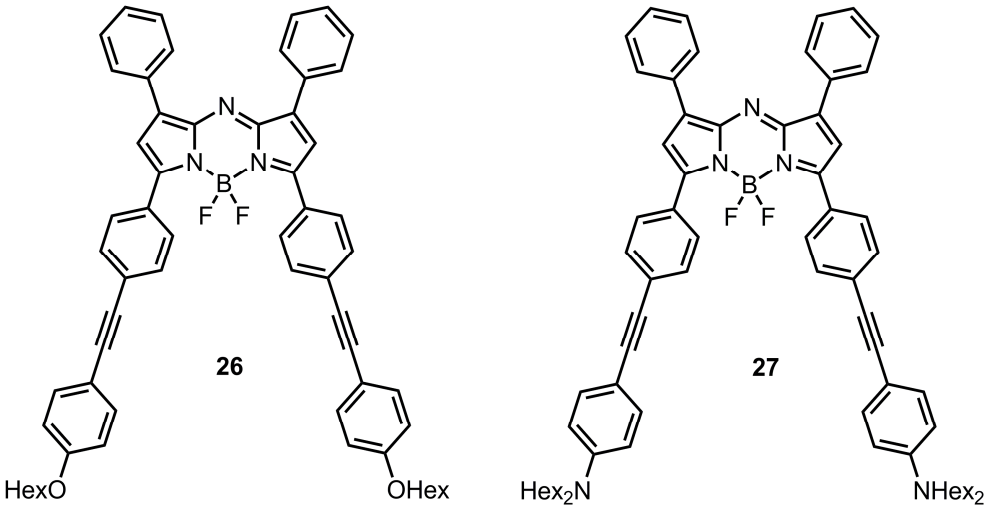


Figure 24: Structure of the compound **26** and **27**

They reported aza-BODIPYs which are functionalized by introducing the donor-π-conjugated groups. Compound **26** has a TPA cross section value of 600 GM between the wavelengths 1300 and 1450 nm, while compound **27** has a rather high TPA cross section value of 1070 GM at 1220 nm because of the fact that compound **27** has stronger electron donating group.

They introduced electron donating groups to the BODIPY core in order to alter the absorption spectrum of the into the near-IR spectral range.

Further design strategies of the two photon absorbing BODIPY dyes will be discussed in the following chapter.

CHAPTER 2

EXPERIMENTAL

2.1. Instrumentation

All chemicals and solvents purchased from Aldrich were used without further purification. ^{1}H-NMR and ^{13}C-NMR spectra were recorded using a Bruker DPX-400 in $CDCl_3$ with TMS as internal reference. Splitting patterns are designated as s(singlet), d (doublet), t (triplet), q (quartet), m (multiplet), p (pentet), dt (doublet of triplet), and br (broad). Column chromatography of all products was conducted using Merck Silica Gel 60 (particle size: 0.040-0.063 mm, 230-400 mesh ASTM) pretreated with eluent. Reactions were monitored by thin layer chromatography using fluorescent coated aluminum sheets.

Absorption spectrometry was performed using a Varian spectrophotometer. Varian Eclipse spectrofluorometer was used to determine the fluorescence emission spectra. All spectroscopy experiments were performed using spectrophotometric grade solvents. Mass spectroscopy measurements were conducted using MS-QTOF at Bilkent University, UNAM, Mass Spectrometry Facility

Quantum yields measurements and calculations were carried out using Rhodamine 6G (excitation 488 nm, THF), and two tetrastyryl-BODIPY dyes[91] (excitation 660 nm and 726 nm respectively) whose quantum yields are known as standard chromophores having quantum yields 0.95, 0.34 and 0.23 successively. All absorbance values were adjusted below 0.1 to avoid self quenching.

The following formula was used to calculate the quantum yields of the target compounds[92].

$$\mathbf{Q = Q_R\,(I/I_R)\ x\ (A_R/A)\ x\ (\ n^2/\ n_R^2)} \qquad (4)$$

where Q_R denotes the quantum yield of reference compound, I_R and I denote integrated area of emission spectrum of the reference and sample successively.

A and A_R stand for the absorbance of corresponding wavelength for sample and reference compounds respectively, n_R and n represent refractive indices of solvents in which standard compounds and samples were dissolved successively. Refractive index value of reference compounds were taken to be 1.4072 for THF, 1.333 for water, 1.4458 for chloroform and 1.3614 for ethanol. All samples were prepared in THF. Nonlinear properties of the compounds **28**, **29**, **30**, **31**, **32** and **33** were studied in THF solution.

Two photon absorption data for compounds **28** and **31** were obtained by Mr. Yaochuan Wang of the Department of Physics Fudan University, Shangai, P.R. China.

Additional experimental evidence for two photon absorption was obtained by Dr. Bülend Ortaç of UNAM, Bilkent University.

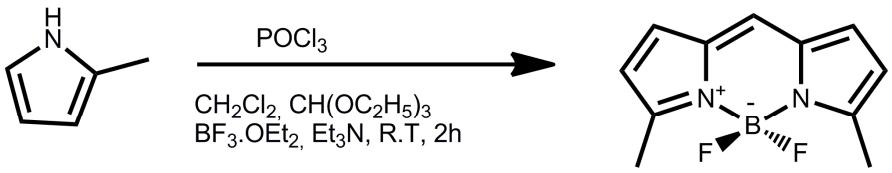
2.2.1 Synthesis of compound 28

2-methyl pyrrole (11.38 mmol, 923 mg) was added to a 250 mL round-bottomed flask containing 150 mL argon-degassed CH_2Cl_2. $CH(OC_2H_5)_3$ (5.69mmol, 0.946 mL) and $POCl_3$ (6.25 mmol, 0.58 mL) were successively added and was stirred for 1h. To the reaction mixture 8 mL Et_3N and 8 mL $BF_3.OEt_2$ were sequentially added. The reaction was monitored by TLC (eluent $CHCl_3$). After 30 min., the reaction mixture was washed three times with water and dried over anhydrous Na_2SO_4. After the evaporation of the solvent, silica gel column chromatography using $CHCl_3$ as the eluent was performed in order to purify the residue (220 mg, 57%).

^{1}H NMR (400 MHz, $CDCl_3$, 300K): δ_H = 7.06 (s, 1H), 6.95 (s, 2H), 6.27 (s, 2H)

^{13}C NMR (100 MHz, $CDCl_3$): δ_C = 158.2, 134.2, 130.1, 126.7, 119.5, 119.5, 119.5, 119.4, 14.9, 14.9, 14.8

HRMS (ESI) calcd for $C_{11}H_{11}BF_2N_2$ (M+H) 221.1061, found 221.1074 Δ = 5.8 ppm.



28

Figure 25: Synthesis of compound **28**

2.2.2 Synthesis of compound 29

2-methyl pyrrole(5.033 mmol, 408.2 mg) and 4-cyanobenzaldehyde (2.288 mmol, 300 mg) were dissolved in a 500 mL round-bottomed flask containing 350 mL argon-degassed CH_2Cl_2. To the reaction solution TFA (one drop) was added and stirred at r.t. for 24h.

After that, a solution of DDQ (2.29 mmol, 519.4 mg) in 100 mL CH_2Cl_2 was added to the reaction mixture. After addition of a DDQ solution, the reaction solution was stirred for additional 1 h. Then, 3 mL NEt_3 and 3 mL $BF_3.OEt_2$ were added. TLC was used to monitor the reaction. (eluent $CHCl_3$)

The reaction mixture was additionally stirred for 30 min. Thereafter, the resulting solution was washed three times with water and dried over anhydrous Na_2SO_4. After the evaporation of the solvent, silica gel column chromatography using $CHCl_3$ as the eluent was performed in order to purify the residue (251 mg, 34.28%).

^{1}H NMR (400 MHz, $CDCl_3$, 300K): δ_H = 7.80 (d, 2H, J= 7.4 Hz), 7.60 (d, 2H, J=7.3 Hz) 6.60 (s, 2H), 6.30 (s, 2H), 2.65 (s, 6H)

^{13}C NMR (100 MHz, $CDCl_3$): δ_C = 158.8, 138.6, 134.1, 132.1, 131.2, 130.1, 120.1, 118.1, 114.0, 46.7, 14.9, 8.6

HRMS (ESI) calcd for $C_{18}H_{14}BF_2N_3$ (M+H) 320.1171, found 320.1176 Δ = 1.5 ppm.

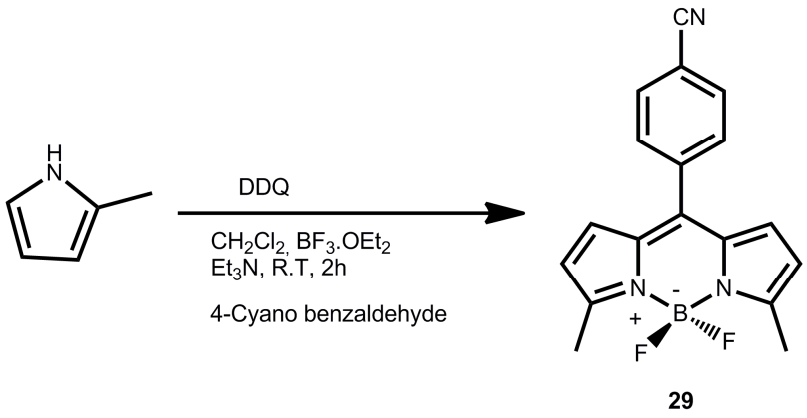


Figure 26 : Synthesis of compound **29**

2.2.3 Synthesis of compound 30

Compound **29** (0.23 mmol, 75 mg) and 4-(2-ethylhexyl)oxybenzaldehyde (0.7 mmol, 164.19 mg) were dissolved in benzene(25 mL). Piperidine (0.5 mL) and glacial acetic acid (0.5 mL) were successively added to the reaction mixture and refluxed for 2 h in the presence of Dean-Stark apparatus. The progress of the reaction was monitored by TLC (eluent $CHCl_3$).

Benzene was evaporated in vacuo and then silica gel column chromatography was carried out to purify the residue ($CHCl_3$ as eluent) (165 mg, 94.66%).

^1H NMR (400 MHz, $CDCl_3$, 300 K): δ_H = 7.80 (d, J= 7.8 Hz, 2H), 7.68-7.56 (m, 6H), 7.32 (d, J= 16.2 Hz, 2H), 6.97-6.89 (m, 4H), 6.66 (d, J= 3.84 Hz), 3.85 (d, 5.4 Hz), 1.75(t, J= 5.7 Hz, 2H), 1.60-1.28(m, 14H), 0.99-0.88(m, 14H)

^{13}C NMR (100 MHz, $CDCl_3$): δ_C = 160.7, 155.7, 139.2, 137.3, 135.5, 132.0, 131.0, 129.3, 128.9, 128.5, 118.2, 116.8, 116.6, 114.9, 113.3, 70.7, 39.3, 30.5, 29.0, 23.8, 23.0, 14.0, 11.1

HRMS (ESI) calcd for $C_{48}H_{58}BF_2N_3O_2$ (M+H) 754.4355, found 754.4419 Δ = 8.5 ppm.

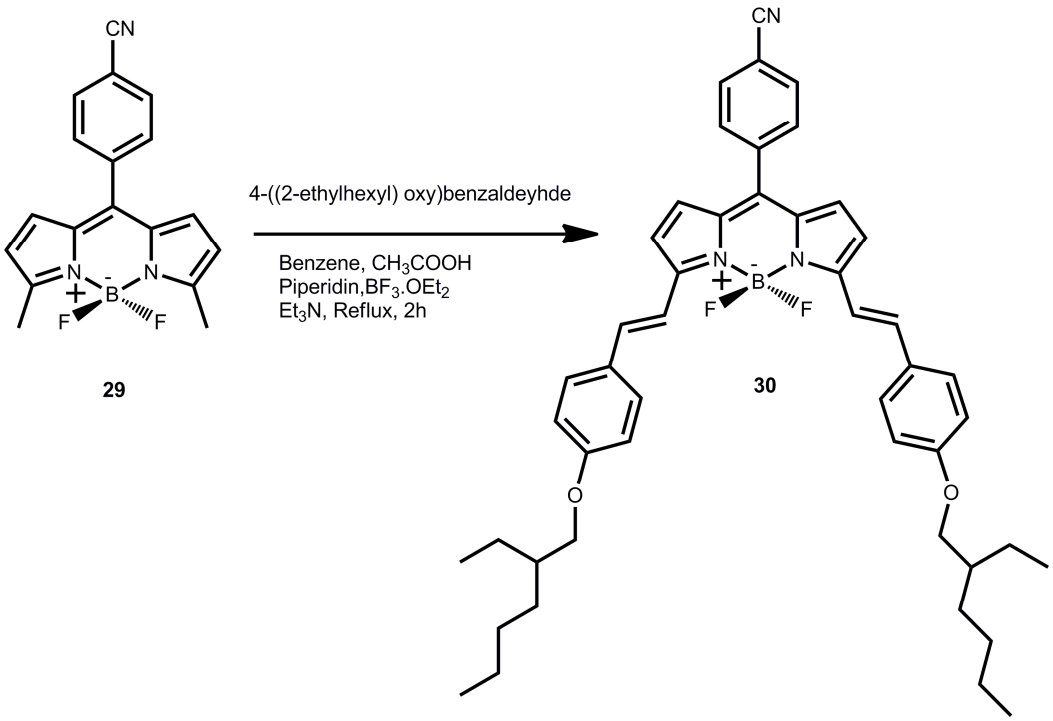


Figure 27: Synthesis of compound **30**

2.2.4 Synthesis of compound 31

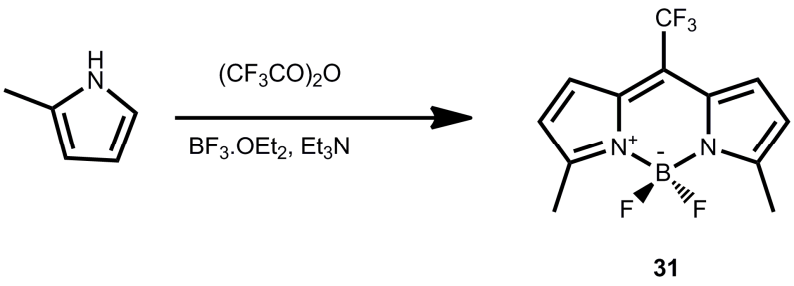
Trifluroaceticacidanhydride (5.85 mmol, 0.82mL) was dropwise added into a 200 mL round bottom flask containing 2-methyl pyrrole(11.71 mmol, 950 mg). The reaction solution was stirred for 20 min. at room temperature. The combined organic mixture was dissolved in 200 mL argon-degassed CH_2Cl_2 and was stirred for 1h. After that, to the reaction mixture 1.5 mL Et_3N and 1.5 mL $BF_3.OEt_2$ were sequentially added and it was stirred for 1h. The resulting solution was washed three times with water and dried over anhydrous Na_2SO_4. The solvent was removed in *vacuo* and then silica gel column chromatography was carried out to purify the residue (as eluent $CHCl_3$). The orange colored fraction was collected (165 mg, 9.79 %).

^{1}H NMR (400 MHz, $CDCl_3$, 300K): δ_H = 7.25 (s, 2H), 6.36 (s, 2H), 2.68 (s, 6H)

^{13}C NMR (100 MHz, $CDCl_3$): δ_C = 161.7, 131.6, 130.3, 123.8, 121.6, 29.6, 15.4

HRMS (ESI) calcd for $C_{18}H_{14}BF_2N_3$ (M-H) 287.0779, found 287.0804

Δ = 8.7 ppm



31

Figure 28 : Syntesis of compound **31**

2.2.5 Synthesis of compound 32

Compound **31** (0.138mmol, 40 mg) and 4-(2-ethylhexyl)oxybenzaldehyde (0.416 mmol, 97.63 mg) were dissolved in benzene(20mL). Piperidine (0.5 mL) and glacial acetic acid (0.5 mL) were successively added to the reaction solution and refluxed for 15 minutes in a Dean-Stark apparatus. The progress of the reaction was monitored by TLC (eluent $CHCl_3$/Hexane) (2:1)

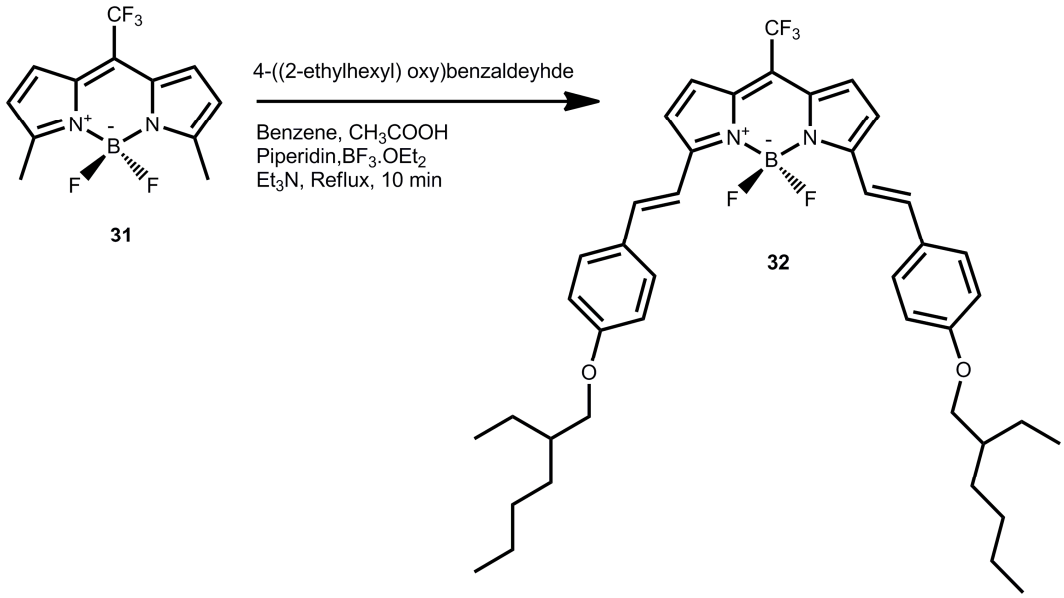
Benzene was evaporated in *vacuo* and then silica gel column chromatography was carried out to purify the residue (80 mg, 80.44 %).

