Journal of Photochemistry and Photobiology A: Chemistry 203 (2009) 211–215

Contents lists available at ScienceDirect

Journal of Photochemistry and Photobiology A: Chemistry

journal homepage: www.elsevier.com/locate/jphotochem

A water-soluble two-photon photopolymerization initiation system: Methylated-β-cyclodextrin complex of xanthene dye/aryliodonium salt

Shujing Li[a,b], Lidong Li[a,*], Feipeng Wu[b], Erjian Wang[b]

[a] School of Materials Science and Engineering, University of Sciences and Technology Beijing, Xueyuan Road 30, Haidian District, Beijing 100083, PR China
[b] Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100080, PR China

ARTICLE INFO

Article history:
Received 25 October 2008
Received in revised form 12 January 2009
Accepted 2 February 2009
Available online 21 February 2009

Keywords:
Photopolymerization
Initiator
Diphenyliodonium salt
Cyclodextrin
Complex

ABSTRACT

An effective two-photon photopolymerization in an aqueous environment was done using a new water-soluble two-photon photopolymerization (TPP) initiation system. This system comprised a photosensitizer dye and the photoinitiator 4,4′-dimethyl diphenyliodonium hexafluorophosphate (DMDPI) encapsulated by methylated-β-cyclodextrin (Me-β-CD). Photochemical properties of the complex were studied in film. We proved that the complex can be used as an effective TPP photoinitiator for two-photon photopolymerization in an aqueous system. Three-dimensional microstructure was successfully fabricated by TPP.

1. Introduction

In recent years, two-photon absorption (TPA) has shown particular promise in applications for three-dimensional (3D) microfabrication [1], high-density optical storage [2,3], biological imaging [4,5], and photodynamic therapy [6]. Many efficient two-photon absorbing compounds based on molecules having linear or quasi-linear D–π–A, D–π–A–π–D or A–π–D–π–A structure in which the magnitude of δ depends on the degree of intramolecular charge transfer upon excitation have been reported [7–11]. Most of these compounds can be used only in a resin system because of their poor solubility in water. This limitation also prevents their use in biological applications. Solving this limitation is very critical for two-photon technique applications in various biomaterials [12,13]. Recently, some water-soluble TPA materials were successfully developed in biological imaging [14–16]. Very few articles have focused on water-soluble two-photon polymerization (TPP) [12,13].

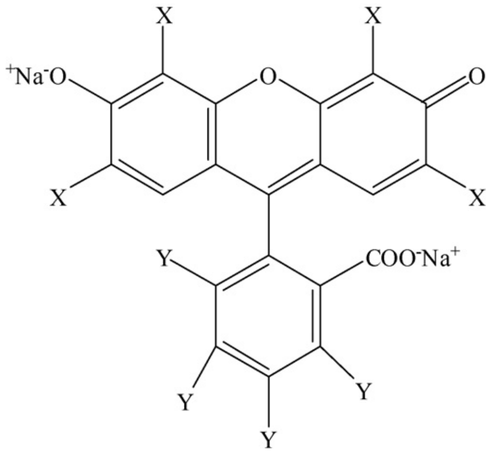
The rate of photopolymerization is mainly influenced by two parameters in TPP: (i) multi-photon absorption cross-section, which provides the probability of multi-photon absorption at a particular frequency and (ii) quantum yield of generated radicals or ions, and the initiation of efficiency of the generated radicals and ions [17]. Designing and synthesizing large cross-section, water-soluble TPA dyes is difficult. Development of a simple method to ensure TPA dyes with a coinitiator that keeps the higher quantum yield of radical generation and initiation of efficiency would be ideal. Several authors have reported that ion pairing and chemical bonding of the dye and onium salt can eliminate the influence by diffusion. It largely increased the efficiency of the resulting photoinitiators, particularly in highly viscous and rigid polymeric systems [18,19]. Ion-pairing complexation cannot be used in an aqueous system because it will dissociate in the polar medium [20–22]. We recently discovered a promising approach to solve this problem using methylated-β-cyclodextrin (Me-β-CD) to bind the dye and coinitiator together to form a supramolecular complex [23]. This method has several advantages. Firstly, this photoactive supramolecular complex can be easily obtained using Me-β-CD complexation. Secondly, the electron transfer between dye and initiator can occur in the intramolecular complex without the limitation of diffusion rate for common bimolecular reactions. This allows for fast photoinduced electron transfer between dye and initiator within the short lifetime of the dye. Thirdly, the supramolecular complex eliminates the dosage of the coinitiator, thereby significantly reducing material damage and toxicity from residual photoreagents.

