All-Photonic Switching of (Fe, Mg) Co-Doped PbS/PVA Nanocomposite Films Under a Pump Laser Illumination

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Abstract:

A new all-photonic switching of nonlinear optical materials with very low signal/noise background was presented. Fe and Mg were used to prepare doped and co-doped PbS/PVA freestanding nanocomposite; films were prepared by a simple chemical method with different doping concentrations. The X-ray diffraction patterns, scanning electron microscope images, and optical absorption spectrum of the prepared films were examined. The crystallinity and optical band gap of the prepared co-doped PbS/PVA were found to be affected by Fe and Mg, doping concentrations. The all prepared samples showed a blue shift in the absorption spectra and the optical band gap was increased when the doping concentration is increased. The all-optical switching effect performance of metal doped and (Fe, Mg) co-doped PbS/PVA with various Fe and Mg concentrations were investigated. The results showed that the (Fe, Mg) co-doped PbS/PVA at 1.2%M Fe and 0.8%M Mg doping concentration can demonstrate an active all-photonic switching device and lead to the realization with maximum modulation depth of 86.5% and switching contrast of 8.8 dB at minimum switching time of 47 ms.

Keywords: All-photonic switching; co-doped PbS/PVA nanocomposite; modulation depth; switching contrast.

المفتاح الفوتوني من مركبات نانوية لأفلام PbS/PVA مشوبة بمعدنين Fe و Mg تحت اضاءة الليزر

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الخلاصة:

تم تقديم مفتاح فوتوني جديد من مواد لاخطية بصرية باقل نسبة الاشارة الى الضوضاء في الاخراج. حيث تم تحضير المركب النانوي كبريتيد الرصاص/بولي فينايل الكحول (PbS/PVA) باستخدام طريقة كيميائية بسيطة بنسب تشويب مختلفة من المعدنين Fe و Mg. تم تشخيص تلك النماذج المحضرة بواسطة حيود الاشعة السينية XRD ومجهر المسح الالكتروني SEM وطيف الامتصاص الضوئي UV-vis. النتائج اظهرت ان التبلورية وفجوة الطاقة البصرية

تتأثران بتغير نسبة التشويب (Fe و Mg). كما اظهرت كل النماذج المحضرة ازاحة نحو الطول الموجي الاقل في طيف الامتصاص عند زيادة نسبة التشويب وان فجوة الطاقة البصرية تزداد بزيادة تركيز التشويب. وان اداء تاثير المفتاح الفوتوني للمركب النانوي المحضر تم التحري عنه. حيث اثبتت النتائج ان المركب النانوي PbS/PVA المشوب بنسب مختلفة من معدن Fe و Mg عند التركيز 1.2%M و 0.8%M، على التوالي يمكن ان يساق كجهاز مفتاح فوتوني فعال وهذا ادى الى ان تحقيقه كجهاز بأعلى عمق تضمين 86.5% وتباين 8.8 dB باقل زمن مفتاحي .47 ms.

الكلمات المفتاحية: المفتاح الفوتوني, مركب نانويPbS/PVA , ثنائي التشويب، عمق التضمين, التباين.

1. Introduction

All-photonic devices, in which photons instead of electrons are used as information carriers, represent the wave of the future in all-optical communications and information processing, that requires to be modulated the signal light using a pump laser beam [1-3]. However, the interaction between photons is only possible in a nonlinear optical (NLO) material [4, 5]. This, in turn, encourage researcher to look for a NLO material with variety of optical nonlinearity mechanisms for developing and making an all-photonic devices such as an all-photonic switching. Therefore, all-photonic switching can be used as a gist element in constructing on-chip all-optical switch networks. All-optical devices using different optical materials and based on nonlinear optical response have received much attention in recent years [6-9]. Recently, studies in metal nanocomposite material, all-photonic switching with low pump power have been reported [10]. Here, we will be focused on the metal doped nanocomposite materials to realize and make all-photonic switching with high performance, in which important parameters like switching time (ST), switching contrast (SC), and modulation depth (MD) are considered.

In the present work, experimental investigations were presented to study the all-optical switching effects for metal doped and (Fe, Mg) co-doped PbS/PVA freestanding nanocomposite films that prepared using various Fe and Mg doping concentrations illuminated by a pump laser at a wavelength of 457 nm.

2. Preparation of metal doped and co-doped PbS/PVA nanocomposite

Preparing of PbS/PVA freestanding nanocomposite film was carried out by a simple chemical method as reported in our previous work [10]. However, 1.2 % M of Fe and 0.8% M of Mg were used to prepare metal doped PbS/PVA nanocomposite freestanding films together, $FeCl_2$ and $MgSO_4$ as a source of iron ions Fe^{2+} and Mg^{2+}, respectively. The selected concentration of the metal ions were added directly to the Pb^{2+}/PVA solution and the preparation process was completed by adding drops of Na_2S to form metal doped PbS/PVA nanocomposites. In addition, co-doped PbS/PVA were also prepared using the same chemical method by selecting a various metal source concentration as listed in Table 1. Finally, the prepared solutions were casted into a glass Petri dish and left to dry naturally at room temperature for 2 days. After the drying process, good quality films with uniform surface were peeled off from the Petri dish with thickness of 80±10 μm.