^{1}H NMR (400 MHz, $CDCl_3$, 300 K): δ_H = 7.69-7.61 (m, 6H), 7.41 (d, J= 16.0 Hz, 2H), 7.28 (d, J= 21.3 Hz, 2H), 7.03 (d, 4.8 Hz, 2H), 6.95 (d, 8.7 Hz, 4H), 3.92 (d, 5.6 Hz, 4H), 1.82-1.73 (m, 2H), 1.60-1.27 (m, 16H), 1.00-0.88 (m , 12H)

^{13}C NMR (100 MHz, $CDCl_3$): δ_C = 161.1, 157.0, 139.0, 133.4, 129.6, 128.8, 128.4, 128.3, 117.9, 116.7, 115.0, 70.7, 39.3, 30.5, 29.1, 23.8, 23.0, 14.0, 11.1

HRMS (ESI) calcd for $C_{42}H_{50}BF_2N_2O_2$ (M+H) 721.3964, found 721.3985

Δ = 2.9 ppm.



2.2.6 Synthesis of compound 33

Compound **31** (0.138mmol, 40 mg) and 4,4-dimethylaminobenzaldehyde (0.416 mmol, 97.63 mg) were dissolved in benzene(20mL). To the reaction mixture piperidine (0.5 mL) and glacial acetic acid (0.5 mL) were successively added and refluxed for 10 minutes in a Dean-Stark apparatus. The progress of the reaction was monitored by TLC (eluent $CHCl_3$/Hexane) (1:1).

Crude product was concentrated under vacuum. The purification of the crude product was performed by using silica gel column chromatography Benzene was evaporated *in vacuo* and then purified by silica gel column chromatography (eluent $CHCl_3$/Hexane) (1:1) (40 mg, 52.66 %)

^{1}H NMR (400 MHz, $CDCl_3$, 300 K): δ_H = 7.60 (m, 4H+2H), 7.36 (d, 2H, J= 14.7 Hz), 7.23 (s, 2H), 6.98 (br, 2H), 6.75 (d, 4H, J= 7.0), 3.10 (s, 12H)

^{13}C NMR (100 MHz, $CDCl_3$): δ_C = 156.6, 151.5, 145.7, 139.2, 130.9, 129.8, 127.4, 124.8, 117.5, 114.8, 112.0, 40.2, 28.9, 23.0, 14.1, 11.0

HRMS (ESI) calcd for $C_{30}H_{28}BF_5N_4$ (M+H) 551.2405, found 551.2564

Δ = 28.9 ppm.

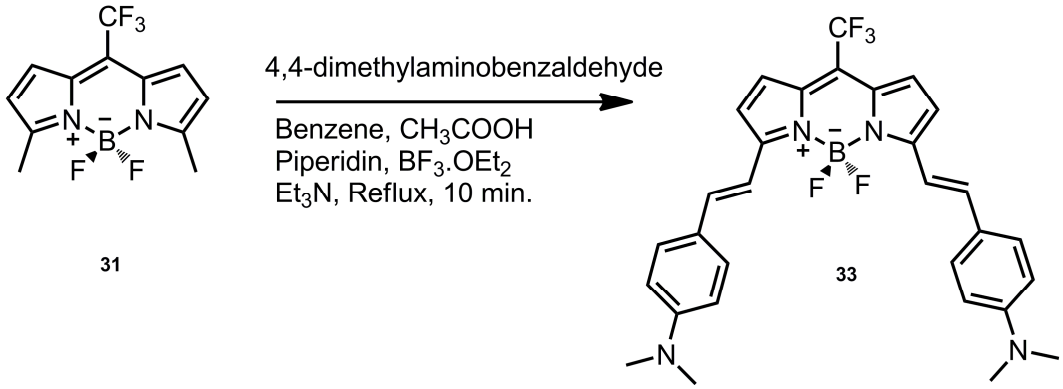


Figure 29 : Syntesis of compound **33**

CHAPTER 3

RESULTS AND DISCUSSIONS

3.1 Aim of the Project

Design and synthesis of two photon absorbing chromophores have attracted plenty of attention in recent years because of their potential applications.

In this study, we have designed and successfully synthesized a novel class of BODIPY derivatives which are expected to exhibit TPA features. We synthesized our target compounds using standard BODIPY chemistry.

As mentioned in chapter one, the choice of the terminal group for the design of two photon absorbing chromophores is of prime importance and D-A-D arrangement is the best in terms of high TPA cross section value. Due to the remarkable features of the BODIPY dyes, such as photostability, good solubility high quantum yields, etc., they are promising compounds for the design of the two photon absorbing chromophores.

Hence, we designed and synthesized compound **30**, **32** and **33** which have D-A-D structure and inherent polarization of the BODIPY core. We also synthesized compound **28**, **29** and **31** in order to have a series of BODIPY derivatives and compare the two photon absorption cross section values of these BODIPY derivatives.

3.2 Design and Synthesis of the Compounds 28, 29 and 31

In order to investigate the effect of the electron withdrawing group on the *meso* position of the BODIPY core, we designed and synthesized compound **28**, **29** and **31**.

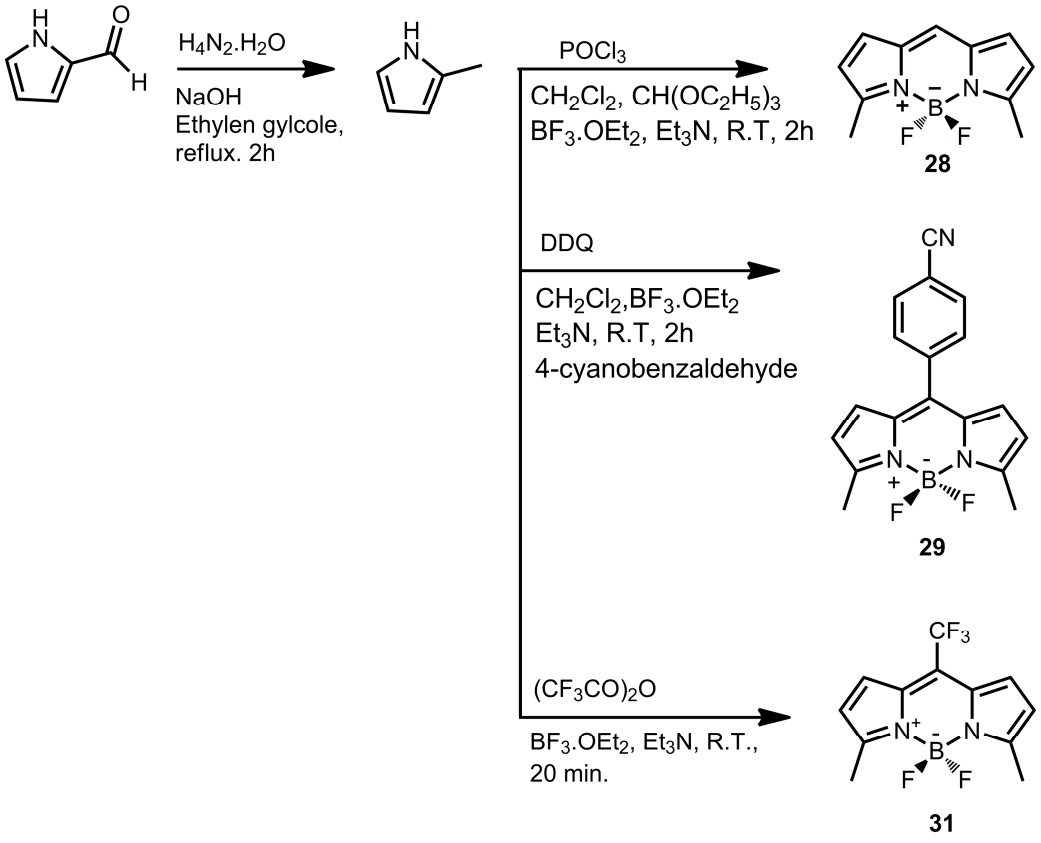


Figure 30 : Reaction scheme for the synthesis of the compounds **28, 29** and **31**

First, we synthesized 2-methyl pyrrole via Wolf-Kischner reduction starting with pyrrole-2-carboxaldehyde. After the synthesis of the 2-methyl pyrrole, we synthesized dimethyl substitued compound **28** which can be considered as a reference to the compounds **29** and **31.** The synthetic pathway for the compound **28** is shown in Figure 30.

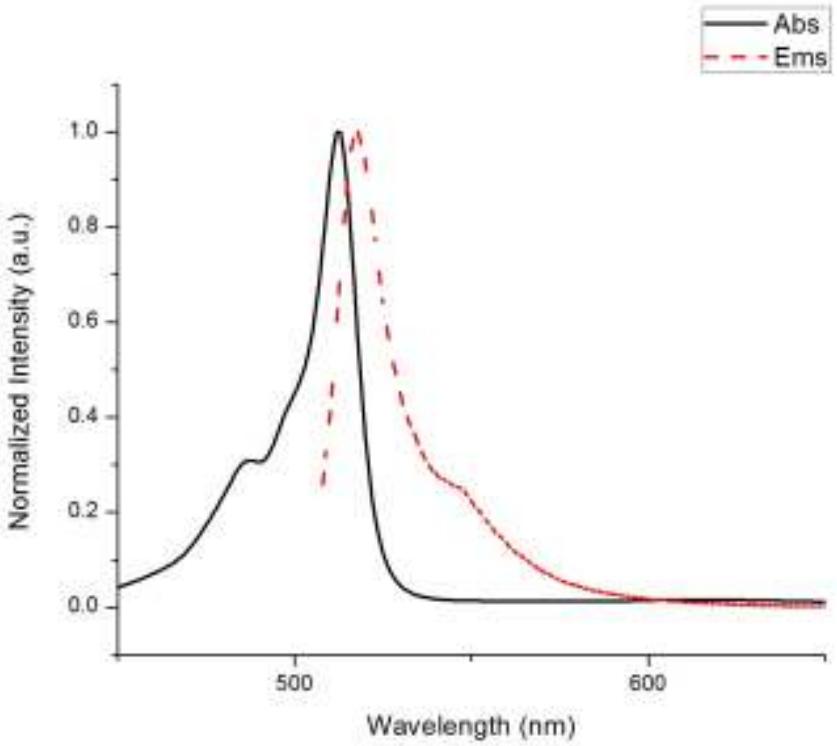


Figure 31 : The absorbance and emission spectra of the compound **28.**

The absorption λ_{max} of compound **28** is at 512 nm and its emission is at 518 nm (Figure 31). The structure of the compound **28** was confirmed by ^{1}H NMR, ^{13}C NMR, mass spectroscopy (Appendix A and B). In the ^{1}H NMR spectrum of the compound **28**, pyrrolic hydrogens resonate at 6.24 ppm and 6.95 ppm. Bridging methine hydrogen at the *meso* position of the BODIPY core resonates at 7.08 ppm.

The synthesis of the compound **29** is accomplished by the reaction of 2-methyl pyrrole with 4-cyanobenzaldehyde under the usual conditions for BODIPY synthesis. In this usual manner of the BODIPY synthesis, 4-cyanobenzaldeyhde reacts with 2-methyl pyrrole in the presence of TFA and DDQ at room temperature, followed by the addition of $BF_3.OEt_2$ and Et_3N. The synthetic pathway for the compound **29** is shown in Figure 30.

Compound **29** has cyanobenzo group on the *meso* position of the BODIPY core as an electron withdrawing group. The presence of 4-cyanobenzo group at the *meso* position of the BODIPY core as an electron withdrawing group gives rise to 5 nm red shift.

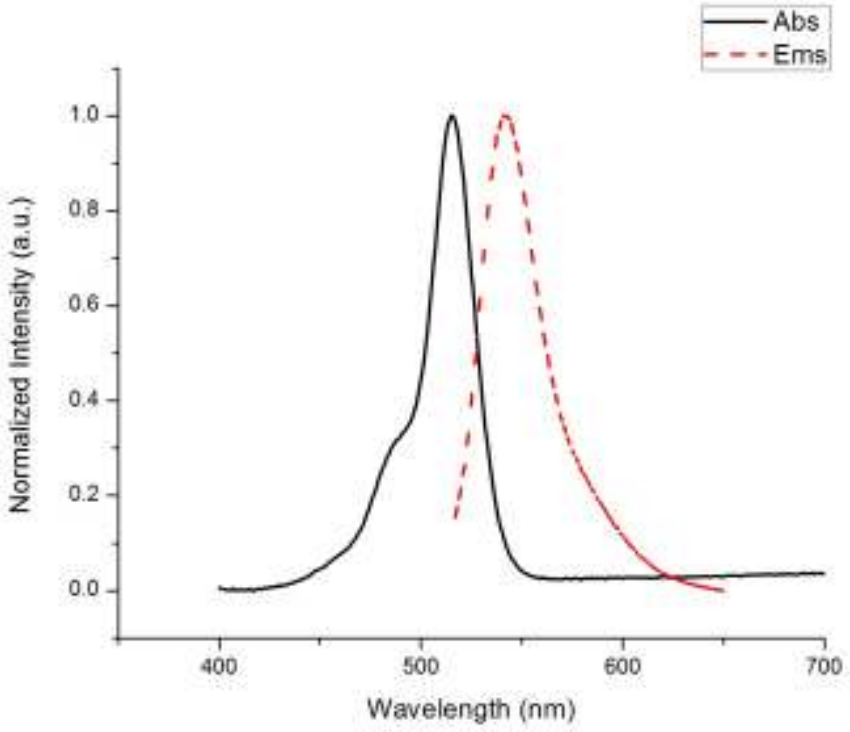


Figure 32 : The absorbance and emission spectra of the compound **29.**

The absorption λ_{max} of compound **29** is at 517 nm and its emission is at 541 nm (Figure 32). The structure of the compound **29** was confirmed by ^{1}H NMR, ^{13}C NMR, mass spectroscopy (Appendix A and B).

In the ^{1}H NMR of the compound **29**, there is no more peak of the pyrrolic hydrogen at the *meso* position of the BODIPY core because compound **29** has a cyanobenzo group at this position. Furthermore, we observed that aromatic hydrogens of the compound **29** resonate at 7.61 ppm as doublet (J = 7.3 Hz) and at 7.77 ppm as doublet (J = 7.4 Hz). Pyrrolic H's resonate at 6.26 ppm and at 6.61 ppm.

The synthesis of the compound **31** is accomplished by the reaction of 2-methyl pyrrole with trifluoroacetic anhydride, followed by the addition of $BF_3.OEt_2$ and Et_3N. The synthetic pathway for the compound **31** is shown in Figure 30.

Compound **31** has trifluoromethyl group on the *meso* position of the BODIPY core as an electron accepting group. The presence of trifluoromethyl group at the *meso* position of the BODIPY core as an electron withdrawing group gives rise to an almost 30 nm red shift.

