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Experimental observation of enhanced reverse saturable absorption in \( \text{Bi}_2\text{Se}_3 \) nanoplates doped PMMA thin film

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Abstract

By employing the ultrafast Z-scan technique, we characterize the nonlinear absorption property of PMMA/Bismuth Selenide (\( \text{Bi}_2\text{Se}_3 \)) composite with varying concentrations. We report the fabrication of bismuth selenide (\( \text{Bi}_2\text{Se}_3 \)) nanoplate (topological insulator (TI)) doped poly methyl methacrylate (PMMA) thin film with varying doping concentrations. The effect of \( \text{Bi}_2\text{Se}_3 \) on structural and linear properties of PMMA thin film has been investigated through UV-Vis spectroscopy, scanning electron microscope (SEM), and Energy dispersive x-ray spectroscopy (EDS) elemental mapping techniques. Furthermore, the nonlinear optical absorption property of PMMA and PMMA/\( \text{Bi}_2\text{Se}_3 \) composites have been performed employing a single beam open aperture z-scan technique under femtosecond laser excitation at 750 nm. The z-scan results exhibit an enhancement of reverse saturable absorption (RSA) property with an increased nonlinear absorption coefficient (\( \beta \)) of the PMMA/\( \text{Bi}_2\text{Se}_3 \) composites compared to pure PMMA measured with intensity at 320 GW cm\(^{-2} \). The RSA response gets enhanced with the increase in doping concentration also. Our experimental observations reveal that PMMA/\( \text{Bi}_2\text{Se}_3 \) composite can provide a promising platform to realize photonic devices such as optical limiters, optical switches, and efficient protectors from high power sources.

1. Introduction

In recent years, there has been tremendous development in the combined fields of metamaterial and plasmonics domain. Researchers have invested great effort to understand the complex physics in that domain and realized them in a multitude of nanophotonic applications [1, 2]. The strong localization of electromagnetic energy in the nanoscale of plasmonic structure triggers to employ it with various functionalities such as photovoltaic devices [3], optical sensors [4], optical filter [5, 6], optical ring resonator [7], and optically assisted magnetic data storage technology [8]. Surface plasmon polaritons (SPP) has been exploited effectively to realize information carrier for ultra-compact inter-chip interconnects and all-optical data processing [9–11]. However, despite immense advancement, plasmonic and metamaterial devices suffer fundamental limitations owing to the high energy dissipation in plasmonic media which prevents to employ especially in the visible to ultraviolet (UV) spectral range [12]. Traditional plasmonic materials (such as gold and silver) suffer from strong dissipation due to the interband electronic transitions and Drude losses [13]. Hence, there has been a surge of research interest aiming to explore alternative low-loss plasmonic materials in the high-frequency spectral range. Researchers are investigating materials such as metallic alloys and oxides, highly doped semiconductors, two-dimensional materials, and more recently Topological insulators (TIs) materials [14, 15]. Recent years have witnessed a growing interest in the study of TI materials as an alternative promising platform capable of overcoming these issues [16].

TIs are a new class of electronic materials that are gaining considerable scientific and technical attention among the scientific community due to their intrinsic properties over other materials [17–19]. TI materials exhibit conducting states at the edge and surface containing a Dirac cone with a helical spin in the momentum...
space while showing bulk insulating properties characterized by a gaped band structure \cite{20,21}. The fascinating behavior of TIs triggers to employ it in a multitude of applications which includes quantum computing \cite{19}, dissipation less electronics \cite{22}, spintronics \cite{23,24}, enhanced thermoelectric \cite{25}, optical recording \cite{26}, high-performance field effect transistor \cite{27}, near-infrared flexible electrodes \cite{28}, thermoelectric and infrared applications \cite{29}, laser photonics and high-speed optoelectronic devices \cite{30–32}, etc.