Here we report a novel water-soluble two-photon photoinitiation system to carry out an effective two-photon photopolymerization in an aqueous system. The photochemical properties and application for TPP of the supramolecular complex were studied in detail. A very clear microfabrication structure was obtained. This new method is very useful for application of the TPP technique in a water system.

---

* Corresponding author. Fax: +86 10 82375712.
E-mail address: lidong@mater.ustb.edu.cn (L. Li).

1010-6030/$ – see front matter. Crown Copyright © 2009 Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.jphotochem.2009.02.007



dye	FL	EO	RB
X	4H	4Br	4Cl
Y	4H	4H	4I

Scheme 1. Chemical structure of FL, EO, RB.

2. Experimental

2.1. Materials

Me-β-CD was obtained from Aldrich Chemical Company. 4,4′-Dimethyl diphenyliodonium hexafluorophosphate (DMDPI) was purchased from TH-UNIS Insight Company Limited. Fluorescein sodium (FL), eosin (EO), rose bengal (RB) were purchased from Beijing Chemical Reagent Company (Beijing, China) (Scheme 1). Acrylamide and bis-acrylamide (AM and bis-AM, Jiangxi Changjiu Biochemical Engineering Co.) were used as received. Hydroxypropyl methyl cellulose (HPMC, 60RT50) was purchased from Repon Chemical Company, and polyvinylpyrrolidone (PVP, Mr, 10,000–70,000) from ShanTou XiLong Chemical Factory (Guang Dong, China).

2.2. Photopolymerization

The light source for photolysis was a 400-W Xenon lamp (filter cut off light of $\lambda < 300$ nm) and the intensity of irradiation was 4.82 mW/cm^2. In the photobleaching experiment, the film-forming material was 10% HPMC aqueous solution. Dye/complex A was added to the solution and poured onto glass substrates. Film thickness was controlled by the scraper and was about 47 μm. Samples were dried in a vacuum oven for 2 h at 45 °C. Photobleaching rate was obtained by the relative change in the maximum optical density of the absorption peak at long wavelength as a function of irradiation time.

2.3. Measurements

For fabrications of 3D microstructures, we employed a mode-locked Ti–sapphire laser whose oscillating wavelength, pulse width and repetition rate were 780 nm, 80 fs and 82 MHz, respectively. The laser source was tightly focused by a 100× oil-immersion objective lens with a high numerical aperture (NA = 1.4, Olympus). The focal point was focused on the liquid sample, which was placed on a *xyz*-step motorized stage controlled by a computer. After laser fabrication, unpolymerized pre-polymers were washed out by using ethanol. The two-photon samples consisted of PVP (1 g), AM (1 g), bis-AM (0.1 g) and H_2O (4 g), FL, EO, RB as sensitizer, and complex A as initiator.

Fluorescence measurements were carried out on a Hitachi F-4500 fluorescence spectrophotometer. UV–vis spectra were recorded on a JASCO V-530 instrument.