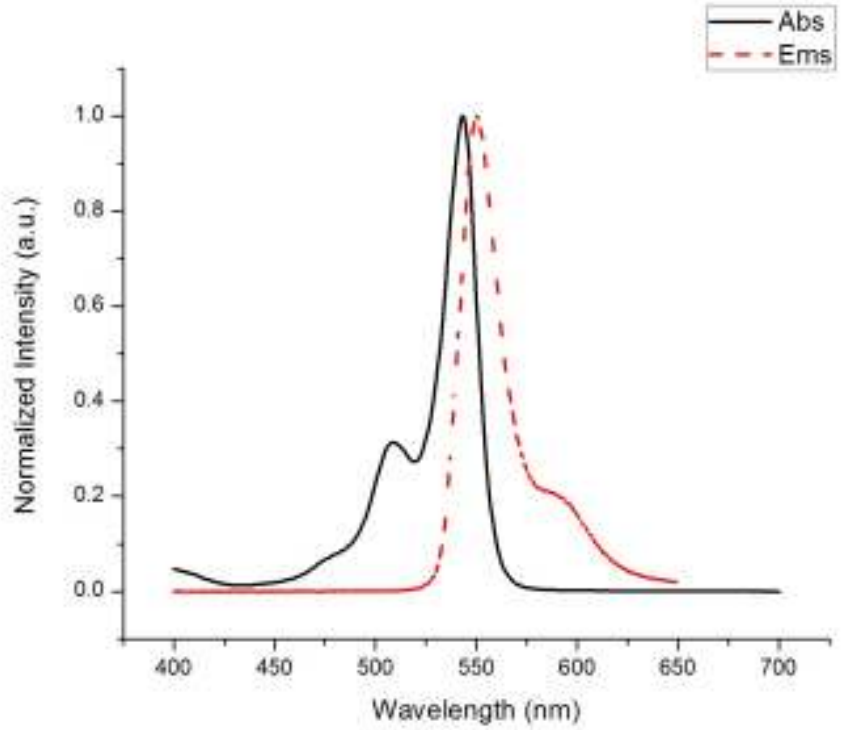


Figure 33 : The absorbance and emission spectra of the compound **31.**

The absorption λ_{max} of compound **31** is at 543 nm and its emission is at 550 nm (Figure 33). The structure of the compound **31** was confirmed by ^{1}H NMR, ^{13}C NMR, mass spectroscopy. Compared to the compound **28**, the BODIPY core of the compound **31** is electron deficient because of the presence of trifluoromethyl group at the *meso* position of the BODIPY core. Consequently, the aromatic hydrogen peaks of the compounds **31** are shifted downfield (Appendix A and B).

3.3 Design and Synthesis of the Compounds 30, 32 and 33

To enhance TPA cross section, we attached electron withdrawing groups at the *meso* position of the BODIPY cores and introduced different electron donating alkoxy- and dialkylamino groups to the 3 and 5 positions of the BODIPY cores. As a result, we created a D-A-D structure and increased the extent of the conjugation.

Furthermore, the extent of charge transfer from the terminus of the compounds to the core also expected to give rise to a substantial enhancement of the TPA cross section value. Attachment of the electron donor terminal groups to the BODIPY cores were performed *via* Knoevenagel condensation.

Introducing electron donor groups to the BODIPY cores results in a substantial red shift, as can be seen by comparing the absorption maxima of compounds **30, 32** and **33** in Figure 34.

Since we were interested in designing and synthesizing two photon absorbing chromophores which have absorption maxima especially in the near-IR region of the spectrum, we introduced electron donating terminal groups to the BODIPY cores, through styryl groups, thus extending the conjugation at the same time.

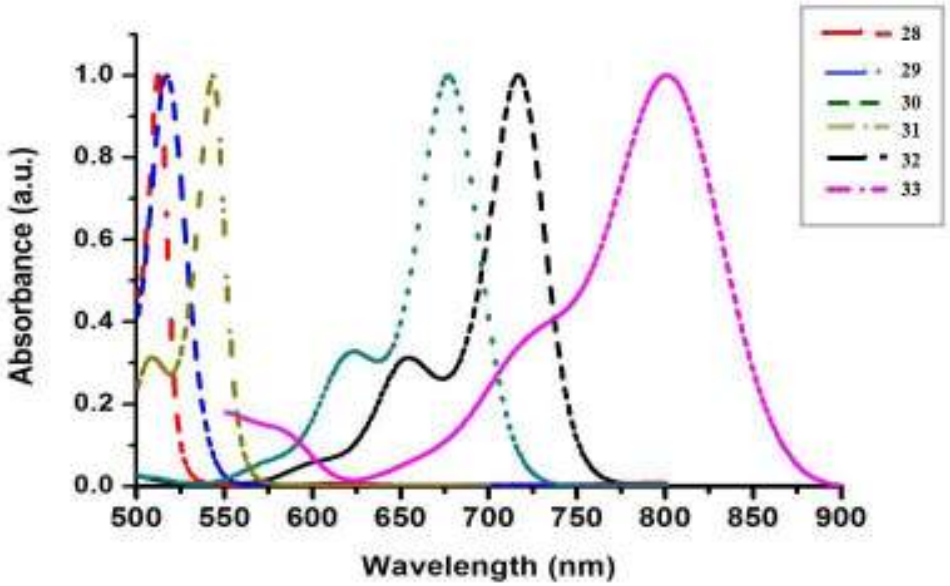


Figure 34 : Absorbance spectra of the compounds **28, 29, 30, 31, 32** and **33.**

After the attachment of the 4,4-dimethylaminobenzaldehyde *via* Knoevenagel condensation to the BODIPY core of the compound **31**, we obtained compound **33**. This attachment gives rise to a spectacular 257 nm red shift. The synthetic pathway for the compound **33** is shown in Figure 35.

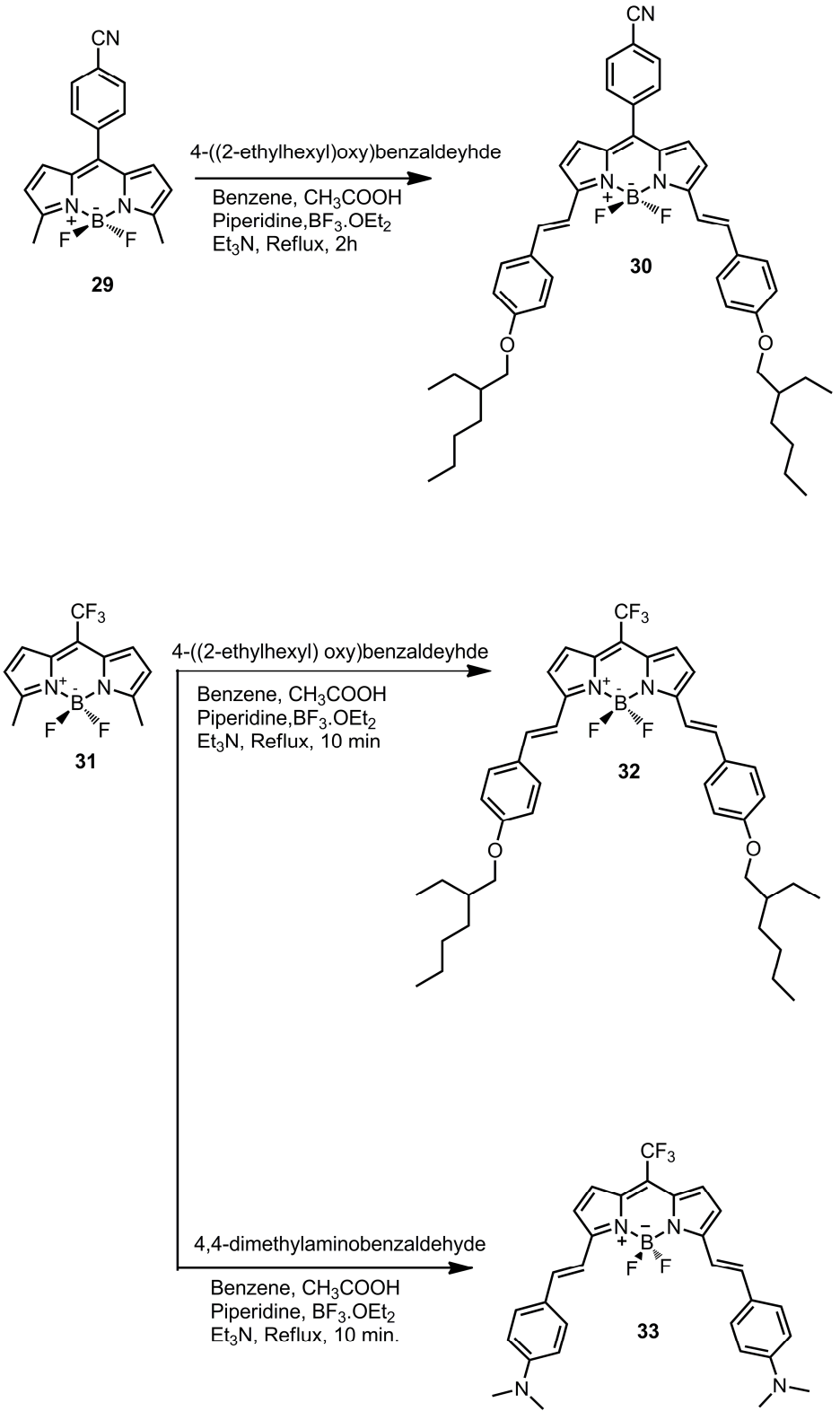


Figure 35 : Reaction scheme for the synthesis of compounds **30, 32** and **33.**

Because of the fact that methyl groups neighboring the BF_2 bridges are slightly acidic, the condensation of these groups with aldehyde results in distyryl BODIPY derivative which has longer wavelength absorption due to the extension of conjugation[93].

The absorption λ_{max} of compound **33** is at 800 nm and its emission is at 844 nm (Figure 36). The structure of the compound **33** was confirmed by ^1H NMR, ^{13}C NMR, mass spectroscopy. In the ^1H NMR spectrum of the compound **33** at 7.38 ppm, we observed trans coupling of newly formed olefinic hydrogens (J = 14.7 Hz) indicating formation of the *trans* (*E*) double bond.

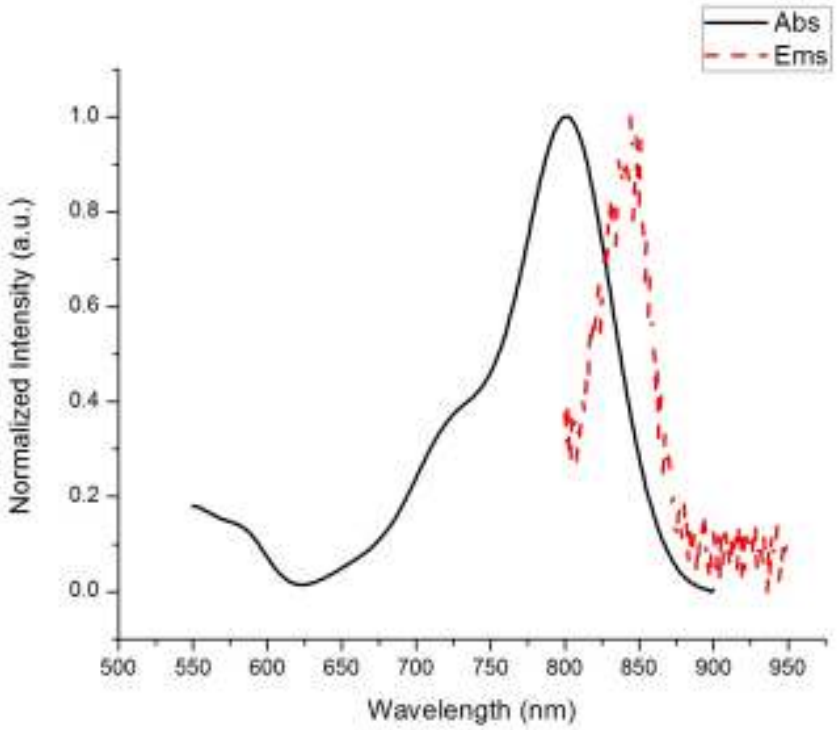


Figure 36 : The absorbance and emission spectra of the compound **33.**

We also introduced another electron donating terminal group (which is 4-(2-ethylhexyl)oxybenzaldehyde) to the compound **31** in order to have D-A-D motif. As a result, we obtained compound **32.** The attachment of the electron donating group 4-(2-ethylhexyl)oxybenzaldehyde gives rise to almost 175 nm red shift (Figure 34).

The absorption λ_{max} of compound **32** is at 717 nm and its emission is at 740 nm (Figure 37). The structure of the compound **32** was confirmed by ^{1}H NMR, ^{13}C NMR, mass spectroscopy. In the ^{1}H NMR spectrum of the compound **32** at 7.41 ppm, we observed trans coupling of newly formed olefinic hydrogens (J = 16.0 Hz) indicating formation of the *trans* (*E*) double bond.

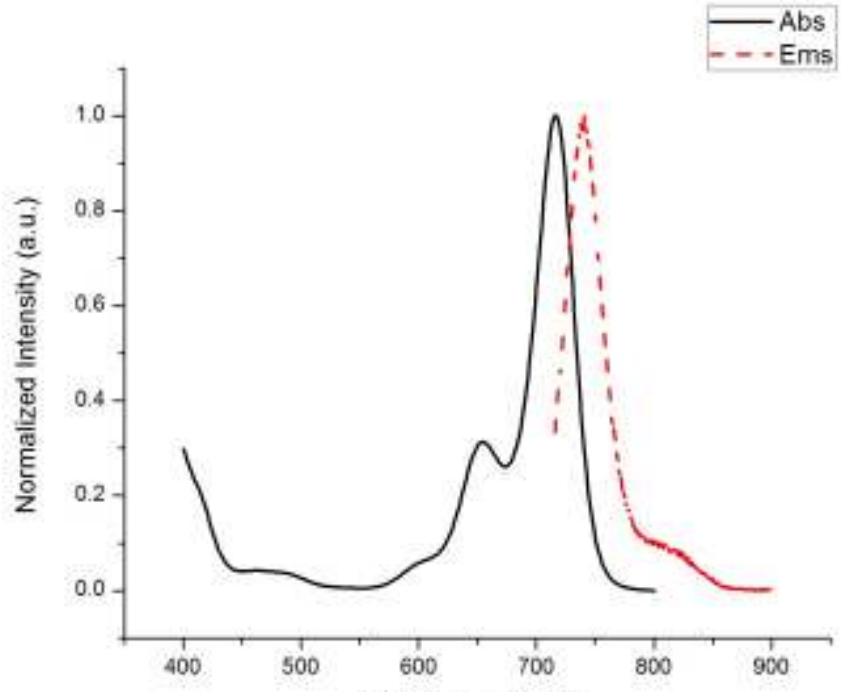


Figure 37 : The absorbance and emission spectra of the compound **32.**

Because of the fact that 4,4-dimethylaminophenyl is stronger electron donating group than 4-(2-ethylhexyl)oxyphenyl group, compound **33** is much more red shifted compared to the compound **32.**

Electron donating terminal group (which is 4-(2-ethylhexyl)oxybenzaldehyde) was also introduced to the compound **29** in order to have D-A-D motif. As a result, we obtained compound **30.** The attachment of the electron donating group 4-(2-ethylhexyl)oxybenzaldehyde gives rise to 160 nm red shift (Figure 34).

The absorption λ_{max} of compound **30** is at 677 nm and its emission is at 708 nm (Figure 38). The structure of the compound **30** was confirmed by ^{1}H NMR, ^{13}C NMR, mass spectroscopy. In the ^{1}H NMR spectrum of the compound **30** at 7.32 ppm, we observed trans coupling of newly formed olefinic hydrogens (J = 16.2 Hz) indicating formation of the *trans* (*E*) double bond.

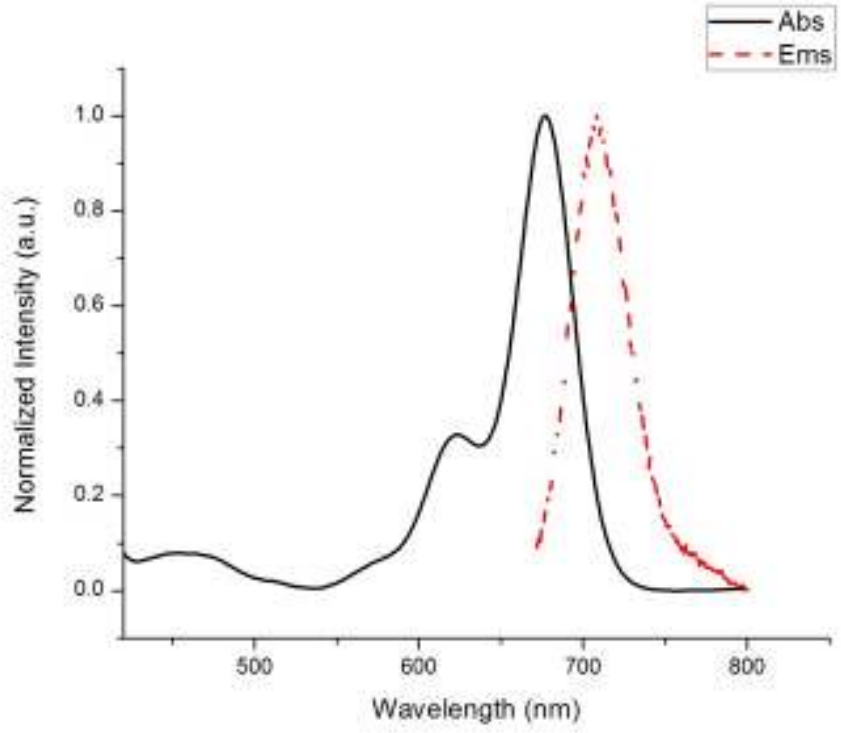


Figure 38 : The absorbance and emission spectra of the compound **30.**

Attaching electron withdrawing groups to the *meso* position of the BODIPY core gives rise to the a slight red shift, as can be seen by comparing the absorption maxima of the compounds **28**, **29** and **31** in the Figure 34. Because of the fact that trifluoromethyl group is stronger electron withdrawing group compared to the cyanobenzo group, the absorption maximum of the compound **31** has 24 nm more red shift than compound **29** does.