Owing to the strong light–matter interaction of TI materials, investigation of linear optical properties as well as nonlinear optical (NLO) properties are attracting a considerable amount of research interest \cite{33–36}. NLO properties of TIs and their different composites have been reported by several groups employing the z-scan technique \cite{36–39}. An intensive amount of work has been reported demonstrating ultrashort pulse generation employing TIs as saturable absorber \cite{40–44}. Among all other TIs, Bi$_2$Se$_3$ which has a relatively large bulk band gap (0.3 eV) and tunable surface band gap (controlled by layer thickness), provides a promising platform to realize optical devices for room temperature application \cite{45,46}. In accordance with the electronic properties, researchers are exploring the nonlinear optical properties of the novel material \cite{39,47–50}. The Bi$_2$Se$_3$ film exhibits excellent saturation absorption (SA) property and has been employed effectively as a saturable absorber in achieving mode lock laser \cite{40,51}. The SA property of different layered Bi$_2$Se$_3$ films has been investigated using the Z-scan method revealing the influence of the second surface state (SS) and the thickness on the SA property of the material \cite{52}. The work provides an effective approach where controllable SA using Bi$_2$Se$_3$ could be achieved by properly tailoring the thickness or the excitation wavelength. Very recently, an effective technique has been reported where the nonlinear optical property of the Bi$_2$Se$_3$ can be well-tailored using ion irradiation by controlling the defects in Bi$_2$Se$_3$ which have been introduced intentionally \cite{53}. There are ample scopes to realize the Ti:Bi$_2$Se$_3$ material in a myriad of applications. On the other hand, Poly-methylmethacrylate (PMMA) is a commonly used polymer for the preparation of thin film as most of the material gets decomposed into PMMA \cite{54–56}. In addition to this, PMMA has moderate properties such as low-cost, high-transparency window with good flexibility, good physical and chemical properties, and easy handling capabilities, which stem researchers to use it in a wide range of applications \cite{57–59}.

In this study, we demonstrate the fabrication of Ti:Bi$_2$Se$_3$ doped PMMA thin film with varying doping concentrations. The structural and linear properties of the PMMA and PMMA/Bi$_2$Se$_3$ composites have been studied through ultraviolet-visible (UV-Vis), SEM, profilometry, and energy-dispersive x-ray (EDX) elemental mapping techniques. Furthermore, the reverse saturation absorption (RSA) property of pure PMMA and PMMA/Bi$_2$Se$_3$ composites has been investigated by employing the ultrafast open aperture (OA) z-scan technique. We observe an enhancement of the RSA property of the PMMA/Bi$_2$Se$_3$ composites compared to pure PMMA. RSA increases effectively with the increase in doping concentration.

### 2. Fabrication of PMMA/Bi$_2$Se$_3$ composites

Bi$_2$Se$_3$ nanoplates were synthesized by a solvothermal method, wherein BiCl$_3$, Se, NaOH, and polyvinyl pyrrolidone (PVP) powders, and ethylene glycol solutions were used as precursors. For the synthesis, suitable amounts of BiCl$_3$ and Se powders were first dissolved in an already prepared solution of PVP and ethylene glycol. To this solution, another solution made by dissolving NaOH in distilled water was added. The resulting solution was stirred for 30 minutes and subsequently sealed in a 50 ml autoclave. The autoclave was then heated to 180°C in a furnace for 36 hours and then cooled naturally to room temperature. The black-colored product was then washed several times in de-ionized water and alcohol and finally dried in a vacuum.

The solutions of Bi$_2$Se$_3$ and PMMA with varying concentrations of Bi$_2$Se$_3$ in PMMA were prepared. A stock solution of Bi$_2$Se$_3$/DMF (55% w/v) was prepared. To this solution, we added the high molecular weight (Mw = 996,000 g mol$^{-1}$) PMMA (by Sigma Aldrich) and Dimethylformamide (DMF) to obtain the varying concentration ratio of Bi$_2$Se$_3$ to PMMA, keeping the concentration of PMMA (7% w/v) in all final solutions fixed. The solutions were stirred for 1 hour to obtain a homogeneous solution. The concentration of Bi$_2$Se$_3$ with respect to PMMA varied to 0.36 and 0.73 wt% in the final solution. The High concentration and high molecular weight of PMMA provide the necessary viscosity which facilitates the formation of desired film thicknesses via spin-coating. The solution was spin-coated on the vitreous quartz substrate at 1000 R.P.M. to form a thin film with thicknesses of about 1 μm. Next, the thin film of PMMA/Bi$_2$Se$_3$ was dried in an oven for 4 hours at 40°C to remove any residue of DMF in the thin film. Finally, the different solutions of pristine PMMA and Bi$_2$Se$_3$/PMMA were used for the analysis.