3. Results and discussion

3.1. The complex formation

The new two-photon initiating system is a photoactive supramolecular complex (complex B). Formation involves two steps (Eqs. (1) and (2)). Complex B comprises xanthene dye and onium salt DMDPI, in which xanthene dye acts as the photosensitizer and DMDPI as the initiator. Firstly, water-insoluble DMDPI was encapsulated by Me-β-CD and became a water-soluble product (Eq. (1)). The obtained complex (complex A) associated with water-soluble xanthene dye via molecular reorganization to form the stable complex B (Eq. (2)). In our previous work, we reported the formation of complex A through encapsulation of Me-β-CD [23]. The stoichiometry of host to guest is 2:1; i.e., one molecule of DMDPI associates with two molecules of Me-β-CD to form a stable host/guest complex (complex A).

$$\mathrm{DMDPI} + 2\mathrm{Me}\text{-}\beta\text{-}\mathrm{CD} \rightleftharpoons (\mathrm{DMDPI}/(\mathrm{Me}\text{-}\beta\text{-}\mathrm{CD})_2) \quad (\mathrm{complexA}) \tag{1}$$

$$\mathrm{DMDPI}/(\mathrm{Me}\text{-}\beta\text{-}\mathrm{CD})_2 + \mathrm{dye} \rightleftharpoons (\mathrm{dye}/\mathrm{DMDPI}/(\mathrm{Me}\text{-}\beta\text{-}\mathrm{CD})_2) \quad (\mathrm{complexB}) \tag{2}$$

The formation of complex B was examined in aqueous solution by fluorescence spectra. FL is a typical compound of xanthene dyes, and a well-known efficient fluorophore. Interaction between the excited FL dye and complex A can be easily detected by fluorescence

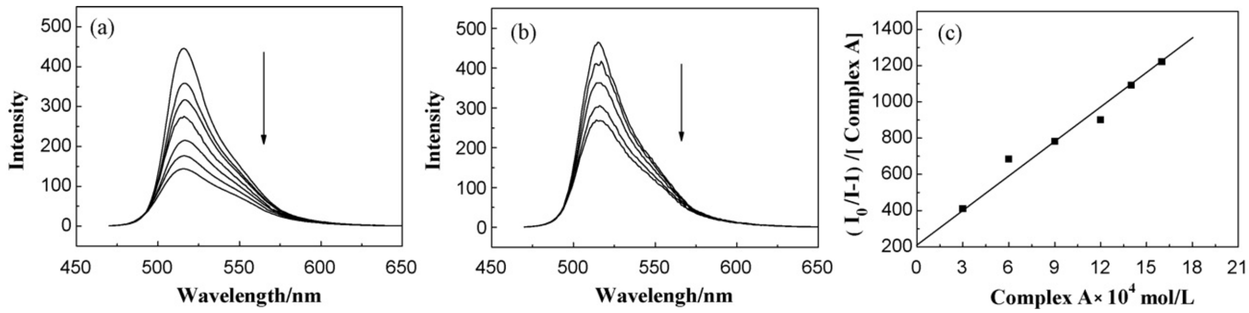


Fig. 1. Steady-state fluorescence spectra of FL dye in aqueous solution and mixed solution (CH_3OH/H_2O = 1:9, v/v) at different concentrations of complex A (a) and DMDPI (b). [complex A] = 0, 3, 6, 9, 12, 14, 16 × 10^{-4} mol/L, [DMDPI] = 0, 3, 6, 9, 12 × 10^{-4} mol/L. (c) Plot of $(I_0/I - 1)$ [complex A] versus [complex A].