Table 1: Description of the (Fe, Mg) co-doped PbS/PVA samples used in our experiment

$1.2FM_1PP$	1.2% M Fe-0.2% M Mg-PbS/PVA
$1.2FM_2PP$	1.2% M Fe-0.8% M Mg-PbS/PVA
$0.8MF_1PP$	0.8% M Mg-0.2% M Fe-PbS/PVA
$0.8MF_2PP$	0.8% M Mg-0.8% M Fe-PbS/PVA

3. Result and Discussion:

3.1 X-ray diffraction

Figure 1(a) and (b) shows the X-ray diffraction (XRD) patterns of the single metal doped and co-doped samples 1.2% M Fe-PbS/PVA, 0.8% M Mg-PbS/PVA, $1.2FM_1PP$, $1.2FM_2PP$, $0.8MF_1PP$, and $0.8MF_2PP$ freestanding nanocomposite films. The diffraction peak which observed at approximately 2θ of 20^o in all prepared nanocomposite films corresponding to the PVA polymer. However, diffraction peaks demonstrated at about 2θ of 29.2^o and shifted slightly toward lower angles due to the fact that the PbS expands for doped samples, which corresponds to the (200) plane of PbS cubic structure when compared by the standard database card 2θ equal to 30^o (ICCD-PDF4 No. 00–0050592). It can be observed from this figure, the XRD peak intensity of metal co-doped PbS/PVA became higher and better crystallinity than single metal dopant. However, the XRD peak intensity increased when the metal Fe and Mg doping concentration increased from 0.2%M to 0.8% M.

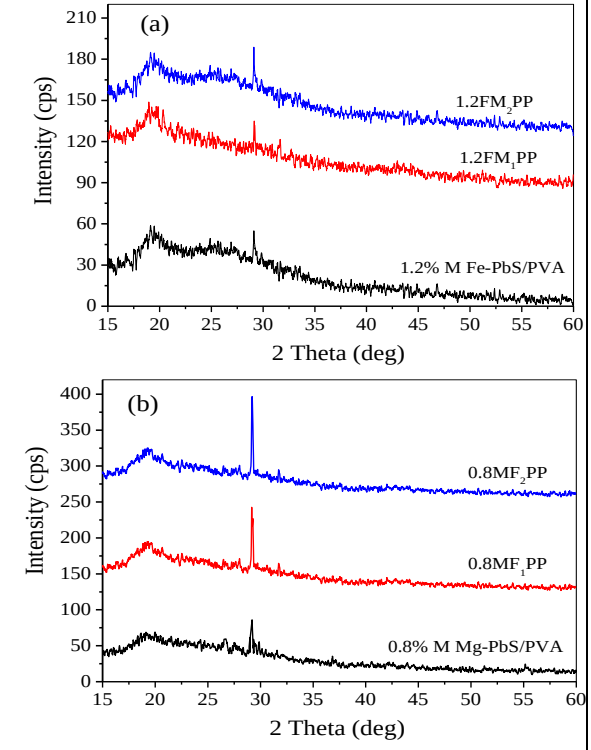

Figure 1: X-ray diffraction patterns of samples: (a) 1.2 %M Fe-PbS/PVA, $1.2FM_1PP$ and $1.2FM_2PP$ and (b) 0.8 %M Mg-PbS/PVA, $0.8MF_1PP$ and $0.8MF_2PP$.

3.2 Scanning electron microscopy

The scanning electron microscopy (SEM) images and particles size distribution for samples 1.2% M Fe-PbS/PVA, $1.2FM_1PP$, and $1.2FM_2PP$ 0.8% M Mg-PbS/PVA are shown in Fig. 2. In Fig. 2, it can be seen that the dominated particle size increased from 15-20 nm to 25-30 nm when Mg doping concentration increased from 0.0 %M to 0.8 %M. In addition, the SEM images and particles size distribution for single doped and co-doped samples 0.8% M Mg-PbS/PVA, $0.8MF_1PP$, and $0.8MF_2PP$ freestanding nanocomposite films are illustrated in Figs. 3. However, as in Fig. 3, the dominated particle size increased from 20-25 nm to 30-35 nm when Fe doping concentration increased from 0.0 %M to 0.2 %M, and decreased to 25-30 nm when Fe concentration increased to 0.8 %M.