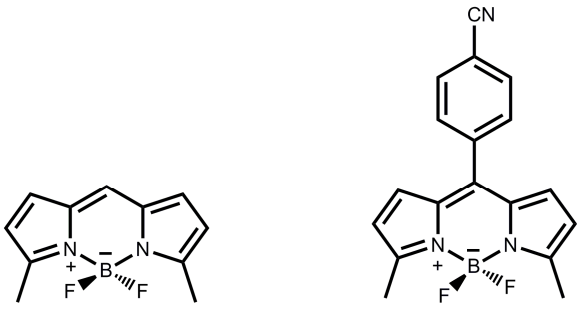


Figure 40 : The structure of the target compounds **28** and **29.**

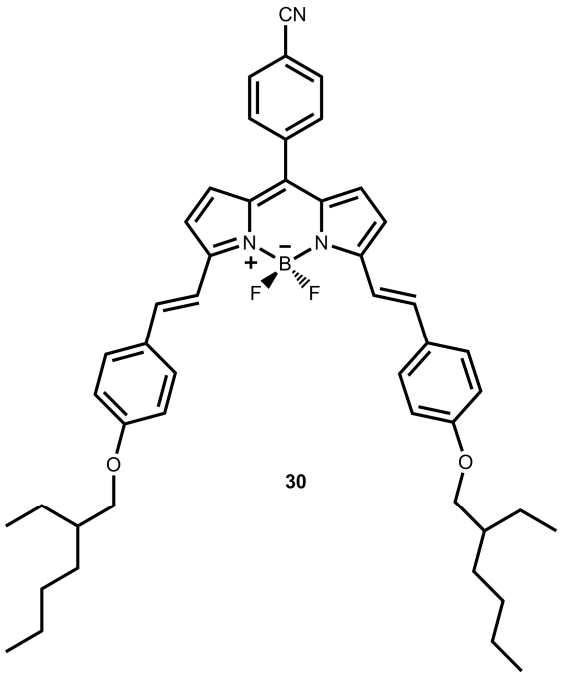


Figure 39: The structure of the target compound **30.**

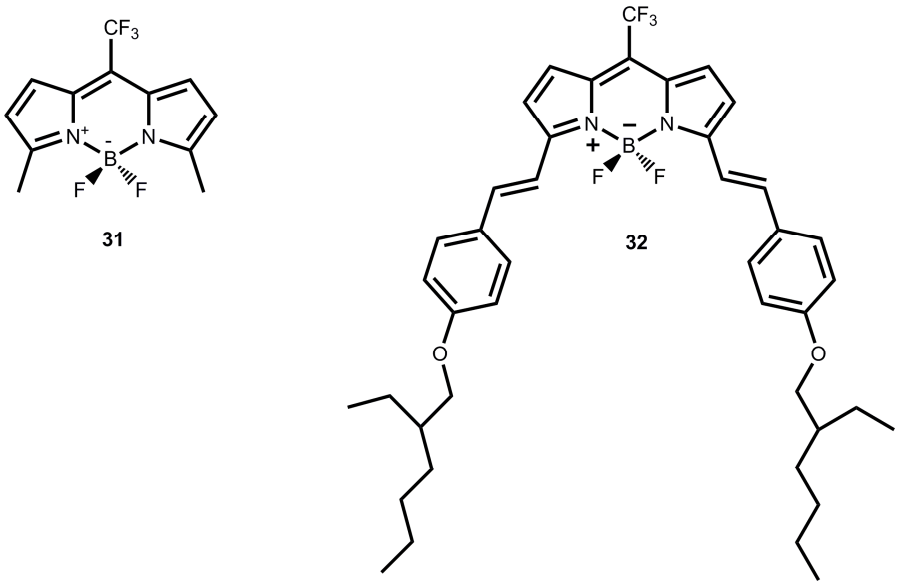


Figure 41 : The structure of the target compounds **31** and **32.**

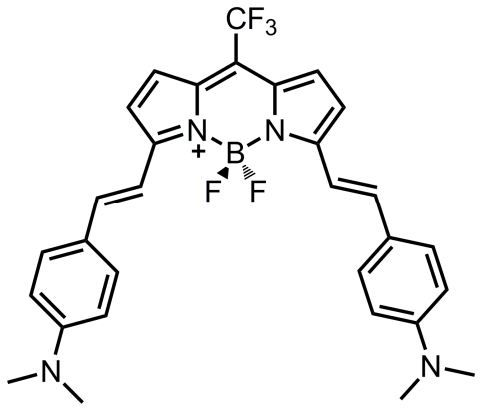


Figure 42 : The structure of the compound **33**

Compound	$\lambda_{max\ (abs)}$ (nm)	$\lambda_{max\ (ems)}$ (nm)	Φ_F $\lambda_{exc(480nm)}$
28	512	518	0.65 [a]
29	517	541	0.07 [a]
30	677	708	0.59[b]
31	543	550	0.41 [a]
32	717	740	0.078[c]
33	800	844	0.004[c]

Table 2 : Single photon absorption of compounds **28-32 in** $CHCl_3$ and quantum yields of compounds **28-33** in THF, a) Excitation at 480 nm b) Excitation at 660 nm c) Excitation at 726 nm.

We used four different reference compounds to calculate quantum yields of our target compounds. These are fluorescein (496 nm, water), Rhodamine 6G (480 nm, EtOH), and two tetrastyryl-BODPIYs (660 nm, THF and 726 nm, THF respectively). In order to have accurate results, absorbance and emission spectra of our target compounds and reference compounds should overlap. Hence, all calculations were performed using reference compounds with suitable overlap of spectra for each compound.

3.4 Two Photon Absorption Measurements

Two photon absorption properties of our target compounds were investigated experimentally by means of a TPEF technique with femtosecond pulsed excitation.

Two photon absorption cross section of the compounds **28** and **31** were measured in THF by two-photon excited fluorescence (TPEF) method.

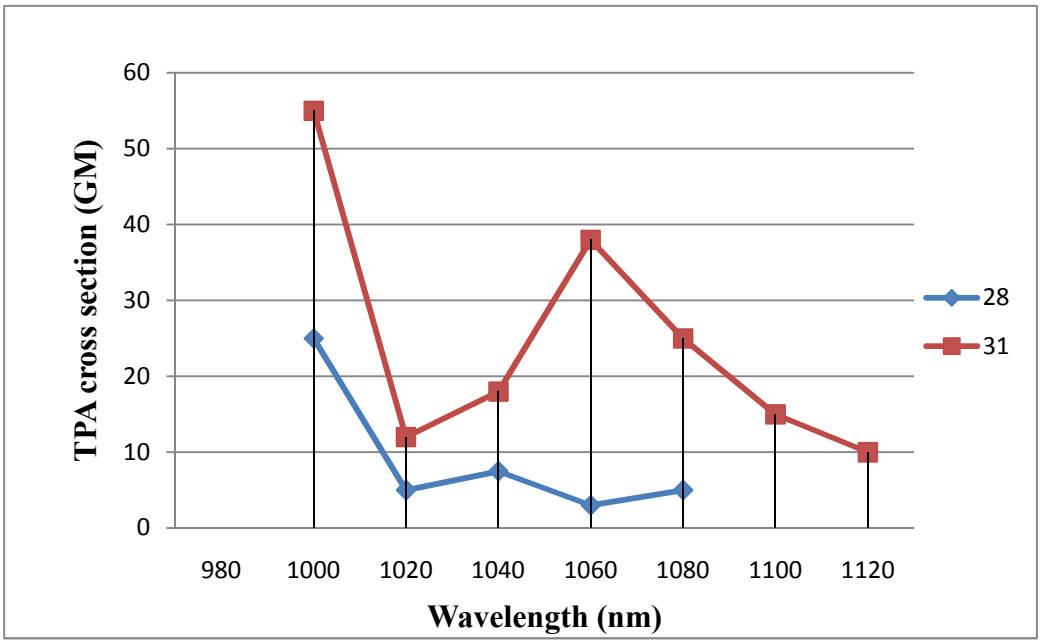


Figure 43 : Two photon absorption cross sections of compounds **28** and **31** in THF.

Compound **28** exhibits moderate two photon absorption cross section value. It has of 25 GM at 1000 nm. While compound **28** shows a rather small TPA cross section, compound **31** exhibits significant TPA cross section, 55 GM at 1000 nm.

TPEF measurements were performed in the 1000–1600 nm spectral range.

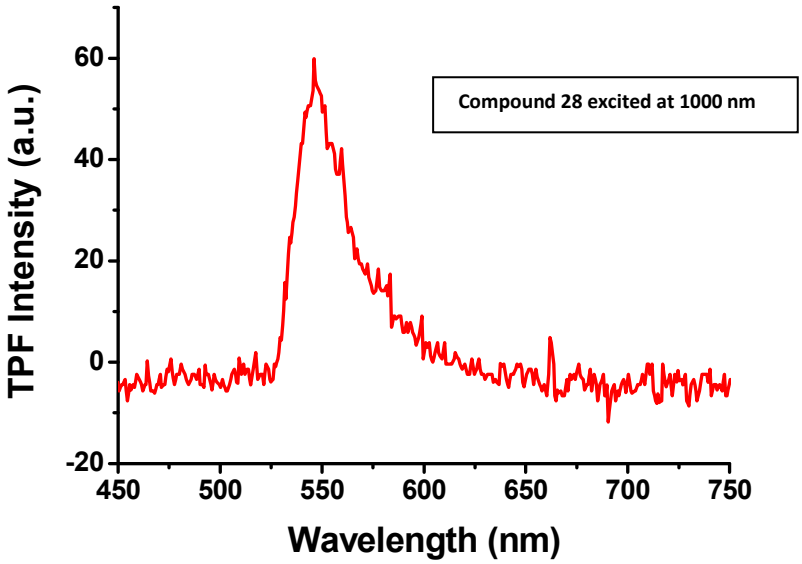


Figure 44 : TPF spectra of Compound **28.**

Compound **31** has a larger two photon absorption cross section compared to the compound **28** because of the fact that the electron withdrawing group trifluoromethyl on the *meso* position of the compound **31** pulls electron density itself and enhances charge transfer efficiency.

Two photon absorption cross section values of the compounds **30**, **31** and **32** cannot be detected by using TPEF method since their quantum yields are too low.

The GM values of these compounds can be determined via another technique known as ‘‘z-scan’’ technique[22]. However, we proved that compound **32** absorbs two photons by using the Tsunami® mode-locked Ti: Sapphire laser method with 100 fs pulse duration. (Figure 47)

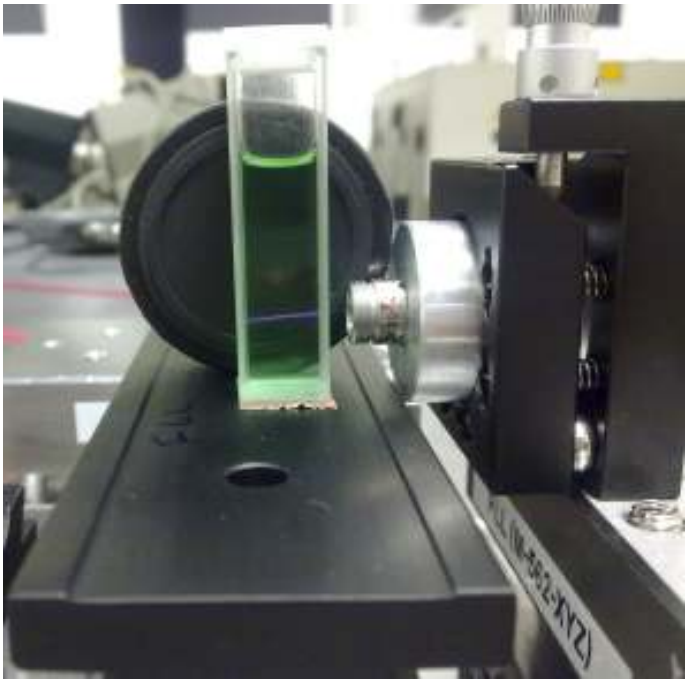


Figure 45 : Single photon excitation of compound **32** by focused light at 750 nm.

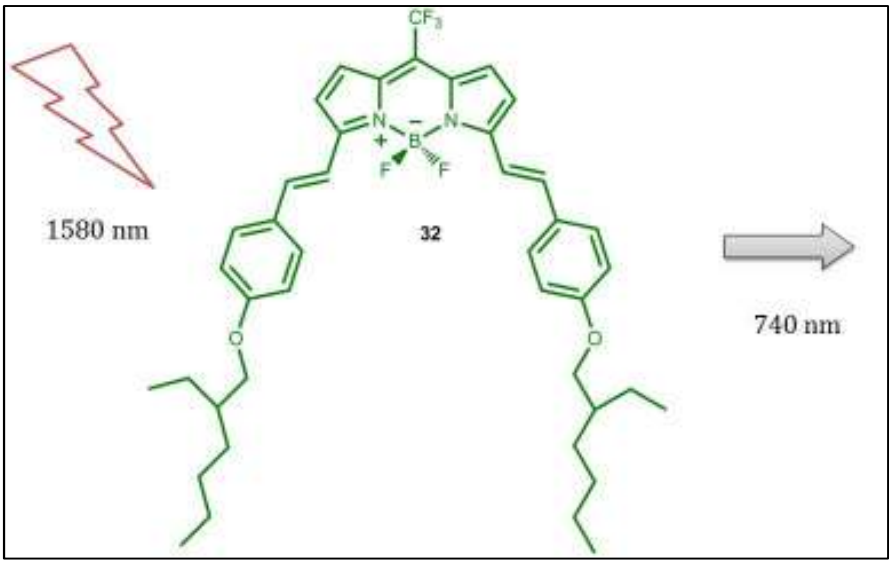


Figure 46 : Two photon excitation of the compound **32.**

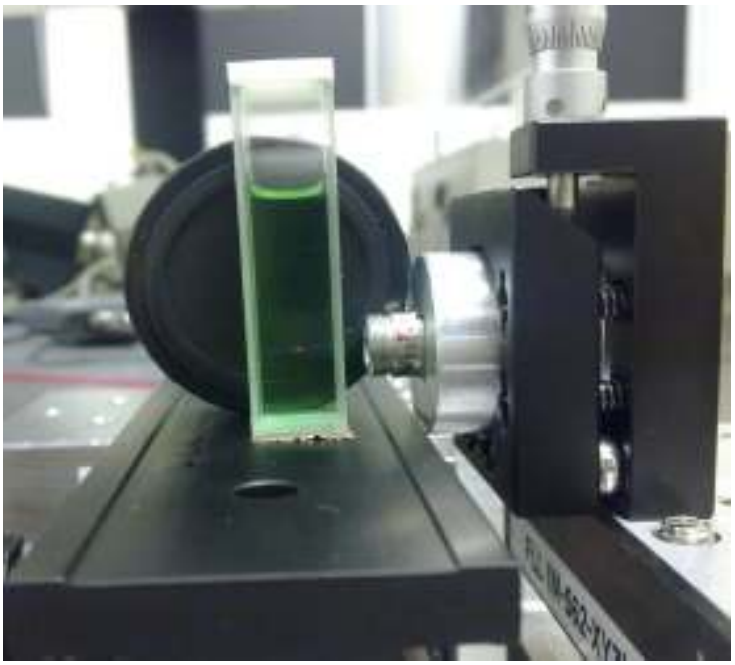


Figure 47 : Two photon excitation of compound **32** by using focused femtosecond pulses of 1580 nm light.

We excited the compound at 1580 nm by using ‘‘z-scan’’ method (Tsunami® mode-locked Ti: Sapphire laser) and observed that compound **32** was excited at a focal volume.

As a conclusion, compound **32** has invariably much larger absorption if it is excited by TPA method and this method confines the excitation of the compound **32** to a focal volume which precludes parasitic emission[53].

4. CONCLUSION

In this study, we have successfully synthesized a novel series of two photon absorbing BODIPY dyes with systematically varied molecular structures which show large two photon absorption cross section. We attempted to find out the relationship between molecular structure and high two photon absorption cross section

It is important to note that the experimentally obtained two photon absorption cross section values of compound **28** and **31** are comparable to or in most cases higher than those of formerly reported two photon absorbing BODIPY dyes.

The GM values of the compounds **30**, **32** and **33** cannot be measured due to the low quantum yields for the determination of the two photon absorption cross section. The determination of the GM values of these compounds will be conducted as a future work in our laboratory.

Compound **30**, **32** and **33** can be used as two photon absorbing dyes in the optical power limiting. These dyes are good candidates for the applications in the optical telecommunication wavelengths since their two absorption maxima are in the 1300-1600 nm.