The UV-Vis absorption spectra of the prepared samples were measured between 200 nm to 1000 nm range by absorption spectrometer and are shown in figure 1. The absorption peak for Bi$_2$Se$_3$ doped thin films appears at 225 nm. The morphology of pure and doped PMMA thin films was investigated, which is shown in figure 2. The synthesized Bi$_2$Se$_3$ nanoplates are shown in figure 2(a) with considerable magnification. The uniform morphology of PMMA thin film on quartz substrate deposited by the spin coating method is shown in
Furthermore, the surface of PMMA/Bi$_2$Se$_3$ thin films for 0.73 and 0.36 wt% concentrations are shown in figures 2(c) and (d), respectively. It is observed that the nanoplates are randomly distributed on the PMMA surface. The Energy-dispersive x-ray spectroscopy (EDS) elemental mapping (Bi and Se) for two different concentrations are shown in figure 3. The elements of Bi and Se are presented in different color scales. The EDS analysis of higher concentration (PMMA/Bi$_2$Se$_3$ 0.73 wt%) is shown in figure 3(a) and shows larger elements than for lower concentration ((PMMA/Bi$_2$Se$_3$ 0.36 wt%) as shown in figure 3(b).

3. Experimental setup and results

The RSA measurement has been carried out by the open aperture (OA) single beam z-scan technique. The schematic of the OA z-scan setup is shown in figure 4. The OA z-scan has been performed using an output of
750 nm from a commercial optical parametric amplifier (TOPAS PRIME, Light Conversion Inc.) which is seeded with a Ti: sapphire regenerative amplifier (Libra He, Coherent Inc.) laser pulse at 808 nm, 150 fs, at 1 kHz repetition rate. The fs laser pulses are focused with a beam waist of 35 $\pm$ 2 $\mu$m using a plano-convex lens of Figure 3. Elemental analysis mapping by SEM/EDX of Bi and Se map for (a) Bi$_2$Se$_3$/PMMA composite with doping concentration 0.73 wt% and (b) Bi$_2$Se$_3$/PMMA composite with doping concentration 0.36 wt%.

Figure 4. ULS: Ultrafast laser source; $M_1$: Silvered mirror; $L_1$: Convex lens; $PL_1$-$PL_4$: Plano-convex lens; $PD$: Photodetector; $AP_1$: Aperture; $HWP$: Half-wave plate; $PBS$: Polarization beam splitter; $BS_1$, $BS_2$: Beam splitter; $VND$: Variable neutral density filter.
The sample is placed in a cuvette of 2 mm path length. A motorized translational stage (GTS 150 Newport) which is connected with a motion controller (ESP 301 Newport), has been employed for the movement of the sample across the focal point. The transmitted beam is collected by Si photodiode (Thorlabs, PDA100A) to recover the OA signal. To avoid saturation, we have placed variable neutral density filters before the photodiode. The OA signals are connected with the lock-in amplifiers (Signal Recovery 7225), which are also triggered by a 1 kHz transistor-transistor logic pulse from the delay generator (SDG Elite) of the laser. We also incorporate another reference signal to avoid pulse to pulse fluctuation where the reference signal is collected by a photodiode (PD1) after passing through a beam splitter (BS1) and focusing lens (L1), and is fed to the lock-in amplifiers. For more precision in the OA experiment, we collect the scattered light signal through a photodetector which is placed at an angle of 50° to the z-axis. The lock-in amplifier and motorized translational stage are connected with LabVIEW 2014 environment for automation and averaging the experimental data.

The NLO properties of pure PMMA and Bi$_2$Se$_3$/PMMA composites have been investigated by OA z-scan method at 750 nm wavelength with a photon energy of 1.65 eV ($2.64 \times 10^{-19}$ J). The input intensity has been fixed at 320 GW cm$^{-2}$. The experimental results are shown in figure 5 which comprises a normalized transmittance of the doped and undoped films. The normalized transmittance of the three curves exhibits a symmetric valley about the focus and lowest value at $z = 0$, which demonstrates the RSA property of the three samples. Figure 5(a)–(c) exhibit the experimental and theoretical data of the OA Z-scan experiment for pure PMMA, PMMA/Bi$_2$Se$_3$ 0.36 wt% and PMMA/Bi$_2$Se$_3$ 0.73 wt%, respectively. It can be observed from the OA z-scan curves that the RSA response property gets enhanced for doped PMMA composites and also increase with the increase in doping concentration. The minimum values of normalized transmittance are 0.96, 0.93, and 0.75.
for pure PMMA, PMMA/Bi$_2$Se$_3$ 0.36 wt% and PMMA/Bi$_2$Se$_3$ 0.73 wt%, respectively. In the qualitative interpretation of the experimentally observed OA z-scan results, we have carried out an analysis based on intensity-dependent absorption [60]. A single Gaussian beam profile with a beam waist $w_0$ can be expressed as,