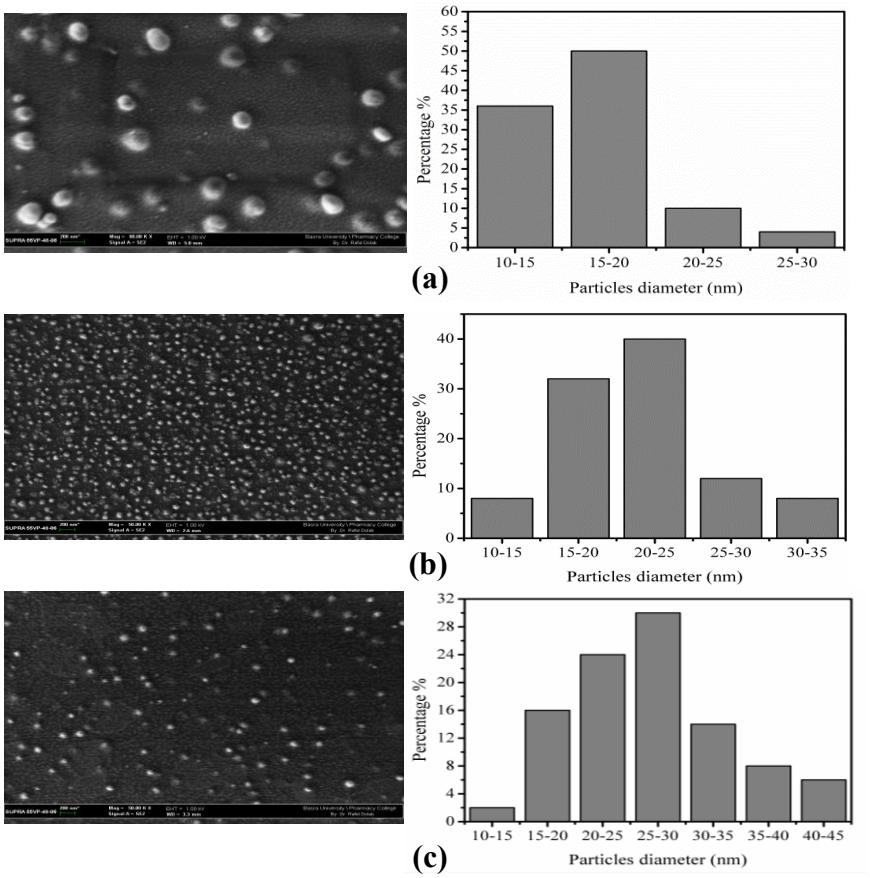

Figure 2 SEM images and particle size distribution of samples: (a) 1.2 %M Fe-PbS/PVA and (b) 1.2FM$_1$PP and 1.2FM$_2$PP.

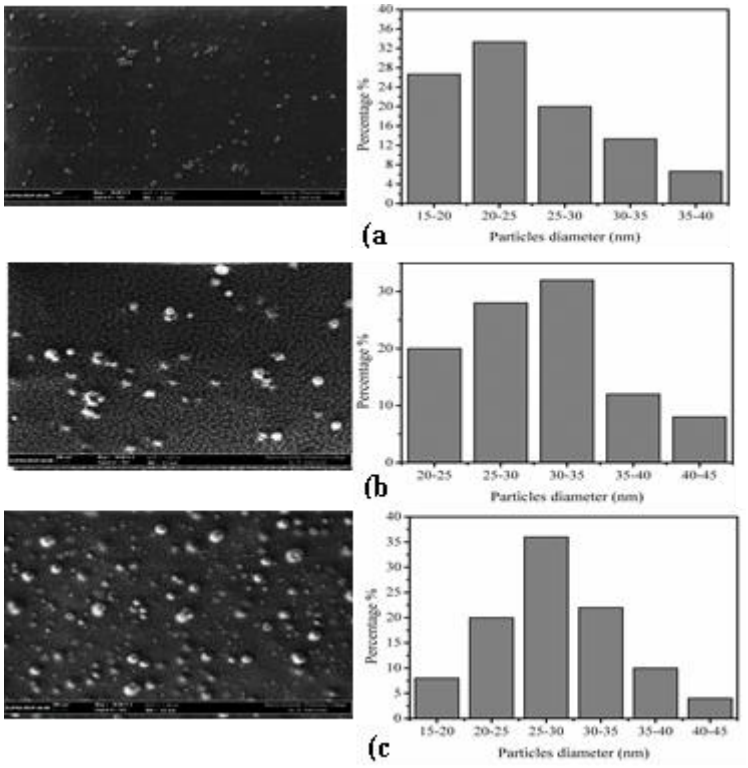

Figure 3 SEM images and particle size distribution of samples: (a) 0.8 %M Mg-PbS/PVA and (b) 0.8MF$_1$PP and 0.8MF$_2$PP.

3.3 UV–VIS spectra and band gap

Figure 4 shows the absorbance spectra of the single doped and co-doped samples 1.2% M Fe-PbS/PVA, 0.8% M Mg-PbS/PVA, $1.2FM_1PP$, $1.2FM_2PP$, $0.8MF_1PP$, and $0.8MF_2PP$ freestanding nanocomposite films. It was noted that all the prepared films with various type of metal doping showed a blue shift in the absorption edge. In addition, the optical band gap increased with increasing the molar ratio of dopant for all prepared samples as shown in the inset of Fig. 4. The energy band gap of semiconductors was calculated using Tauc's formula [11] and the particle size was estimated using Iwan Moreels equation was estimated [12]. As seen in Fig. 4(a), the optical band gap increased as Fe and Mg doping concentration ranged from 0.2% M to 0.8% M, which was determined to be 2.69 eV and 2.71 eV, respectively, for samples $1.2FM_1PP$ and $1.2FM_2PP$; but for $0.8MF_1PP$ and $0.8MF_2PP$ samples was 2.65 eV and 2.7 eV, respectively. In addition, we observe a clear decreasing of particles size, which was equal to 2.76 nm and 2.73 nm for samples $1.2FM_1PP$ and $1.2FM_2PP$, respectively; while for samples $0.8MF_1PP$ and $0.8MF_2PP$ was found to be 2.8 nm and 2.76 nm, respectively. PbS had a large excitation Bohr radius of 18 nm [11]. Thus, a strong quantum confinement of electrons and holes happened in the PbS nanoparticles, which led to regulate the value of the band gap by controlling the particle size according to the effective mass model [13].