After introducing a heavy atom such as iodine at the 2, 6 positions of the BODIPY cores of the compound **28**, **29** and **31,** they will be promising candidates as photosensitizer for PDT since they can be excited at 1000-1120 nm where the incident light reaches the maximal penetration depth into the biological tissues (Table 1). Our initial data will guide other researchers in optimizing the design of near IR excitable photodynamic sensitizers. However, it is clear that BODIPY dyes, with rational derivatization can lead to efficient TPA absorbing chromophores.

REFERENCES

1. Göppert-Mayer, M., *Ann. Phys*. **1931**, 401, 273.
2. Kaiser, W.; Garrett, C.G.B., *Phys. Rev. Lett*. **1961**, 7, 229.
3. Pawlicki, M.; Collins, H.A.; Denning, R. G. and Anderson H.L, *Angew. Chem. Int. Ed.*, **2009**, 48, 3244.
4. Sutherland, R.L.,*Handbook of Nonlinear Optics*, Marcel Dekker Inc. Newyork, **2003.**
5. Friedrich, DM.; Mc Clain, WM.,*Annu Rev Phys Chem,* **1980,** 31, 559.
6. Parthenopoulos, D. A. and Rentzepis P. M., *Science*, **1989**, 245, 843.
7. Gilles, U.; Didier, P; Yves, M. and Ziessel, R, *Org. Biomol. Chem*.,**2009**, 7, 3639.
8. Belfield K. D.; Bondara M. V. and Przhonska O. V., *J. Fluoresc*., **2006**, 16, 111.
9. Stiel H., Teuchner K.; Paul A.; Freyer W. and Leupold D., J. *Photochem. Photobiol., A,* **1994**, 80, 289.
10. Abbotto, A.; Beverina, L.; Bozio, R.; Bradamante, S.; Ferrante, C.; Pagani, G. A.; Signorini, R. *Adv. Mater*. **2002**, 12, 1963
11. He , G.S.; Markowics, P.P.; Lin, T.-C.; Prasad, P.N. *Nature*, **2002**, 415,767.
12. Zhou, W.; Kuebler, S. M.; Braun, K. L.; Yu, T.; Cammack, J. K.;Ober, C. K.; Perry, J. W.; Marder, S. R. *Science*, **2002**, 296, 1106.
13. Cumpston, B. H. et al. *Nature* **1999**, 398, 51.
14. Calvete, M.; Yang, G.Y.;Hanack, M., Synth. Met. **2004**, 141,231.
15. Lakowicz, JR., *Topics in fluorescence spectroscopy*, Plenum Press Newyork, **2003.**
16. Denk, W, Proc. Natl. Acad. Sci. U.S.A. **1994**, 91, 6629.
17. Marchesini,R. ; Melloni, G.; Pezzoni, G.; Savi, G.; Zunino, F.; Docchio, F.; Fava, G., *Lasers Surg. Med.,* **1986**, 6, 323-327.
18. Izard, N.; Menard, C.; Riehl, D.; Doris, C.; Mioskowski, Anglaret, E., *Chem. Phys. Lett*., **2004**, 391,124.

19. Fischer, W.G.; Partridge, W.P.; Dees, Jr. C.; Wachter, E.A., *Photochemistry and Photobiology*, **1997**, 66, 141.

20. Prasad, P.N., *Introduction to Biophotonics*, Wiley Newyork,**2003.**

21. Scrimgeour, J.; Sharp, D.N.;Blanford, F.,C.; Roche, O.M.; Denning, R.G.; Turberfield,A.J., *Adv. Mater*.,**2006**, 18, 1557.

22. Bouit, P.A.; Kamada, K.; Feneyrou, P.; Berginc, G.; Toupet, L.; Maury, O. and Andraud, C., *Adv. Mater*., **2009**, 21, 1151.

23. Pawlicki, M.; Collins, H.A.; Denning, R.G. and Anderson H.L., *Angew. Chem. Int. Ed*., **2009**, 48, 3244.

24. Rumi, M.; Ehrlich, J. E. , Heikal, A. A.; Perry, J. W.; Barlow, S.; Hu, Z.; McCord-Maughon, D.; Parker, T. C.; Röckel, H. ; Thayumanavan, S.; Marder, S. R. ; Beljonne, D.; Bredas, J.-L., *J. Am. Chem. Soc*. **2000**, 122, 9500.

25. Signorini, R; Ferrante,C.; Pedron, D.; Zerbetto, M.; Cecchetto, E.; Slaviero, M.; Fortunati, I.; Collini, E.; Bozio, R.; Abbotto, A.; Beverina, L.; Pagani, G. A., *J. Phys. Chem. A,* **2008**, 112, 4224.

26. Padilha, L. A; Webster, S.; Hu, H. ; Przhonska, O. V.; Hagan, D. J.; Stryland, E. W.Van; Bondar, M. V.; Davydenko, I. G.; Slominsky, Y. L. ; Kachkovski, A. D., *Chem. Phys.,* **2008**, 352, 97.

27. Peticolas, W. L. ; Goldsborough, J. P.; Rieckhoff, K. E., *Phys. Rev. Lett.* **1963**, 10, 43.

28. Kogej, T.; Beljonne, D.; Meyers, F.; Perry, J.W.; Marder, S.R.; Bredas, J.L., *Chem. Phys. Lett*. **1998**, 298, 1.

29. Marder, S.R. and et al., *J. Am. Chem. Soc,***2005**, 127,7282.

30. Li, X.; Zhao, Y.; Wang, T.; Shi, M.; Wu, F., *Dyes and Pigments,***2007,** 74,108.

31. Liu,B.; Liu, J.; Wang, H-Q.; Zhao, Y-D; Huang, Z-L., *Journal of Molecular Structure,**2007, 833,82.*

32. Jagatap, B. N.; Meath, W. J., *J. Opt. Soc. Am. B,***2002**, *19*, 2673.

33. Ramakrishna, G.; Goodson, T., III. *J. Phys. Chem. A* **2007**, *111*, 993.

34. Nguyen, K. A.; Rogers, J. E.; Slagle, J. E.; Day, P. N.;Kannan, R.; Tan, L.-S.; Fleitz, P. A.; Pachter, R. *J. Phys.Chem. A,***2006**, *110*, 13172.

35. Ehrlich, J. E. , Wu, X. L.; Lee, I.-Y. S.; Hu, Z.-Y.; Röckel, H.; Marder, S. R.; Perry, J.W., *Opt. Lett*. **1997**, 22, 1843.

36. Makarov, N. S.; Drobizhev, M.; Rebane, A., *Opt. Express,* **2008**, 16, 4029.

37. Albota, M.; Beljonne, D.; Bredas, J. L.; Ehrlich, J. E.; Fu, J. Y.; Heikal, A. A.; Hess, S. E.; Kogej, T.; Levin, M. D.; Marder, S. R.; McCord-Maughon, D.; Perry, J. W.; Rockel, H.; Rumi, M.; Subramaniam, G.; Webb, W. W.; Wu, X. L.; Xu, C. *Science* **1998**, *281*.

38. Ventelon, L.; Charier, S.; Moreaux, L.; Mertz, J.; Blanchard- Desce, M., *Angew. Chem*. **2001**, 113, 2156 – 2159; *Angew. Chem. Int. Ed***. 2001**, 40, 2098.

39. He, G. S. ; Xu, G. C.; Prasad, P. N.; Reinhardt, B. A.; Bhatt, J. C.; Dillard, A. G., *Opt. Lett*. **1995**, 20, 435.

40. Kim, O.-K. ; Lee, K.-S.; Woo, H. Y.; Kim, K.-S.; He, G. S.; Swiatkiewicz, J.; Prasad, P. N., *Chem. Mater***. 2000**, 12, 2838.

41. Perry, J. W.; Barlow, S.; Ehrlich, J. E.; Heikal, A. A.; Hu, Z.-Y.; Lee, I.-Y. S.; Mansour, K.; Marder, S. R.; Röckel, H.; Rumi, M.; Thayumanavan, S.; Wu, X.-L., *Nonlinear Opt*. **1999,** 21, 225.

42. Mongin, O.; Porres, L.; Charlot, M.; Katan, C.; Blanchard- Desce, M., *Chem. Eur. J*. **2007**, 13, 1481.

43. Aujard, I.; Benbrahim, C.; Gouget, M.; Ruel, O.; Baudin, J.-B.; Neveu, P.; Jullien, L. *Chem.*s*Eur. J.* **2006**, *12*, 6865.

44. Wang, X.; Krebs, L. J.; Al-Nuri, M.; Pudavar, H. E.; Ghosal, S.;Liebow, C.; Nagy, A. A.; Schally, A. V.; Prasad, P. N. *Proc. Natl. Acad. Sci. U.S.A.* **1999**, *96*, 11081.

45. Porres, L.; Mongin, O.; Katan, C.; Charlot, M.; Pons, T.; Mertz, J.; Blanchard Desce, M. *Org. Lett*. **2004**, *6*, 47.

46. Ventelon, L.; Moreaux, L.; Mertz, J.; Blanchard-Desce, M. *Synth. Met*. **2002**, *127*, 17.

47. Huang, Z.-L.; Lei, H.; Li, N.; Qiu, Z.-R.; Wang, H.-Z.; Guo, J.-D.; Luo, Y.; Zhong, Z.-P.; Liu, X.-F.; Zhou, Z.-H. *J. Mater. Chem.* **2003**, 13, 708.

48. Marder, S. R.; Torruellas, W. E.; Blanchard-Desce, M.; Ricci, V.; Stegeman, G. I.; Gilmour, S.; Bredas, J. L.; Li, J.; Bublitz, G. U.; Boxer, S. G. *Science* **1997**, *276*, 1233.

49. Drobizhev, M.; Stepanenko, Y.; Dzenis, Y.; Karotki, A.; Rebane, A.; Taylor, P. N.; Anderson, H. L.; *J. Phys. Chem. B,* **2005**, 109, 7223.

50. Lee, S.; Thomas, K. R. J.; Thayumanavan, S.; Bardeen, C. J. *J. Phys. Chem. A* **2005**, *109*, 9767.

51. Reinhardt, B. A.; Brott, L. L.; Clarson, S. J.; Dillard, A. G.; Bhatt, J. C.; Kannan, R.; Yuan, L.; He, G. S.; Prasad, P. N. *Chem. Mater.* **1998**, *10*, 1863.

52. Pati, S. K.; Marks, T. J.; Ratner, M. A. *J. Am. Chem. Soc.* **2001**, *123*, 7287.

53. Zipfel, W. R. ; Williams, R. M.; Webb, W.W., *Nat. Biotechnol*.**2003**, 21, 1369.

54. Woodburn, K.W.; Fan, Q.; Kessel, D. et al., *J Clin Laser Med Surg,* **1996**, 14, 343.

55. Dougherty, TJ.; Gomer, C.J.; Henderson, B.W. et al,. *J Natl Cancer Inst*, **1998**, 90, 889.

56. Rockson, S.G; Lorenz, D.P.; Cheong, W.F; Woodburn, K.W., *Circulation,* **2000**, 102, 591.

57. Chen, B.; Pogue, B.W.; Hoopes, P.J.; Hasan, T., *Crit Rev Eukaryot Gene Expr* **2006**, 16, 279.

58. Kessel, D.; Luo, Y.; Deng, Y.; Chang, C.K., *Photochem Photobiol* **1997,** 65, 422, 426

59. Huang, X.; El-Sayed, I. H.; Qian, W. and El-Sayed, M. A., *J. Am. Chem. Soc*., **2006**, 128, 2115.

60. Ogawa, K. and Kobuke, Y., *Anti-Cancer Agents in Medicinal Chemistry***, 2008,** 8, 269.

61. Ogawa, K.; Ohashi, A.; Kobuke, Y.; Kamada, K.; Ohta, K. *J. Am. Chem. Soc.,* **2003**, 125, 13356.

62. Ogawa, K.; Ohashi, A.; Kobuke, Y.; Kamada, K.; Ohta, K. *J. Phys. Chem. B*., **2005**, 109, 22003.

63. Ogawa, K. et al., *Mol. Cryst. Liq. Cryst*., **2007**, 471, 61.

64. Kawata,S.; Kawata, Y., *Chem. Rev*. **2000**, 100, 1777.

65. Schafer, K. J. ; Hales, J.M.; Balu, M.; Belfield, K.D.; Stryland, E.W. Van ; Hagan, D.J, . *J. Chem. Photochem. Photobiol. A*., **2004**, 162, 497

66. Watanabe,T.; Akiyama,M.; Totani, K.; Kuebler, S.M. ; Stellacci, F.; Wenseleers, W.; Braun, K. L.; Marder, S. R.; Perry, J. W., *Adv. Funct. Mater*. **2002**, 12, 611.

67. Lu,Y.; Hasegawa,F.; Goto,T.; Ohkuma,S.; Fukuhara, S. ; Kawazu, Y.; Totani, K.; Yamashita,T.; Watanabe,T., *J. Mater. Chem*. **2004**, 14, 75.

68. Denk, W.; Strickler, J. H.; Webb, W. W., *Science*, **1990**, 248, 73.

69. Spangler, C. W., J. Mater. Chem. 1999, 9, 2013-2020.

70. T. J. Mckay, J. Staromlynska, P. Wilson, J. Davy, *J. Appl. Phys*. **1999**, 85, 1337.

71. Tutt, L.W.; Kost, A., *Nature*, **1992**, 356, 225.

72. Pittman, M.; Plaza,P.; Martin, M. M.; Meyer, Y. H.; *Opt. Commun.* **1998**, 158,201.

73. McEwan,K.; Lewis,K.; Yang, G.-Y.; Chng, L.-L.; Lee, Y.-W.; Lau, W.-P.; Lai, K.-S.,*Adv. Funct. Mater*. **2003**, 13, 863.

74. Shirk, J. S. ; Pong, R. G. S.; Bartoli, F. J.; Snow, A. W., *Appl. Phys. Lett.,***1993**, 63, 1880.

75. Loudet, A.; Burgess, K., *Chem. Rev.* **2007**, 107, 4891.

76. Treibs A., Kreuzer F. H., *Justus Liebigs Ann. Chem.*, **1968**, *718*, 208

77. Rurack, M. Kollmannsberger, J. Daub, *Angew. Chem*. **2001**,113, 396 – 399; *Angew. Chem. Int. Ed*. **2001**, 40, 385-387

78. Song, L.N.; Ulrich; G.; Ziessel, R.; Kiss, A.; Renard, P-Y. And Romieu, A., *Org. Lett*., **2009**, 10, 2049-2052

79. Ozlem, S and Akkaya, E.U., *J. Am. Chem. Soc.,***2009**,131,48-49

80. Barin, G.; Yilmaz, M.D.; Akkaya, E.U., *Tetrahedron Lett*.,**2009**,50,1738-1740

81. Bozdemir, O.A.; Guliyev, R.; Buyukcakir, O.; Selcuk, S.; Kolemen, S.; Gulseren, G.; Nalbantoglu, T.; Boyaci, H.; Akkaya, E.U., *J. Am. Chem. Soc,***2010**, 132, 8029-8036

82. Bozdemir, O.A.; Sozmen, F.; Büyükçakır, O.; Guliyev, R.; Cakmak, Y.; and Akkaya, E.U., *Org. Lett*., **2010**, 12, 1400-1403

83. Coskun, A.; Yilmaz, M.D.; Akkaya, E. U. *Org. Lett*., **2007**, 9, 607.

84. Coskun, A.; Deniz, E.; Akkaya, E. U. *Tetrahedron. Lett*., **2007**, 48, 5359.

85. Coskun, A. and Akkaya, E. U., *J. Am. Chem. Soc*., **2005**, 127, 10464.

86. Atilgan, S.; Ekmekci, Z.; Dogan, A.L.; Guc, D.; Akkaya, E.U. *Chem.Commun*., **2006**, 4398.

87. He, G.S.; Tan, L-S.; Zheng, Q.; Prasad, P.N., *Chem. Rev*. **2008**, 108,1245-1330

88. Zhang, D.; Wang, Y.; Xiao, Y.; Qian, S.; and Qian, X., *Tetrahedron,* **2009**, 65, 8099-8103

89. Didier, P.; Ulrich, G.; Mely, Y. And Ziessel, R., *Org. Biomol. Chem*., **2009**,7, 3639-3642

90. Boit, P-A.; Kamada, K.; Feneyrou, P.; Berginc, G.; Toupet, L.; Maury, O.; Adraud, C., *Adv. Mater.,* **2009**, 21, 1151-1154