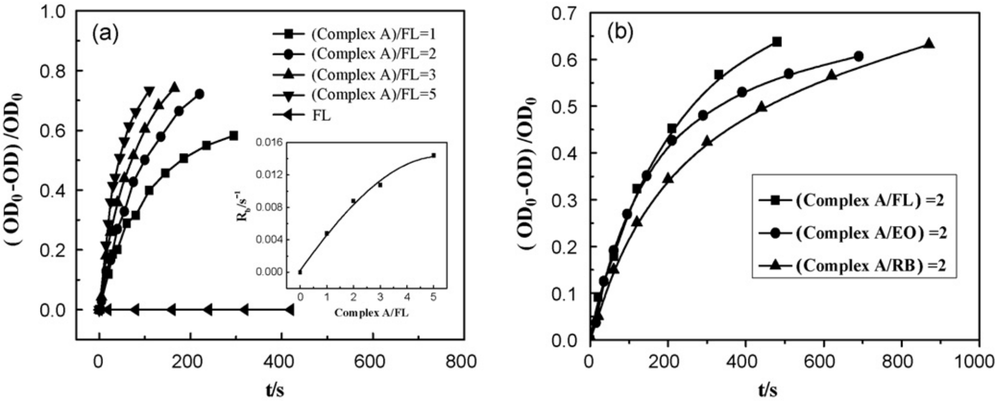


Fig. 2. (a) Photobleaching rate as a function of complex A/FL ratio (complex A)/FL = 1, 2, 3, 5. (b) Photobleaching rate of different halogen-substituted xanthene dyes.

quenching. Fig. 1a and b shows the changes in emission spectra of FL dye observed upon addition of complex A and uncomplexed DMDPI, respectively. Remarkable fluorescence quenching occurred with addition of complex A, which became more significant at higher concentration. Fluorescence intensity decreased in a stepwise fashion in DMDPI. This difference in spectral changes indicated that a supramolecular complex of FL dye and complex A was formed. The supramolecular complex accelerated the quenching of FL.

The formation of a new complex (complex B) between FL and complex A indicated that dynamic and static quenching occurred in the solution. Systems that exhibit both types of quenching obey Eq. (3) [24].

$$\frac{I_0}{I} = (1 + K_a[Q])(1 + K_{SV}[Q]) = 1 + (K_a + K_{SV})[Q] + K_a K_{SV}[Q]^2 \quad (3)$$

where I_0 and I are the emission intensities in the absence and presence of quencher [Q], respectively, K_{SV} is the Stern–Volmer constant for dynamic quenching, and K_a is the association constant of the ground state complex of FL and complex A.

Based on the data of K_{SV}, that was determined using lifetime quenching measurement to be 174 M^{-1} obtained. K_a value was obtained from the modified Stern–Volmer equation. Plotting $(I_0/I - 1)/[Q]$ versus [Q] gave $(K_a + K_{SV})$ as the intercept and $K_a K_{SV}$ as the slope of the graph. The plot of $(I_0/I - 1)/[Q]$ versus [Q] is shown in Fig. 1c. A good linear relationship was observed, confirming complex formation (complex B) in the ground state. The association constant K_a obtained from the plot in aqueous solution was 145 M^{-1}. From these above results it can be concluded that the complex B was formed from the static charge interaction of the anionic FL dye and the cationic onium salt DMDPI and further stabilized by Me-β-CD complexation.