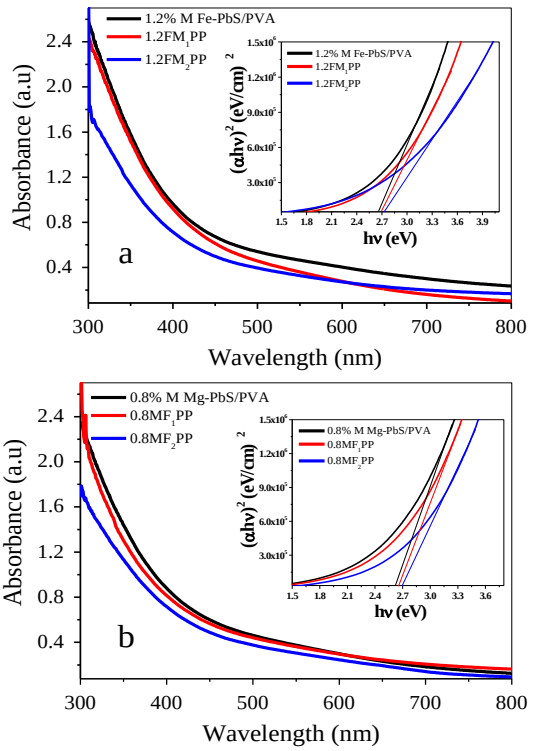

Figure 4 Optical absorption spectra of (a) 1.2 %M Fe-PbS/PVA, $1.2FM_1PP$ and $1.2FM_2PP$ and (b) 0.8 %M Mg-PbS/PVA, $0.8MF_1PP$ and $0.8MF_2PP$. The inset is the plot of $(\alpha h\upsilon)^2$ versus $h\upsilon$.

3.4 All-optical switching effects

The all-optical switching effects of the prepared films were investigated by the new optical pump-probe technique presented earlier [10]. All measurements were performed with a CW He-Ne laser beam at the wavelength of 633 nm with input power of 1 mW was used as a probe beam; and a diode pumped solid state laser beam at the wavelength of 457 nm was used as a pump beam. All the input pump laser beams were shot at the same spot on the sample.

The all-optical switching effect of 1.2 %M Fe-PbS/PVA and co-doped samples $1.2FM_1PP$ and $1.2FM_2PP$ freestanding nanocomposite films are illustrated in Fig. 5. On the other hands, Fig. 6 shows the all-optical switching effect for the samples 0.8 %M Mg-PbS/PVA, $0.8MF_1PP$, and $0.8MF_2PP$

nanocomposite films. In these figures we measured the transmitted intensity (T) of samples as a function of time (t) at four different modulation frequencies f_m of 5, 10, 15, and 20 Hz, and three pump beams power P_p of 10, 19, and 31 mW. As compared to the 1.2% M Fe and 0.8% M Mg single doped PbS/PVA films, the freestanding nanocomposite samples $1.2FM_1PP$ and $0.8MF_1PP$ had high all-optical switching effects with reduced optical signal background. Further doping leads to a decrease of optical signal background with high switching effects for samples $1.2FM_2PP$ and $0.8MF_2PP$. That is to say the $1.2FM_2PP$ and $0.8MF_2PP$ films prepared by co-doping had the highest all-optical switching effects and photoinduced optical anisotropy with signal background decreasing in the output. This could be due to the high crystallinity of the nanocomposite films.