91. Buyukcakir, O.; Bozdemir, O.A; Kolemen, S.; Erbas; S.; Akkaya, E.U., *Org. Lett.,* **2009,**11,4644-4647

92. Lakowicz, J.R. *Principles of Fluorescence Spectroscopy*, Kluwer Academic, Plenum Publishers, **1999**

93. Dost, Z.; Atilgan, S.; Akkaya, E.U., *Tetrahedron*, **2006**, 62, 8484.

APPENDIX A

NMR SPECTRA

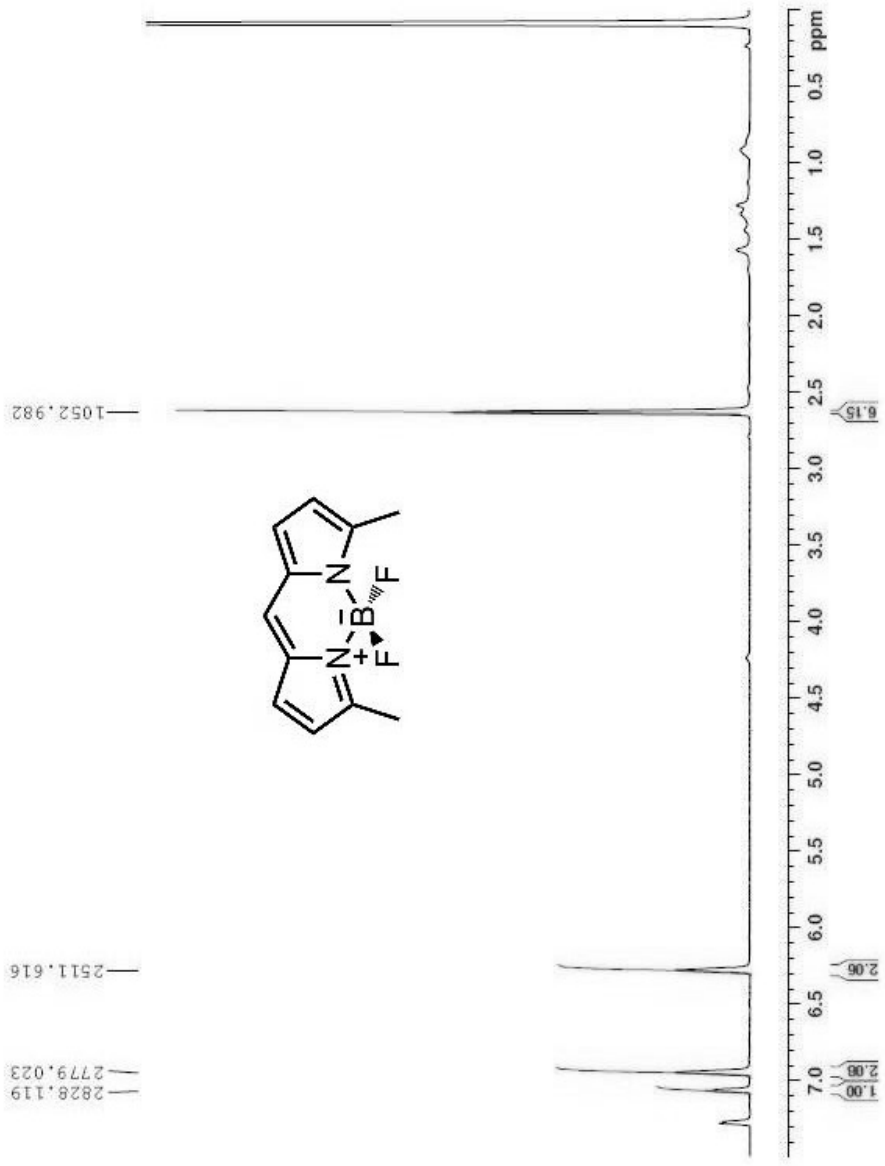


Figure 48 : ^{1}H spectrum of compound **28** in $CDCl_3$

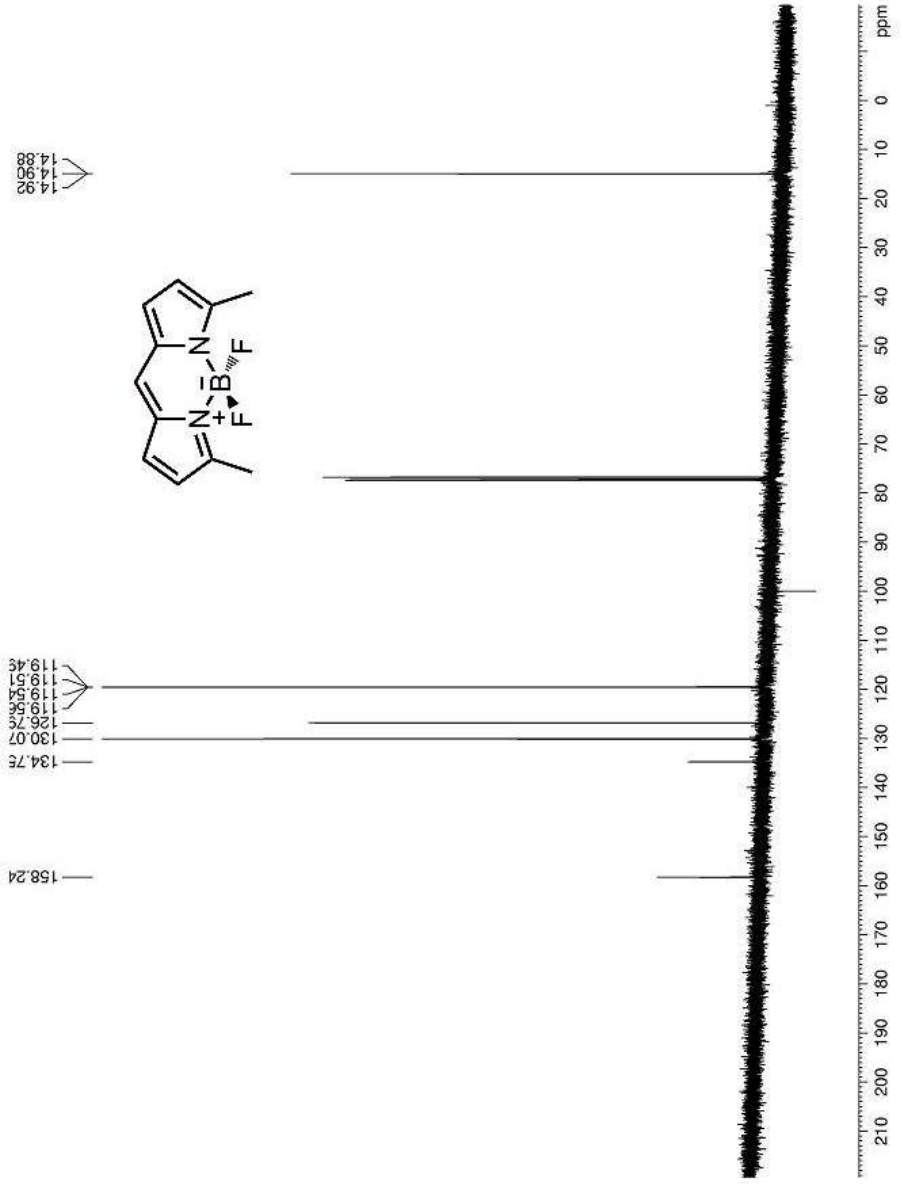


Figure 49 : ^{13}C spectrum of compound **28** in $CDCl_3$

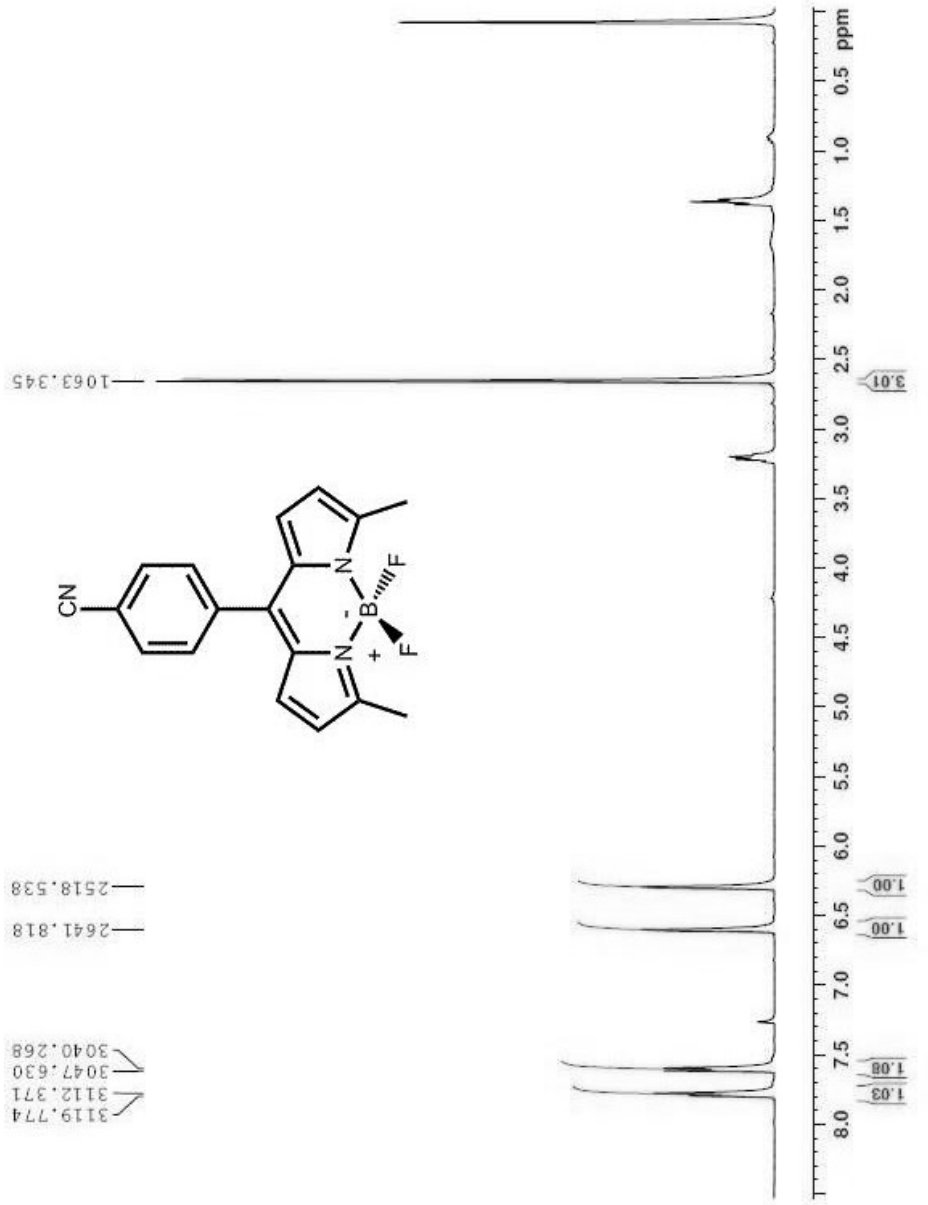


Figure 50 : ^{1}H spectrum of compound **29** in $CDCl_3$

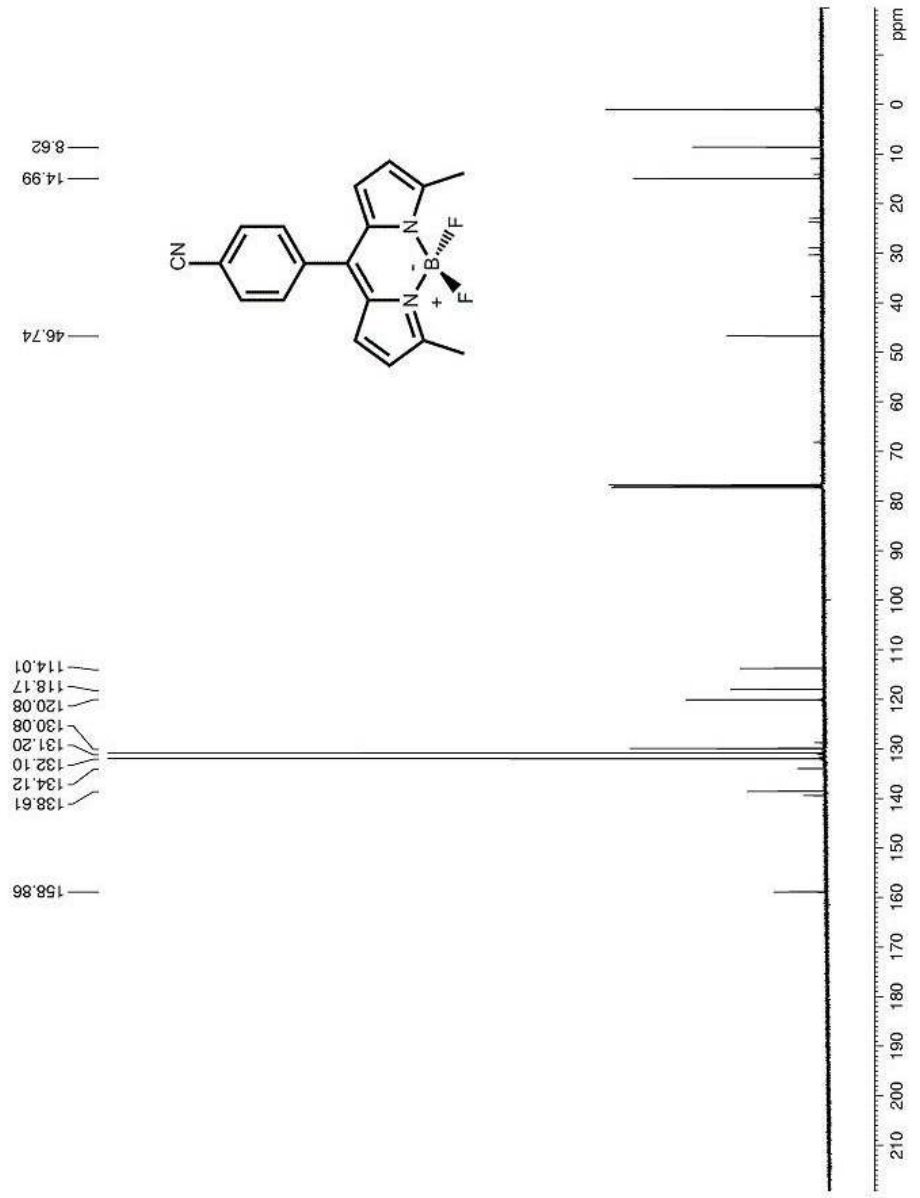


Figure 51: ^{13}C spectrum of compound **29** in $CDCl_3$

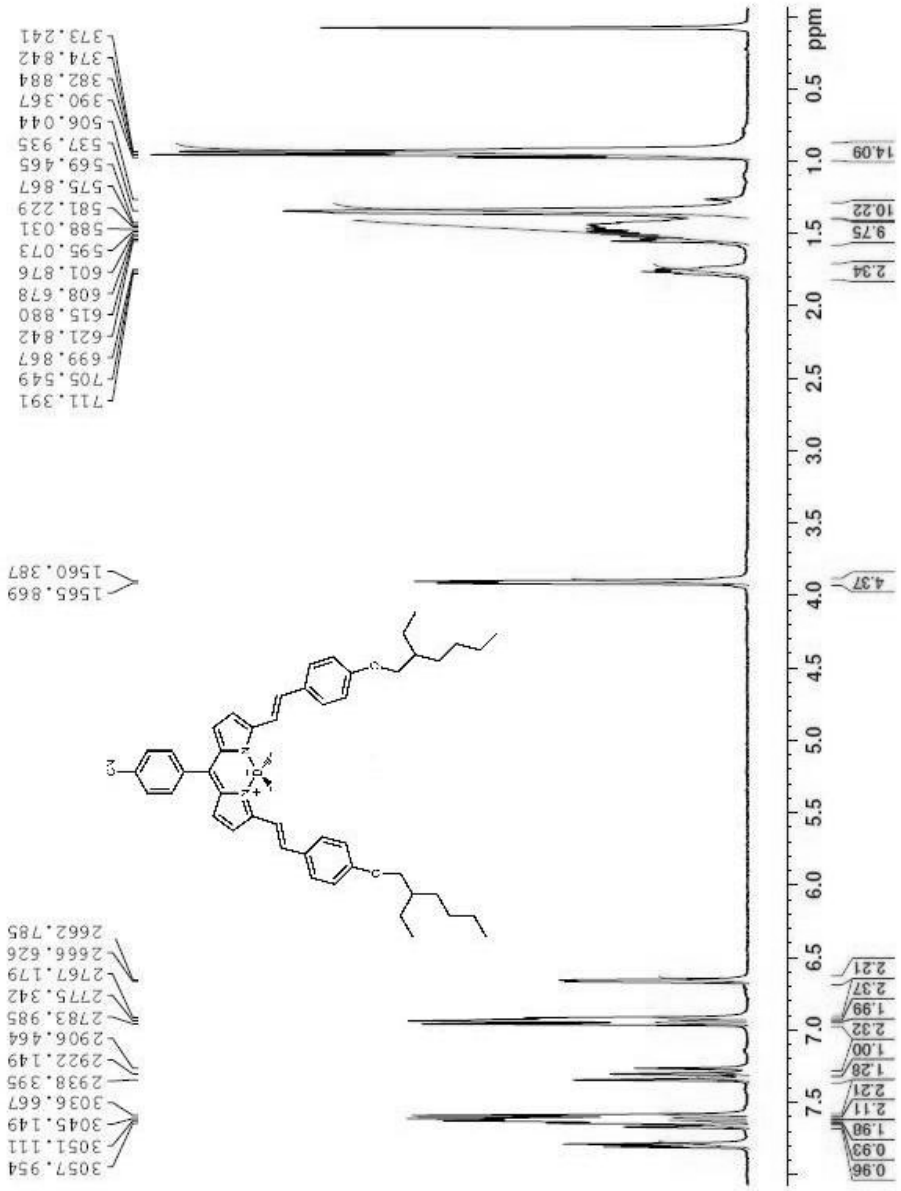


Figure 52 : ^{1}H spectrum of compound **30** in $CDCl_3$