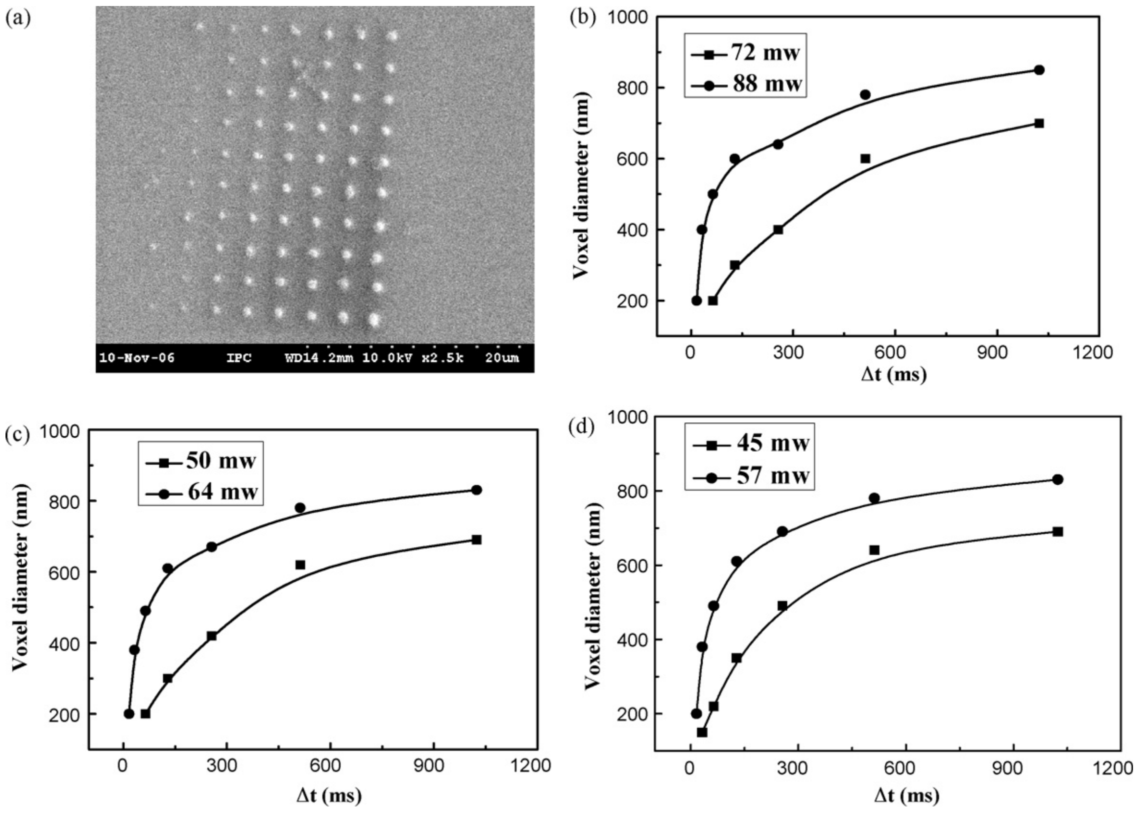


Fig. 3. (a) Scanning electron micrograph image of voxels formed under different exposure durations, complex A/RB (57 mw). (b–d) Exposure time-dependent voxel size under different laser pulse energies, 3b. FL, 3c. EO, 3d. RB.

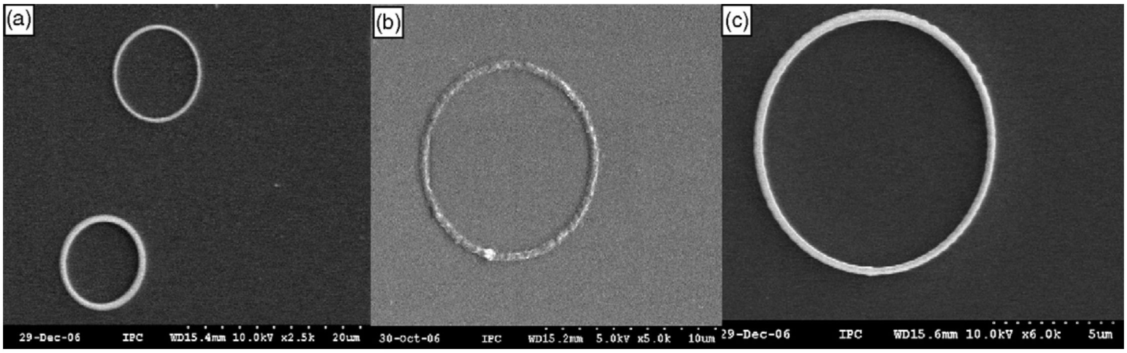


Fig. 4. Transmission electron microscopy images of microstructures fabricated via TPP of AM/bis-AM in PVP film. (a) FL, (b) EO, and (c) RB.

3.2. Photochemical reaction of complex B in film

As reported in the literature, the dyes displayed identical photochemical and photophysical behavior caused by one- or two-photon excitation [25]. The single-photon method could be used to study the primary photoreaction of a two-photon photoinitiation system. Complex B was a photoactive compound consisting of a light absorber (xanthene dye) acting as the electron donor, and complex A acting as the electron acceptor. The diffusion-controlled intermolecular reaction barely occurred within the very short lifetime of the S_1 state ($<10^{-9}$ s). The formation of complex B will therefore decrease the diffusion effect and increase the initiating efficiency.