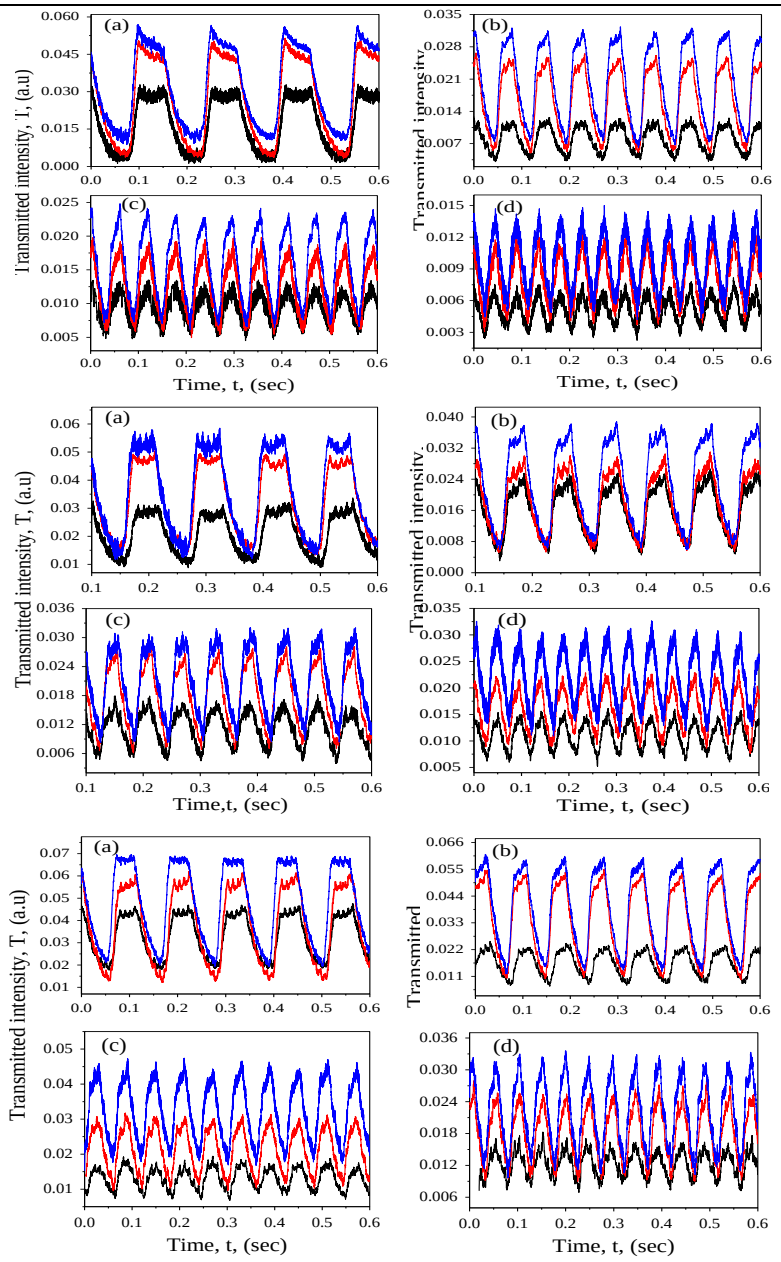

Figure 5 Effect of metal doped and co-dopedPbS/PVA films on all-optical switching under different pump beam powers with different modulation frequency for samples (I) 1.2%M Fe-PbS/PVA (II) $1.2FM_1PP$ and (III) $1.2FM_2PP$: (a) 5 Hz, (b) 10 Hz, (c) 15 Hz, and (d) 20 Hz. Pump powers are (bottom, black, 10 mW), (middle, red, 19 mW), and (top, blue, 31 mW.