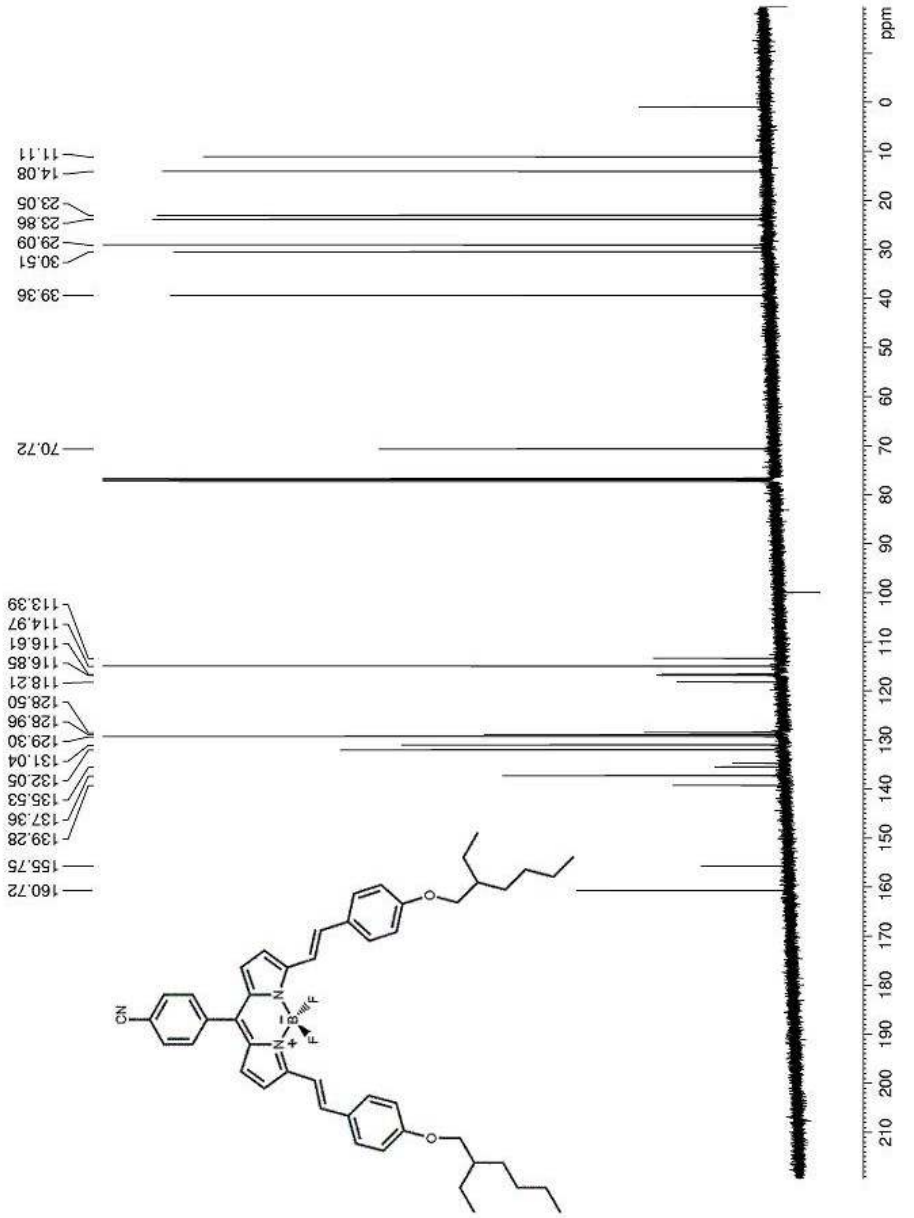


Figure 53: ^{13}C spectrum of compound **30** in $CDCl_3$

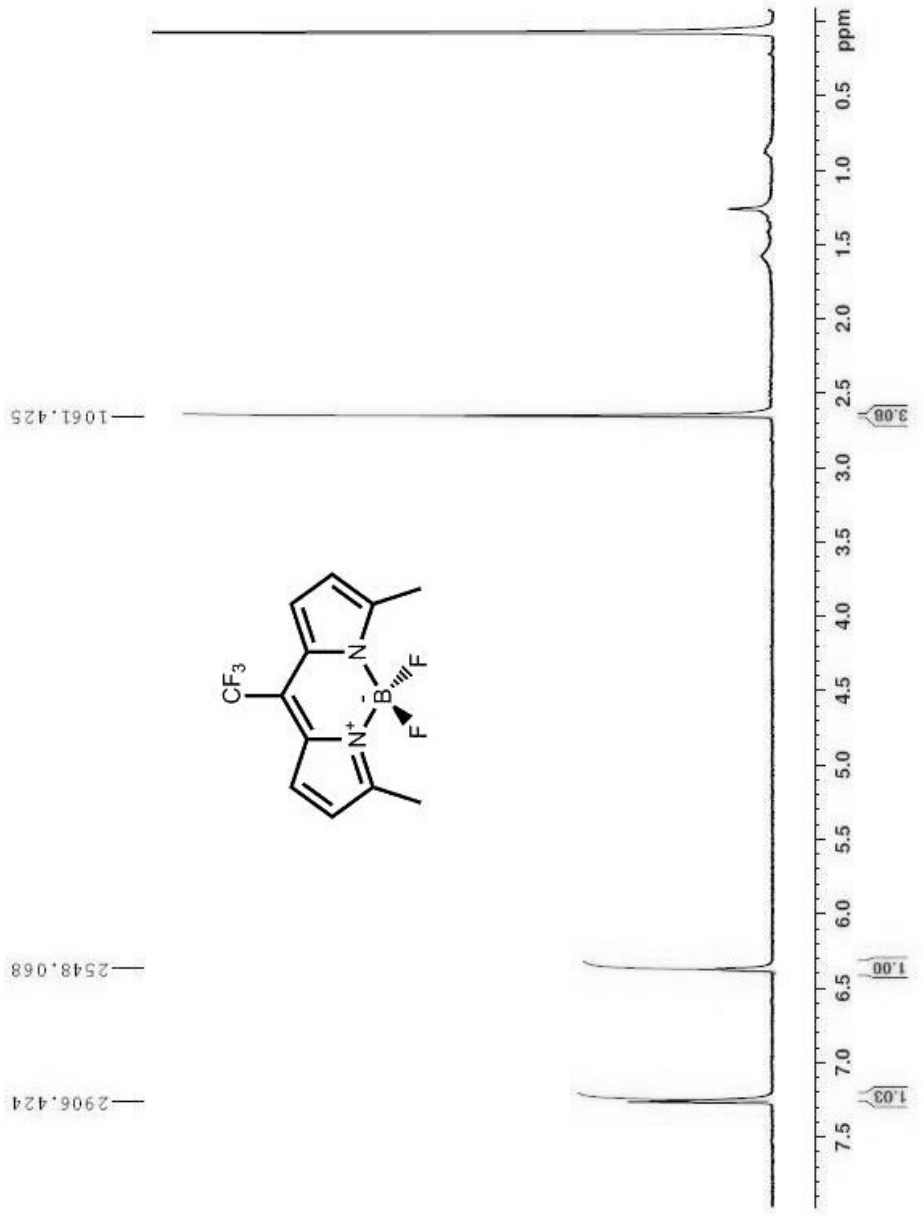


Figure 54 : ^{1}H spectrum of compound **31** in $CDCl_3$

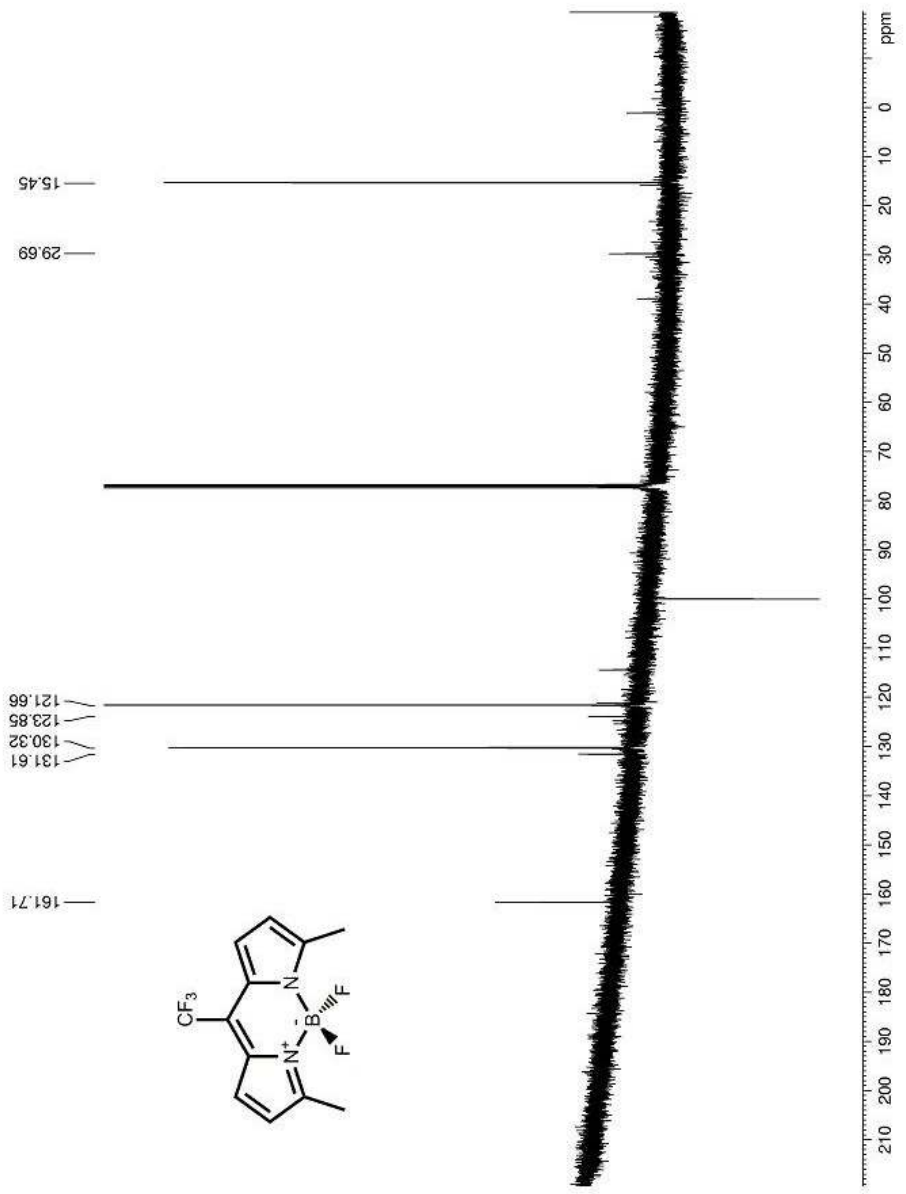


Figure 55: ^{13}C spectrum of compound **31** in $CDCl_3$

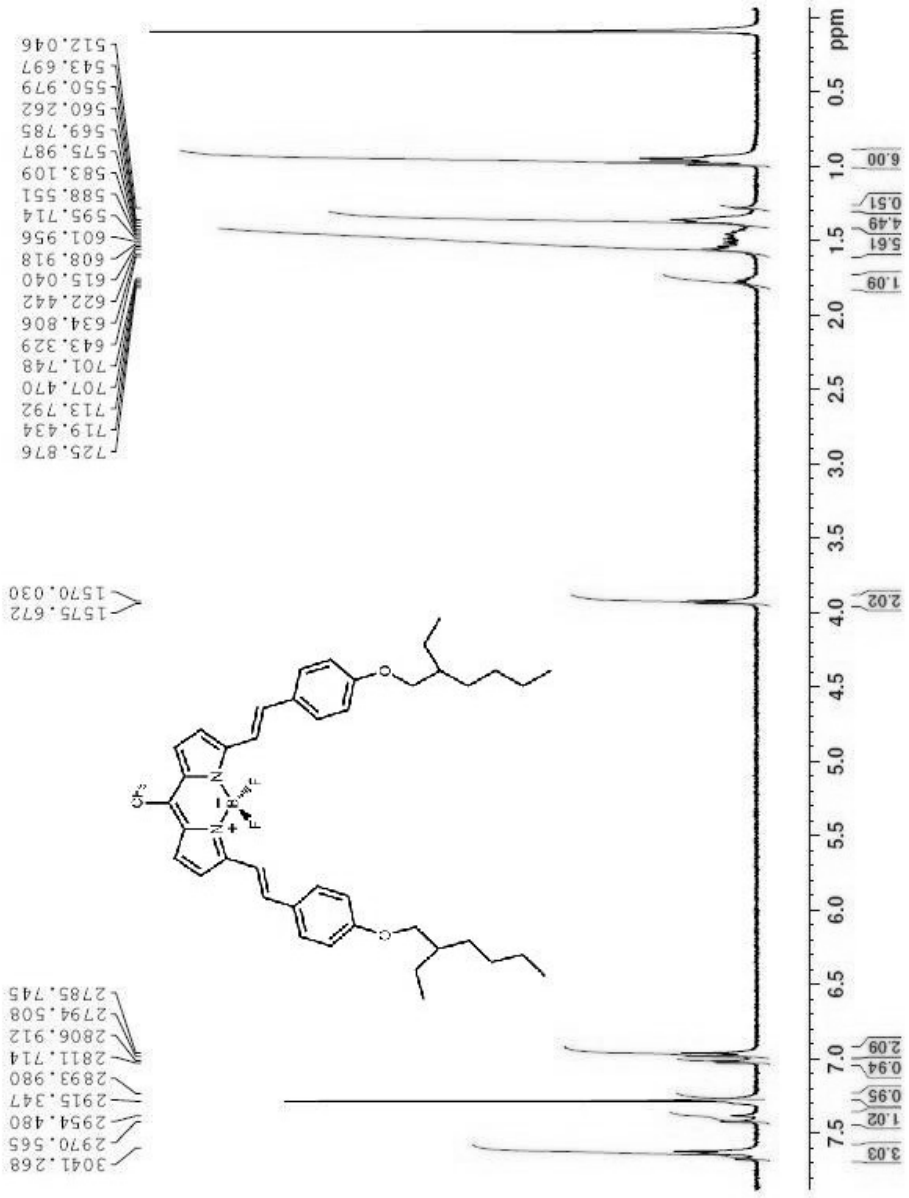


Figure 56 : ^{1}H spectrum of compound **32** in $CDCl_3$

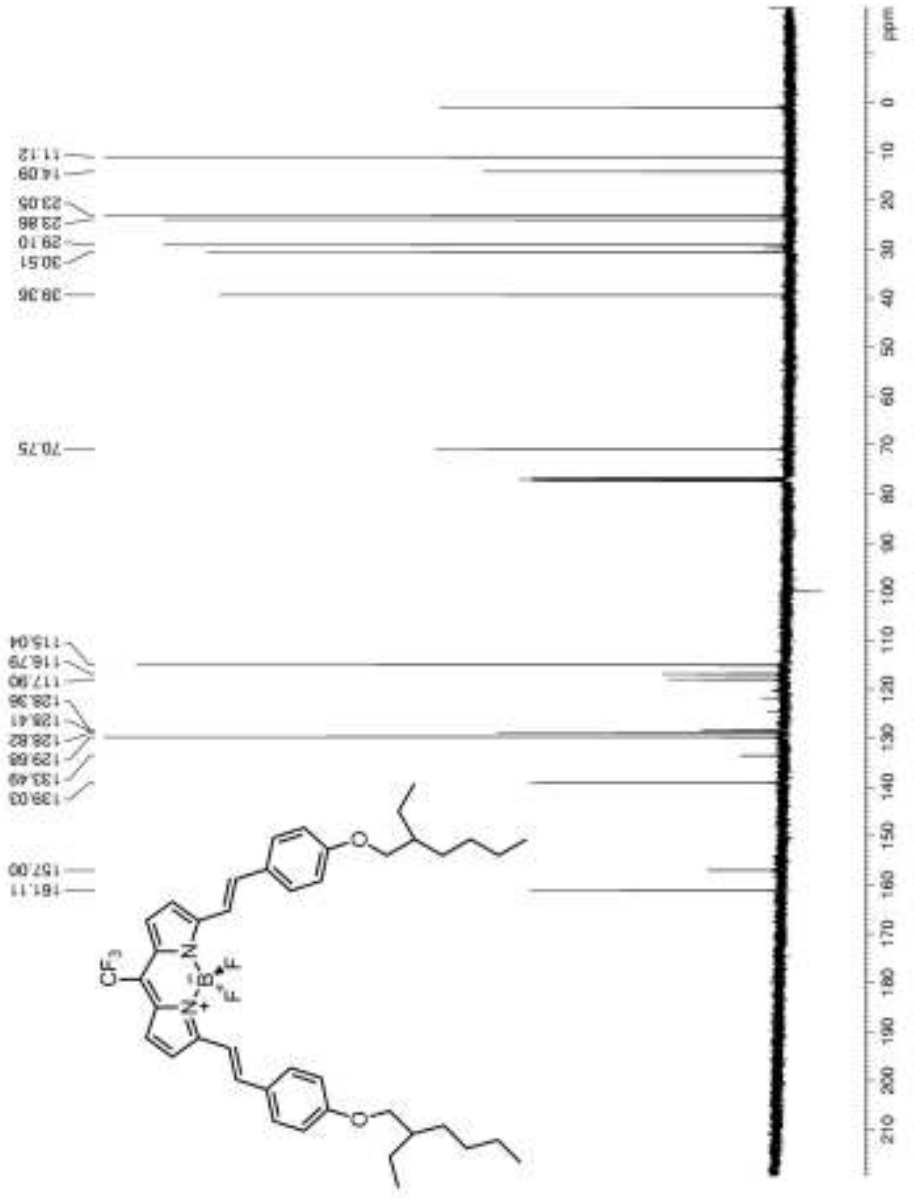


Figure 57: ^{13}C spectrum of compound **32** in $CDCl_3$

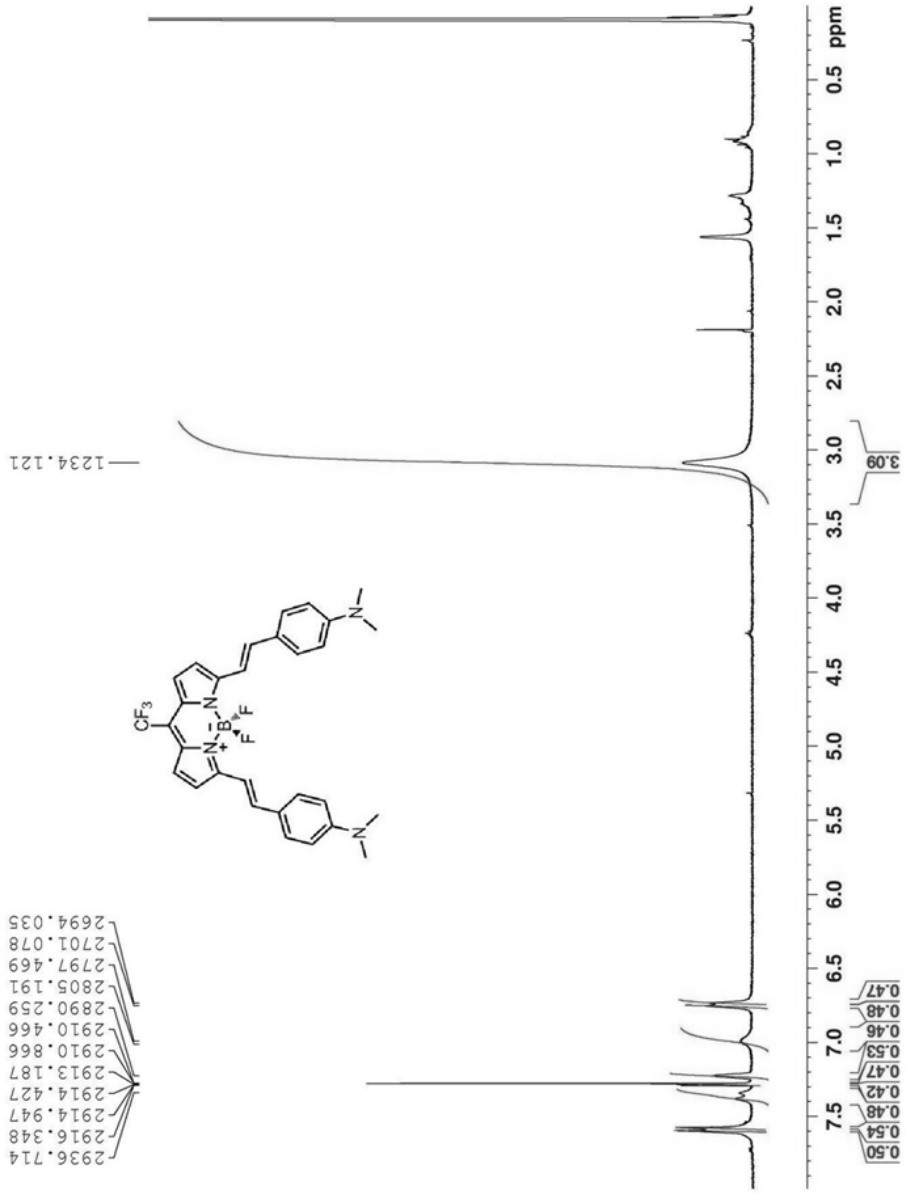


Figure 58 : ^{1}H spectrum of compound **33** in $CDCl_3$

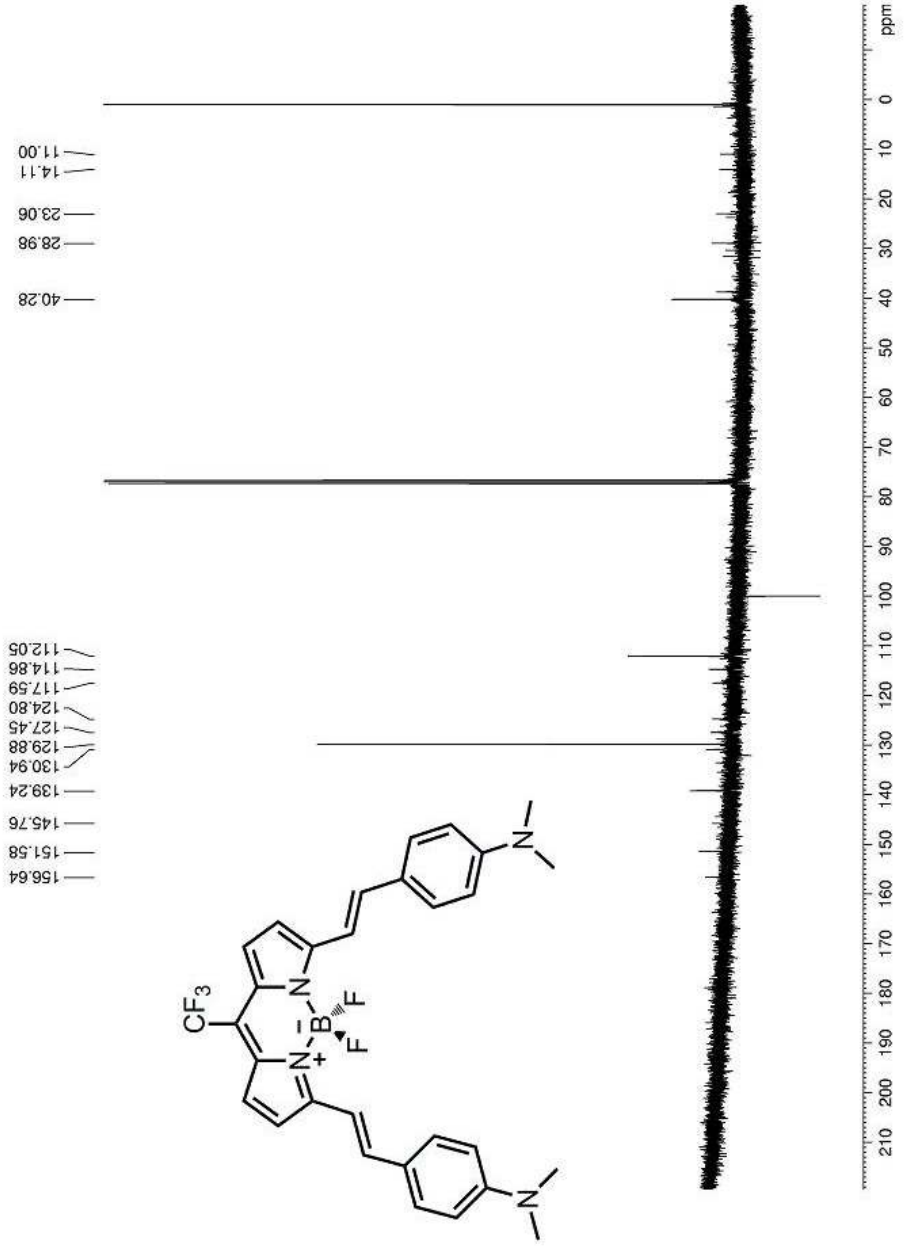


Figure 59 : ^{13}C spectrum of compound **33** in $CDCl_3$

APPENDIX B

MASS SPECTRA

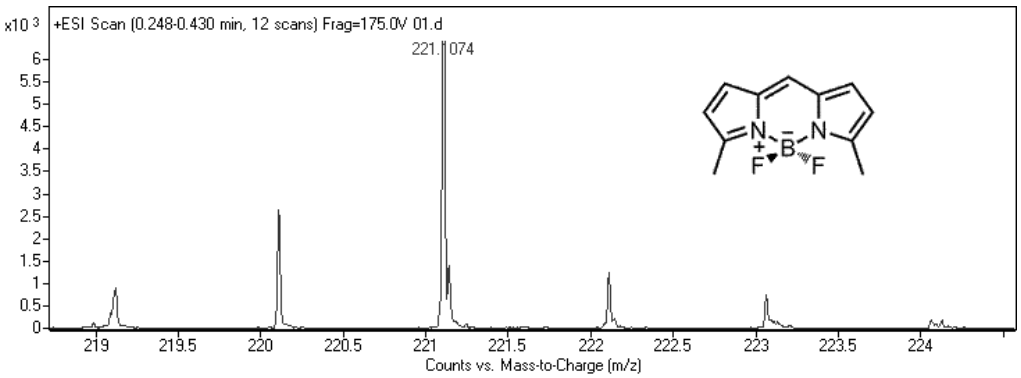


Figure 60 : ESI-HRMS of compound **28**