Upon the irradiation of visible light, they easily undergo fast electron transfer from the excited FL to DMDPI, resulting in the aryl radical along with dye photobleaching. We carried out a series of photobleaching experiments of complex B in HPMC film to evaluate the primary photochemical reaction of complex B.

The influence of molar ratio of (complex A)/FL on photobleaching rate in HPMC film was examined (Fig. 2a). Remarkable enhancement of rate was observed with increasing concentration of complex A, but FL photobleaching did not occur in the absence of complex A. These results demonstrated that formation of complex B is a key factor. It determines if fast electron transfer between FL and complex A is possible via intermolecular interaction within the very short lifetime of the excited state of FL. The lower the molar ratio of complex A/FL is, the higher the formation of complex B is, and therefore the higher the rate of photobleaching is. In the practical application, a larger amount of residual initiator in the product is unfavorable; a molar ratio of 2:1, which provides a satisfactory rate, was used in subsequent studies.

The influence of halogen substitution of FL dye, such as EO and RB, on photobleaching rate in the film was studied. The photobleaching rate R_b was in the order FL ($4.59 \times 10^3\,\mathrm{s}^{-1}$) > EO ($3.31 \times 10^3\,\mathrm{s}^{-1}$) > RB ($2.09 \times 10^3\,\mathrm{s}^{-1}$) (Fig. 2b). Substitution of the halogen atom in the skeleton of FL dye (particularly in the ortho position of the phenoxyl group of FL) played an important part in electron transfer. The higher the electrophilic effect of the halogen atoms is, the lower the electron cloud density on the phenoxyl anion is, and thus the electrostatic attraction of the phenoxyl anion to the DMDPI gradually decreased from FL to RB. Steric hindrance (which depended on the size of the halogen substituent) increased the distance between cation and anion. These two factors may decrease the degree of orbital overlap and weaken the interaction between donor and acceptor. As a result, xanthene dyes with halogen atom substituents had slower photobleaching rates. These results were also observed in the ion-pair complex, as previously reported [20,21].

3.3. Two-photon polymerization

The photobleaching experiments showed that the formation of complex B played an important part in the primary photochemical reaction in the film. Xanthene dyes can also act as two-photon dyes, so we carried out the two-photon initiating polymerization experiments of complex B.

TPP microstructures were fabricated in a viscous PVP solution. For studies of the photoinitiation ability for different dye-sensitized systems, the formation of voxels (two-photon solidified small-volume elements) responsible for photopolymerization was recorded in the identical initiator concentration of 10^{-4} M. Fig. 3 shows the scanning electron microscopy (SEM) image of voxels formed under different exposure durations, and the relationship of voxel size as a function of exposure time under different laser pulse energies.

The above experiments clearly show that TPP proceeded smoothly for all dye-sensitized systems (even under very low concentrations of the photoinitiator complex A). Polymerization efficiency was higher for EO and RB than for FL. This may be because oxygen inhibition may become more important for TPP carried out in the viscous system, as well as the difference in value of TPA section δ between them. This phenomenon is commonly seen in radical-type polymerization due to the formation of the much less active peroxide radical. As a result, TPP in air using EO and RB dye as photosensitizer was favorably enhanced polymerization efficiency compared with FL dye.

For the fabrication of 3D microstructures, we employed a mode-locked Ti–sapphire laser whose oscillating wavelength, pulse width and repetition rate were 780 nm, 80 fs and 82 MHz, respectively. Formation of a polymeric microstructure was accomplished by photocrosslinking of AM/bis-AM with PVP in an initiation system with irradiation of the laser. Unexposed resin was washed away with ethanol/water solution after fabrication.