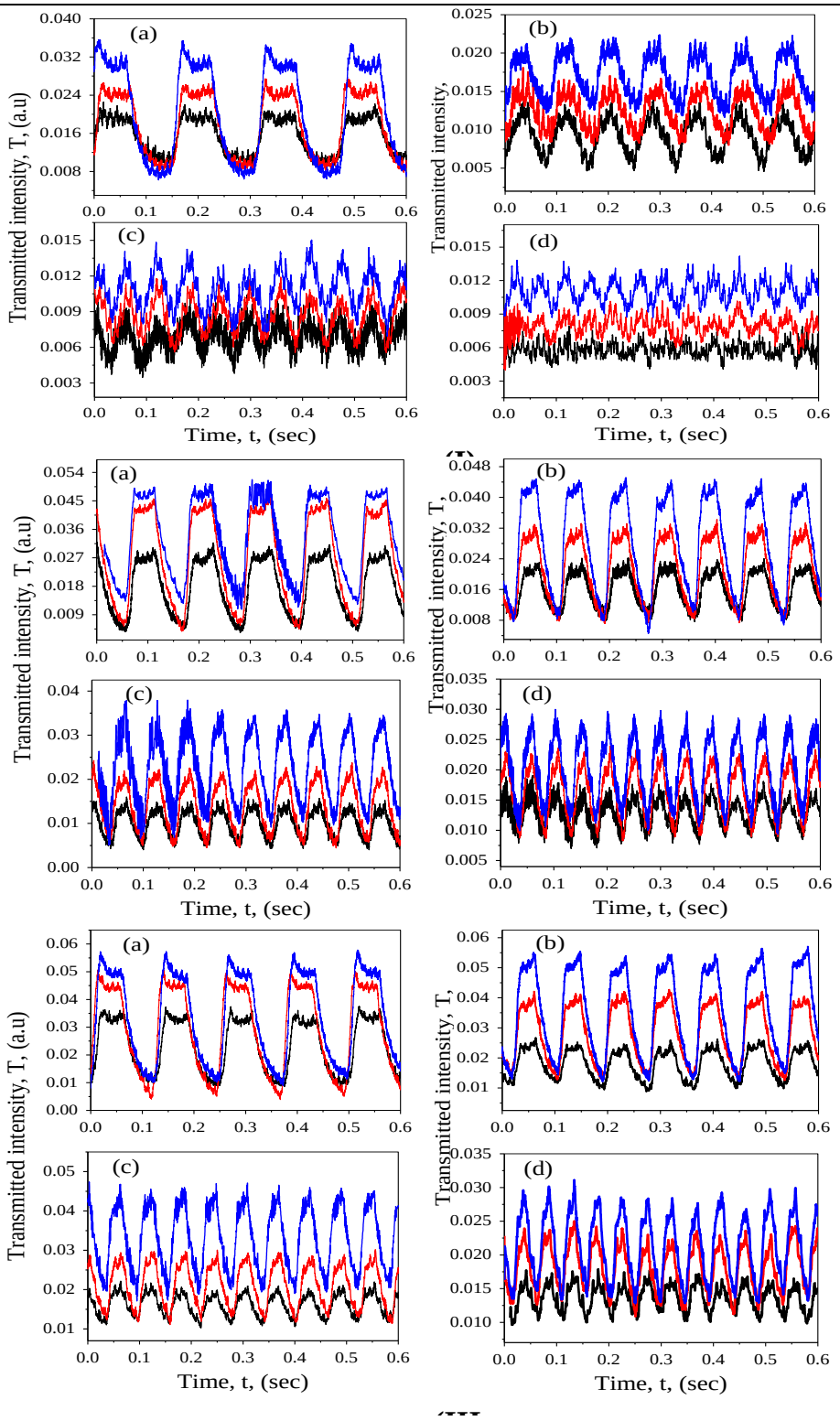

Figure 6 Effect of metal doped and co-doped PbS/PVA films on all-optical switching under different pump beam powers with different modulation frequency for samples (I) 0.8%M Mg-PbS/PVA (II) 0.8MF_1PP and (III) 0.8MF_2PP: (a) 5 Hz, (b) 10 Hz, (c) 15 Hz, and (d) 20 Hz. Pump powers are (bottom, black, 10 mW), (middle, red, 19 mW), and (top, blue, 31 mW).

3.4.1 Parameters of all-photonic switching

To achieve good all-photonic switching in all-optical communication systems of the sample, some important parameters such as high modulation depth, high switching contrast, and good switching time are required.

The variations in modulation depth and switching contrast as a function of pump laser beam at different modulation frequencies were studied. The results are illustrated in Fig. 7 for the prepared samples 1.2 %M Fe-PbS/PVA, 1.2FM$_1$PP, and 1.2FM$_2$PP; and in Fig. 8 for the 0.8 %M Mg-PbS/PVA, 0.8MF$_1$PP, and 0.8MF$_2$PP freestanding nanocomposite films. It is seen that the MD and SC in the all prepared single doped and co-doped PbS/PVA films increased at the same modulation frequency, and decreased with increasing the modulation frequency. This is because at higher frequency, the electrons did not have enough time to return to the equilibrium state. But at Mg and Fe doping concentration of 0.8 %M (1.2FM$_2$PP and 0.8MF$_2$PP), the MD and SC exhibited higher values as the pump power increased and modulation frequency decreased. The higher values of MD and SC were discussed to be attributed to the large population of excited electrons which resulted in the strongest photoinduced anisotropy. The obtained results have led to the realization of all-photonic switching with improved or comparable performance, including high MD, SC, and fast ST compared to the case of other materials [14-16].