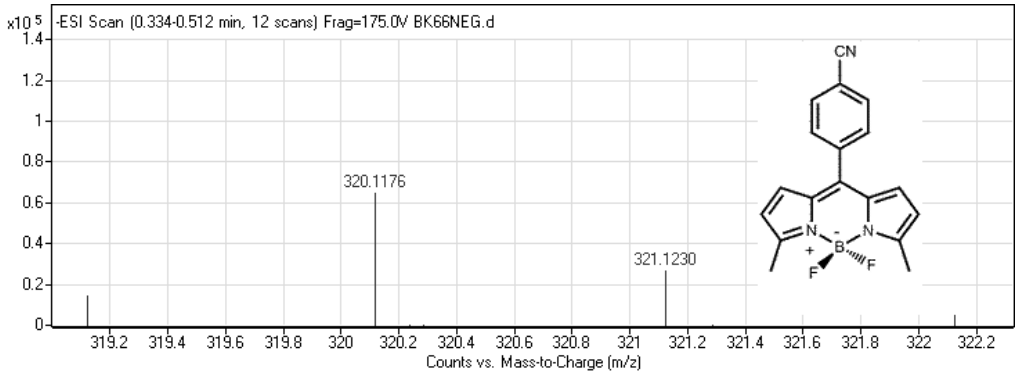
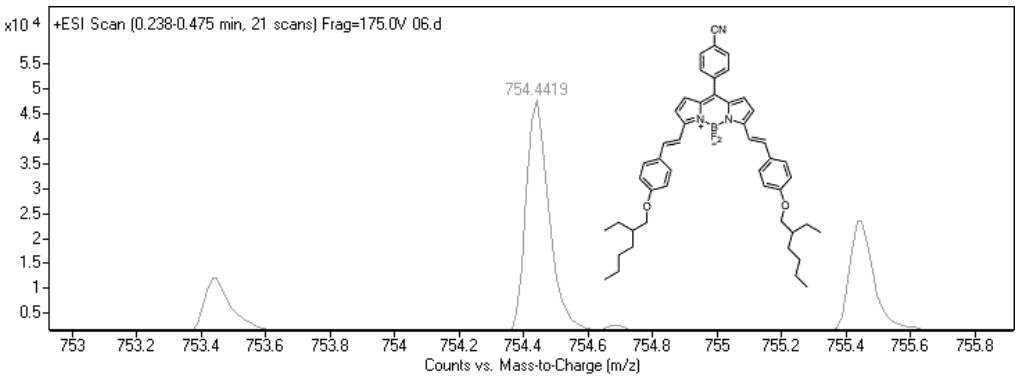
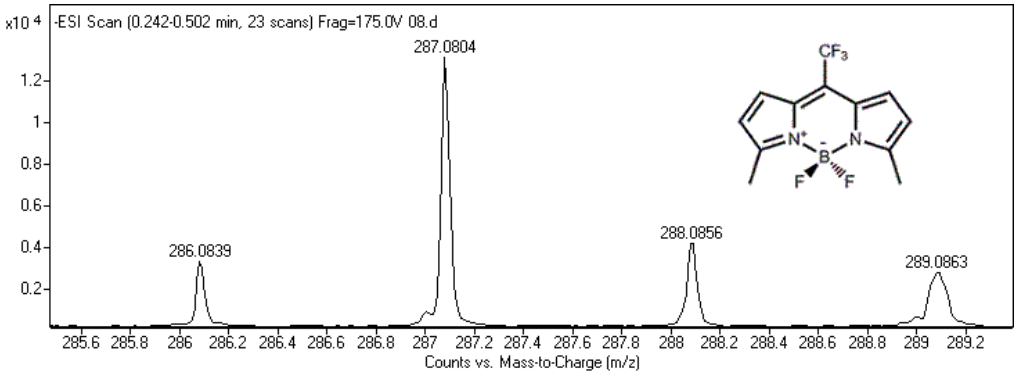


Figure 61 : ESI-HRMS of compound **29**


x10 4
+ESI Scan (0.238-0.475 min, 21 scans) Frag=175.0V 06.d
754.4419
CN
O
O
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
753
753.2
753.4
753.6
753.8
754
754.2
754.4
754.6
754.8
755
755.2
755.4
755.6
755.8
Counts vs. Mass-to-Charge (m/z)


x10 4
-ESI Scan (0.242-0.502 min, 23 scans) Frag=175.0V 08.d
287.0804
286.0839
288.0856
289.0863
CF3
N+
B
N
F
F
1.2
1
0.8
0.6
0.4
0.2
285.6
285.8
286
286.2
286.4
286.6
286.8
287
287.2
287.4
287.6
287.8
288
288.2
288.4
288.6
288.8
289
289.2
Counts vs. Mass-to-Charge (m/z)

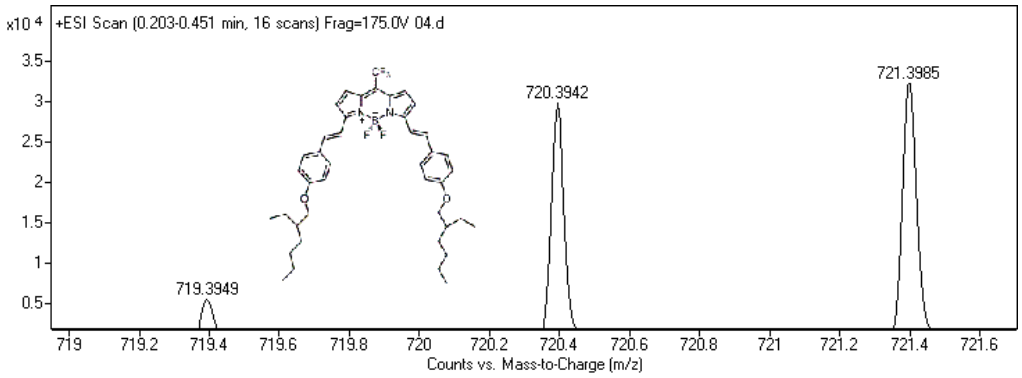


Figure 64 : ESI-HRMS of compound **32**

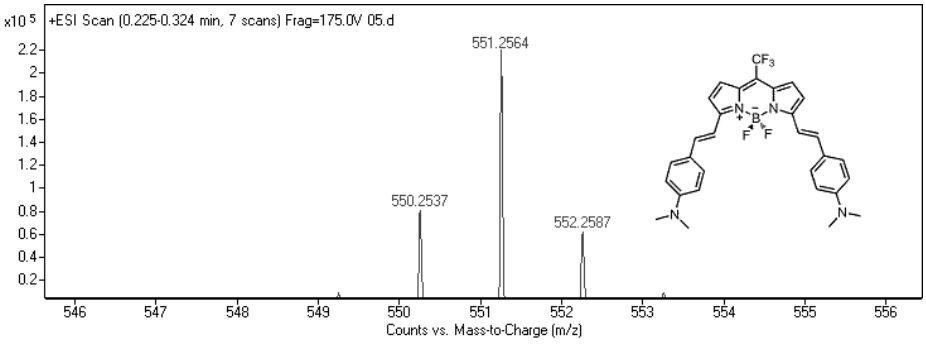


Figure 65 : ESI-HRMS of compound **33**