$$I_L(Z, r) = \frac{I_0}{1 + (z^2/Z_R^2)} \exp \left( -\frac{2r^2}{w^2(z)} \right) \exp \left( \frac{r^2}{\tau_p^2} \right)$$

(1)

where $I_0$ is the intensity at the focus point, $Z_R = (\pi w_0^2/\lambda)$ is the Rayleigh length, $\tau_p$ represent the input pulse width and the beam waist $w(z)$ is represented by $w^2(z) = w_0^2 (1 + z^2/\pi)$. The propagation of lightwave through the nonlinear medium can be expressed as

$$\frac{dI}{dz} = -\alpha(I)I$$

(2)

where $\alpha(I)$ is the intensity-dependent absorption coefficient. The total absorption coefficient combining the SA coefficient and the two-photon absorption (TPA) coefficient, can be expressed as,

$$\alpha(I) = \frac{\alpha_0}{1 + I/I_{sat}} + \beta \frac{I}{I_{sat}}$$

(3)

where $I$ and $I_{sat}$ are laser radiation intensity and saturation intensity, respectively. $\beta$ is the nonlinear absorption coefficient. The first term on the right-hand side describes negative nonlinear absorption such as SA, whereas the second term represents positive nonlinear absorption such as RSA, TPA, etc. To obtain the transmitted intensity of the incident light beam, equation (3) has been substituted in equation (2) and finally, the intensity equation has been solved using the Crank-Nicholson method. The transmission curve obtained from the OA z-scan experiment has been fitted theoretically. The nonlinear absorption coefficient $\beta$ and $I_{sat}$ have been evaluated from the theoretical fittings of the experimental data. Since, the three samples have the absorption peaks in the wavelength range 200 nm–250 nm (figure 1), the origin of RSA could be attributed to the excited state absorption (ESA) or a two-photon absorption (TPA) process [61]. The calculated $I_{sat}$ and $\beta$ values for pure and doped PMMA composites have been summarized in table 1. It is observed from the table that $\beta$ values have been significantly increased with higher concentrations in doped PMMA than in pure PMMA composites.

Furthermore, to characterize the optical limiting property of the samples, we have placed the samples at the focal point. The optical limiting behavior is measured at 750 nm wavelength and shown in figure 6, where

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### Table 1. Saturation intensity ($I_{sat}$) and NLA coefficient ($\beta$) are calculated by fitting the experimental data for pure and doped-PMMA composites.

| Sample (nm) | Input intensity (GW/cm$^2$) | $I_{sat}$ (GW/cm$^2$) | $\beta$ (cm/GW) |
|-------------|----------------------------|-----------------------|-----------------|
| Pure PMMA   | 320                        | 0.009                 | 0.0027          |
| PMMA/Bi$_2$Se$_3$ (0.36 wt%) | 320 | 0.08       | 0.0055          |
| PMMA/Bi$_2$Se$_3$ (0.73 wt%) | 320 | 0.29       | 0.0285          |
normalized transmission is plotted against the varying input intensity. It is observed that PMMA composites exhibit strong optical limiting behaviour as normalized transmittance decreases with the increase in pump intensities. The optical limiting threshold is measured to be 158 GW cm$^{-2}$, 105 GW cm$^{-2}$, and 55 GW cm$^{-2}$ for pure PMMA, PMMA/Bi$_2$Se$_3$ 0.36 wt% and PMMA/Bi$_2$Se$_3$ 0.73 wt%, respectively. Thus, limiting threshold decrease with the increase in doping concentration of the nanoplates indicating efficient optical limiting behaviour.