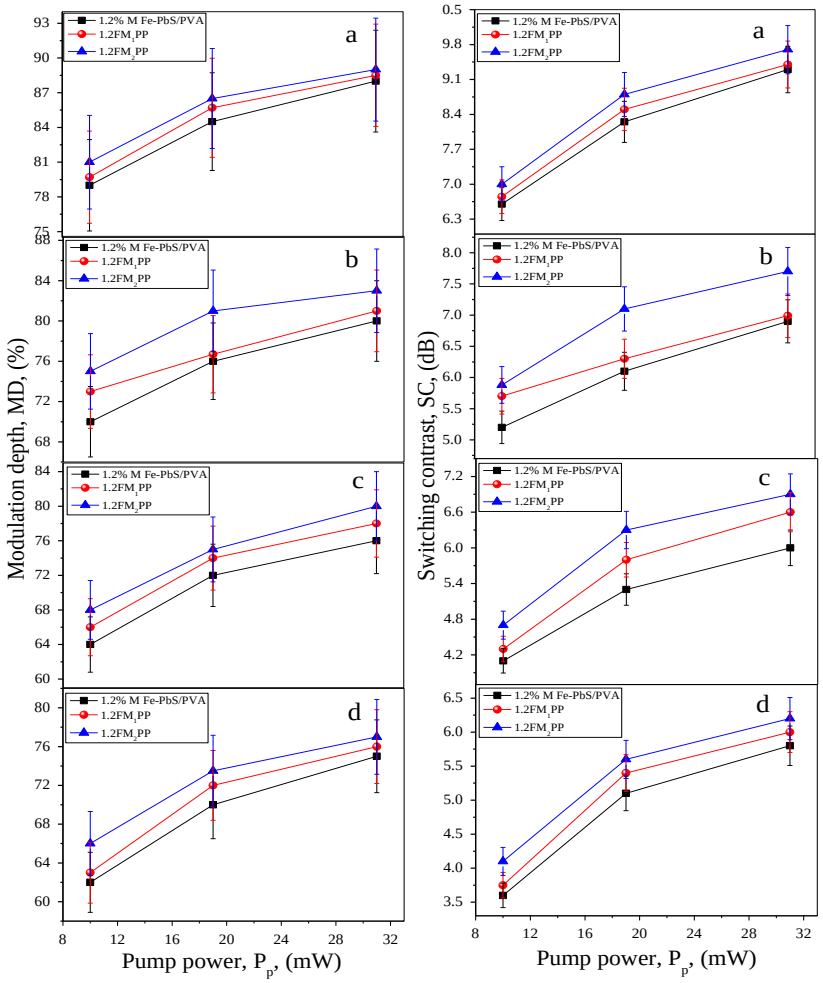

Figure 7 Variation of (I) modulation depth and (II) switching contrast with pump beam powers under different modulation frequency for samples 1.2% Fe-PbS/PVA, 1.2FM$_1$PP and 1.2FM$_2$PP.

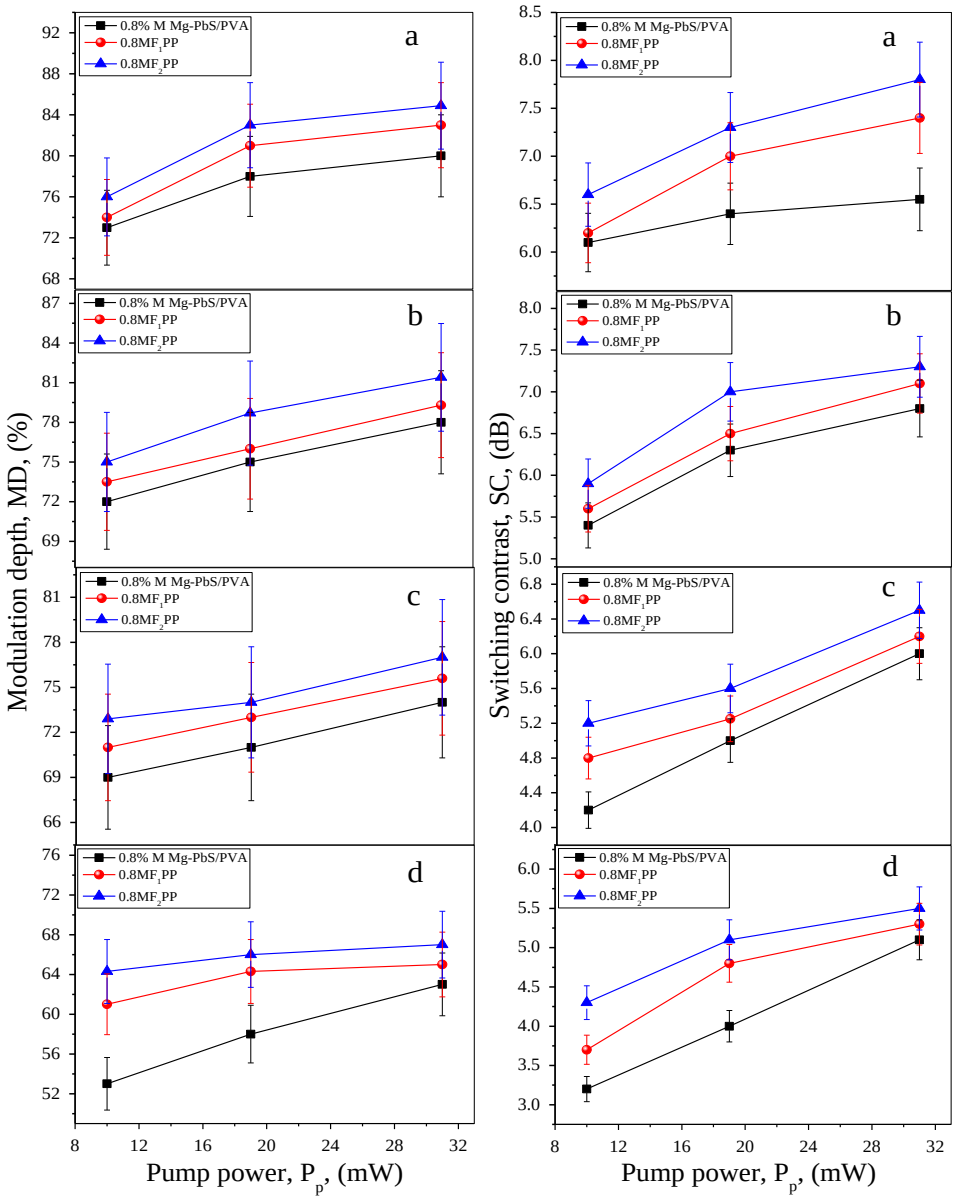

Figure 8 Variation of (I) modulation depth and (II) switching contrast with pump beam powers under different modulation frequency for samples 0.8% Mg-PbS/PVA, 0.8MF_1PP, and 0.8MF_2PP.