Fig. 4 shows the transmission electron microscopy (TEM) images of circle microstructures fabricated using this novel two-photon-induced polymerization initiation system based on different dyes (FL, Eo) and RB as the photosensitizer. It proved that the complex B system can be used as an effective two-photon initiator in an aqueous system. The line width was about 400 nm at this stage. In our next study, we will focus on improvement of the resolution of the line width of the microstructures.

4. Conclusions

We developed a novel two-photon-induced polymerization initiation system employing commercial photosensitizer dye and photoinitiator DMDPI in which two functional components were assembled to a supramolecular complex (complex B) with the help of Me-β-CD. Complex B had good solubility in water, and can be used as the initiator in TPP in film. Formation of supramolecular complex facilitated the electron transfer in photosensitized radical generation and decreased the amount of the coinitiator, thus significantly reducing material damage and toxicity from residual photo reagents. This technique opens a new path for nanoscale microfabrication using TPP in an aqueous system.

Acknowledgement

The authors are grateful to the National Natural Science Foundation of China for the funding support (50603031).

References

[1] B.H. Cumpston, S.P. Ananthavel, S. Barlow, D.L. Dyer, J.E. Ehrlich, L.L. Erskine, A.A. Heikal, S.M. Kuebler, Y.S. Lee, D. McCord-Maughon, J.Q. Qin, H. Rockel, M. Rumi, X.L. Wu, S.R. Marder, J.W. Perry, Two-photon polymerization initiators for three-dimensional optical data storage and microfabrication, Nature 398 (1999) 51–54.

[2] H.B. Sun, S. Kawata, Two-photon photopolymerization and 3D lithographic microfabrication, Adv. Polym. Sci. 170 (2004) 169–273.

[3] D.A. Parthenopoulos, P.M. Rentzepis, Three-dimensional optical storage memory, Science 245 (1989) 843–845.

[4] Y.Q. Tian, C.Y. Chen, Y.J. Cheng, A.C. Young, N.M. Tucker, A.Y. Jen, Hydrophobic chromophores in aqueous micellar solution showing large two-photon absorption cross-sections, Adv. Funct. Mater. 17 (2007) 1691–1697.

[5] W. Denk, J.H. Strickler, W.W. Webb, Two-photon laser scanning fluorescence microscopy, Science 248 (1990) 73–76.

[6] M. Albota, D. Beljonne, J.L. Brédas, J.E. Ehrlich, J.Y. Fu, A.A. Heikal, S.E. Hess, T. Kogej, M.D. Levin, S.R. Marder, D. McCordMaughon, J.W. Perry, H. Röckel, M. Rumi, G. Subramaniam, W.W. Webb, X.L. Wu, C. Xu, Design of organic molecules with large two-photon absorption cross sections, Science 281 (1998) 1653–1656.

[7] S.J. Chung, K.S. Kim, T.C. Lin, G.S. He, J. Swiatkiewicz, P.N. Prasad, Cooperative enhancement of two-photon absorption in multi-branched structures, J. Phys. Chem. B. 103 (1999) 10741–10745.

[8] K.D. Belfield, A.R. Morales, J.M. Hales, D.J. Hagan, E.W. Van Stryland, V.M. Chapela, J. Percino, Linear and two-photon photophysical properties of a series of symmetrical diphenylaminofluorenes, Chem. Mater. 16 (2004) 2267–2273.

[9] E. Zojer, D. Beljonne, T. Kogej, H. Vogel, S.R. Marder, J.W. Perry, J.L. Bredas, Tuning the two-photon absorption response of quadrupolar organic molecules, J. Chem. Phys. 116 (2002) 3646–3658.

[10] M. Rumi, J.E. Ehrlich, A.A. Heikal, J.W. Perry, S. Barlow, Z. Hu, D. McCord-Maughon, T.C. Parker, H. Roeckel, S. Thayumanavan, S.R. Marder, D. Beljonne, J.L. Breodas, Structure–property relationships for two-photon absorbing chromophores: bis-donor diphenylpolyene and bis(styryl)benzene derivatives, J. Am. Chem. Soc. 122 (2000) 9500–9510.