4. Conclusion

In conclusion, we have demonstrated the RSA of pure and Bi$_2$Se$_3$-doped PMMA composites with the OA Z-scan technique at 750 nm wavelength in the femtosecond time scale. The structural and linear properties of pure and doped composites have been investigated by UV-Vis spectroscopy, SEM, and EDS elemental mapping techniques. Our experimental results revealed that compared to pure PMMA, Bi$_2$Se$_3$-doped PMMA composites exhibit a stronger RSA response, and the response also gets enhanced with increased doping concentration. The experimental data were fitted perfectly by the Z-scan theory. Our observations demonstrate that Bi$_2$Se$_3$-doped PMMA with high concentration could provide a very promising platform to realize optical devices such as optical limiters and optical shutters.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

[1] Zhao D, Lin Z, Zhu W, Lesec H J, Xu T, Agrawal A, Zhang C and Huang K 2021 Nanophotonics 10 2283–308
[2] Zheludev N I and Kisvhar Y S 2012 Nat. Mater. 11 917–24
[3] Atwater H A and Polman A 2010 Nature Materials 9 203–13
[4] Liu N, Weiss T, Mesch M, Languth L, Eigenthaler U, Hirscher M, Sonnichsen C and Giessen H 2010 Nano Lett. 10 11103–7
[5] Hosseini A, Nejati H and Massoud Y 2007 Opt. Express 15 15280–6
[6] Hosseini A, Nejati H and Massoud Y 2008 Opt. Express 16 1475–80
[7] Hosseini A and Massoud Y 2007 Appl. Phys. Lett. 90 181102
[8] Tsiatmas A, Atmatzakis E, Papasimakis N, Fedotov V, Luk’yanchuk B, Zheludev N I and de Abajo F J 2013 New J. Phys. 15 113035
[9] Ozay F 2006 Science 311 189–93
[10] Kim J T, Ju J J, Park S, Kim M S, Park S K and Lee M H 2008 Opt. Express 16 13133–8
[11] Hosseini A, Nieuwoudt A and Massoud Y 2006 Opt. Express 14 7291–8
[12] West P R, Ishii S, Naik G V, Ermani N K, Shalaev V M and Boltasseva A 2010 Laser Photonics Rev. 4 795–808
[13] Naik G V, Shalaev V M and Boltasseva A 2013 Adv. Mater. 25 3264–94
[14] Naik G V, Kim J and Boltasseva A 2011 Opt. Mater. Express 1 1090–9
[15] Wang A X and Kong X 2013 Materials 6 3024–52
[16] Touzert J and Serna R 2017 Opt. Mater. Express 7 2299–325
[17] Qi X L and Zhang S C 2011 Rev. Mod. Phys. 83 1057
[18] Fu L, Kane C L and Mele E J 2007 Phys. Rev. Lett. 98 106803
[19] Hasan M Z and Kane C L 2010 Rev. Mod. Phys. 82 3045
[20] Roushan P, Seo J, Parker C V, Hor Y S, Hsieh D, Qian D, Richardella A, Hasan M Z, Cava R J and Yazdani A 2009 Nature 460 1106–9
[21] Qi X L, Hughes T L and Zhang S C 2008 Phys. Rev. B 78 195424
[22] Chechelsky J G, Ye J, Onose Y, Iwasa Y and Tokura Y 2012 Nat. Phys. 8 729–33
[23] Xiao X, Yang S A, Liu Z, Li H and Zhou G 2013 Sci. Rep. 3 7898
[24] Cao Y et al 2013 Nat. Phys. 9 499–504
[25] Xu Y, Gan Z and Zhang S C 2014 Phys. Rev. Lett. 112 226801
[26] Watanabe K, Sato N and Miyako N 1983 J. Appl. Phys. 54 1256–60
[27] Zhu H et al 2013 Sci. Rep. 3 1–5
[28] Peng H, Dang W, Cao J, Chen Y, Wu D, Zheng W, Li H, Shen Z X and Liu Z 2012 Nat. Chem. 4 281–6
[29] Mishra S, Satpathy S and Jepsen O 1997 J. Phys. Condens. Matter 9 461
[30] Zheng K, Luo L B, Zhang T F, Liu Y H, Yu Y Q, Lu R, Qiu H L, Li Z I and Huang J A 2015 J. Mater. Chem. C 3 9154–60
[31] Zhang H, Yao J, Shao J, Li H, Li S, Bao D, Wang C and Yang G 2014 Sci. Rep. 4 5876
[32] Qiao H et al 2015 Adv. Nano 9 1886–94
[33] Bao Q and Loh K P 2012 Nano Nano 6 3677–94
[34] Di Pietro P, Vitucci F, Nicoliotti D, Baldassarre L, Calvani P, Cava R, Hor Y, Schade U and Lupi S 2012 Phys. Rev. B 86 045439
[35] Yu H, Zhang H, Wang Y, Zhao C, Wang B, Wen S, Zhang H and Wang J 2013 Laser Photonics Rev. 7 77–83
[36] Wang Y, Liu S, Yuan J, Wang P, Chen J, Li J, Xiao S, Bao Q, Gao Y and He J 2016 Sci. Rep. 6 33070
[37] Zhang H, Virally S, Bao Q, Ping L K, Massar S, Godbout N and Kockaer P 2012 Opt. Lett. 37 1856–8
[38] Wang K et al 2013 ACS Nano 7 9260–7
[39] Lu S, Zhao C, Zou Y, Chen S, Chen Y, Li Y, Zhang H, Wen S and Tang D 2013 Opt. Express 21 2072–82
[40] Zhao C, Zou Y, Chen Y, Wang Z, Lu S, Zhang H, Wen S and Tang D 2012 Opt. Express 20 27886–95
[41] Lee J, Koo J, Jhon Y M and Lee J H 2014 Opt. Express 22 6165–73
[42] Chi C, Lee J, Koo J and Lee J H 2014 Laser Phys. 24 105106
[43] Liu H, Zheng X W, Liu M, Zhao N, Luo A P, Luo Z C, Xu W C, Zhang H, Zhao C J and Wen S C 2014 Opt. Express 22 6868–73
[44] Sotor J, Sobon G, Macherzynski W, Paletko P, Grodecki K and Abramski K M 2014 Opt. Mater. Express 4 1–6
[45] Zhang H, Liu C X, Qi X L, Dai X, Fang Z and Zhang S C 2009 Nat. Phys. 5 438–42
[46] Sun L, Lin Z, Peng J, Weng J, Huang Y and Luo Z 2014 Sci. Rep. 4 1–9
[47] Gupta A and Srivastava S 2020 J. Appl. Phys. 127 244302
[48] Vargas A, Basak S, Liu F, Wang B, Panaitescu E, Lin H, Markiewicz R, Bansil A and Kar S 2014 Acs Nano 8 1222–30
[49] Zang C, Qi X, Ren L, Hao G, Liu Y, Li J and Zhong J 2014 Appl. Surf. Sci. 316 341–7
[50] Sharma A, Bhattacharyya B, Srivastava A, Senguttuvan T and Husuale S 2016 Sci. Rep. 6 19138
[51] Dou Z, Song Y, Tian J, Liu J, Yu Z and Fang X 2014 Opt. Express 22 24055–61
[52] Zhang J, Jiang T, Zhou T, Ouyang H, Zhang C, Xin Z, Wang Z et al 2018 Photonics Research 6 C8–14
[53] Tan Y, Guo Z, Shang Z, Liu F, Böttger R, Zhou S, Shao J, Yu X, Zhang H and Chen F 2016 Sci. Rep. 6 21799
[54] Martinez A, Uchida S, Song Y W, Ishigure T and Yamashita S 2008 Opt. Express 16 11337–43
[55] Aithal S, Aithal S and Bhat G 2011 Optical nonlinearity of dye-doped polymer film using z-scan technique 2011 2nd International Conference on Photonics (IEEE) 1–5
[56] Zhang X L, Liu Z B, Zhao X, Yan X Q, Li X C and Tian J G 2013 Opt. Express 21 25277–84
[57] Hussan R M, Mahdi Z F and Faris R A 2013 Iraqi Journal of Laser 12 27–35
[58] Anandalli M H, Bhajantri R, Maidur S R and Patil P S 2020 J. Mater. Sci., Mater. Electron. 31 10531–47
[59] Shubar M, Saadon H and Abbas S F 2019 Studying of nonlinear optical properties of binary bi12so4 and bi12te4/pmma nanocomposite films by z-scan technique J. Phys. Conf. Ser. 1234 012059 (IOP Publishing)
[60] Bhattacharya S, Maiti R, Das A C, Saha S, Mondal S, Ray SK, Bhaktha S and Datta P K 2016 J. Appl. Phys. 120 013101
[61] Srinivas N N, Rao S V and Rao D N 2003 JOSA B 20 2470–9