[11] B.A. Reinhardt, L.L. Brott, S.J. Clarson, A.G. Dillard, J.C. Bhatt, R. Kannan, L. Yuan, G.S. He, P.N. Prasad, Highly active two-photon dyes: design, synthesis, and characterization toward application, Chem. Mater. 10 (1998) 1863–1874.

[12] J.D. Pitts, P.J. Campagnola, S.L. Goodman, Submicron multiphoton free-form fabrication of proteins and polymers: studies of reaction efficiencies and applications in sustained release, Macromolecules 33 (2000) 1514–1523.

[13] P.J. Campagnola, D.M. Delguidice, G.A. Epling, K.D. Hoffacker, A.R. Howell, J.D. Pitts, S.L. Goodman, 3-Dimensional submicron polymerization of acrylamide by multiphoton excitation of xanthene dyes, Macromolecules 33 (2000) 1511–1513.

[14] H.Y. Woo, B. Liu, B. Kohler, D. Korystov, A. Mikhailovsky, G.C. Bazan, Solvent effects on the two-photon absorption of distyrylbenzene chromophores, J. Am. Chem. Soc. 127 (2005) 14721–14729.

[15] H.Y. Woo, J.W. Hong, B. Liu, A. Mikhailovsky, D. Korystov, G.C. Bazan, Water-soluble [2.2]paracyclophane chromophores with large two-photon action cross sections, J. Am. Chem. Soc. 127 (2005) 820–821.

[16] H.Y. Woo, D. Korystov, A. Mikhailovsky, T.Q. Nguyen, G.C. Bazan, Two-photon absorption in aqueous micellar solutions, J. Am. Chem. Soc. 127 (2005) 13794–13795.

[17] C.D. Li, L. Luo, S.F. Wang, W.T. Huang, Q.H. Gong, Y.Y. Yang, S.J. Feng, Two-photon microstructure-polymerization initiated by a coumarin derivative/iodonium salt system, Chem. Phys. Lett. 340 (2001) 444–448.

[18] J.H. He, V.S. Mendoza, Synthesis and study of a novel hybrid UV photoinitiator: p-benzoyldiphenyliodonium hexafluorophosphate, J. Polym. Sci. Polym. Chem. Ed. 34 (1996) 2809–2816.

[19] J.H. He, J.C. Zhang, Sensitized photolysis of diphenyliodonium through intra-ion-pair electron transfer-a novel near-UV photoinitiator: diphenyliodonium 9-anthroate, J. Photochem. Photobiol. A: Chem. 107 (1997) 249–252.

[20] W.H. Zhou, J.M. Liu, Z.R. Liu, E.J. Wang, A novel pathway to photoinduced colour formation of colourless fluorane dye using iodonium salts as activators, J. Photochem. Photobiol. A: Chem. 112 (1998) 173–178.

[21] W.H. Zhou, E.J. Wang, Photoinduced electron transfer in the ion pair compound (XTOn): influence of ionic association, J. Photochem. Photobiol. A: Chem. 96 (1996) 25–29.

[22] J.N. Demas, Excited-State Lifetime Measurements, Academic Press, New York, 1983.

[23] S.J. Li, F.P. Wu, E.J. Wang, L.D. Li, Photoreactive inclusion complex of aryliodonium salt encapsulated by methylated-β-cyclodextrin, J. Photochem. Photobiol. A: Chem. 197 (2008) 74–80.

[24] C.B. Murphy, Y. Zhang, T. Troxler, V. Ferry, J.J. Martin, W.E. Jones, Probing förster and dexter energy-transfer mechanisms in fluorescent conjugated polymer chemosensors, J. Phys. Chem. B 108 (2004) 1537–1543.

[25] A. Diaspro, M. Robello, Two-photon excitation of fluorescence for three-dimensional optical imaging of biological structures, J. Photochem. Photobiol. B: Biol. 55 (2000) 1–8.