Figure 9 shows the modulation frequency dispersion of switching contrast for all the prepared single doped and co-doped PbS/PVA freestanding nanocomposite films for various input pump powers of 10, 19, and 31 mW. The ST decreased with increasing modulation frequency and pump powers for single and co-doped samples, which leads to fast ST (fast response time) for the 1.2FM_2PP and 0.8MF_2PP over the entire modulation frequency. This could be attributed to the more defects induced by a combined doping with Fe and Mg.

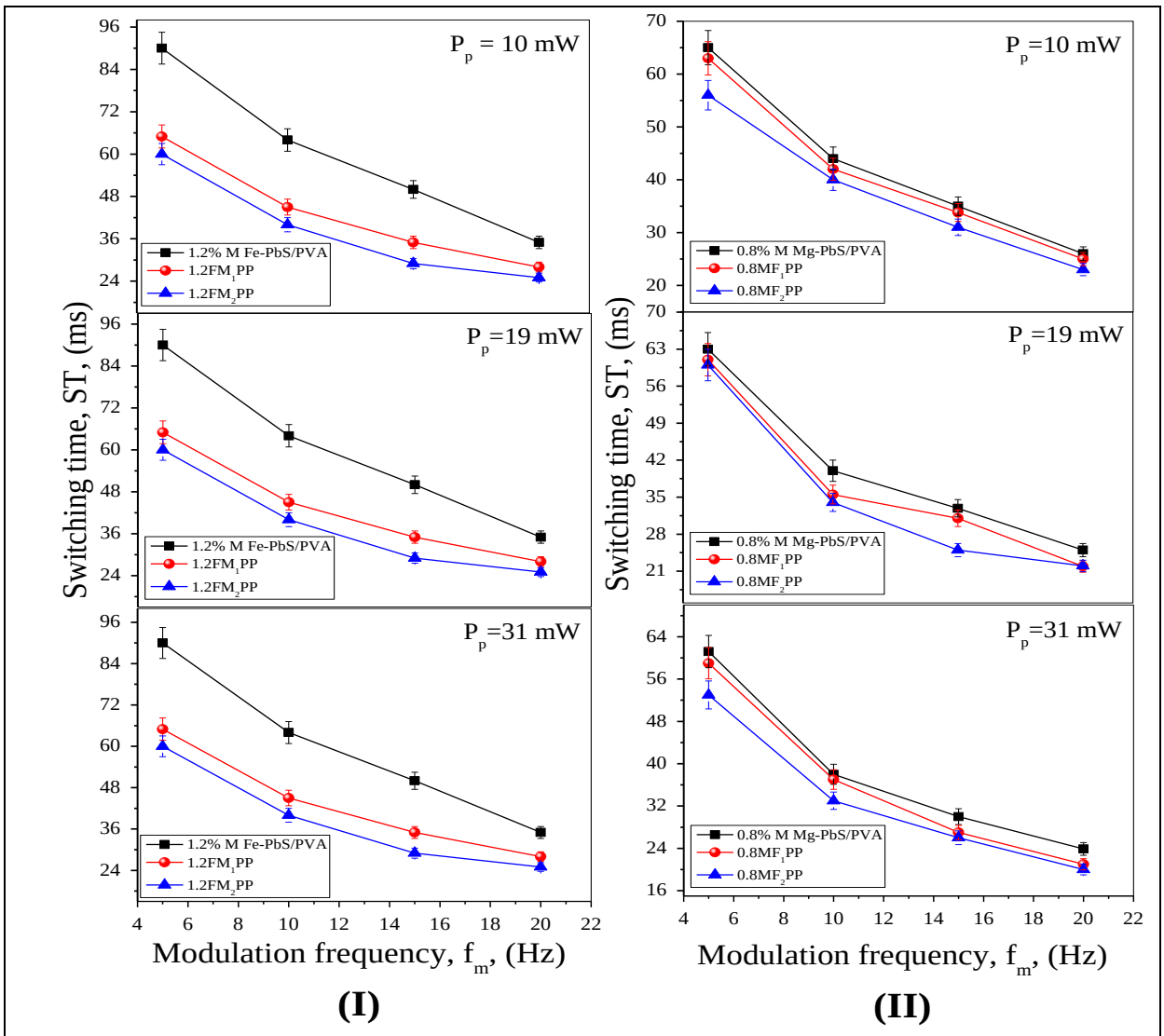

Figure 9 Switching time with modulation frequency under different pump beam powers for samples (I) 1.2% Fe-PbS/PVA, 1.2FM$_1$PP, and 1.2FM$_2$PP and (II) 0.8%M Mg-PbS/PVA, 0.8MF$_1$PP, and 0.8MF$_2$PP with different doping concentrations.

4. Conclusions

The single doped and (Fe, Mg) co-doped PbS/PVA freestanding nanocomposite films with various Fe and Mg doping concentrations were prepared using a simple and fast chemical method. The performances of the all-optical switching of the films were investigated. The results showed that the doped PbS/PVA nanocomposite films can be used as a nonlinear optical material by achieving all-photonic switching. Compared with the all-optical switching performance of single doped PbS/PVA, co-doped PbS/PVA nanocomposite films have a better switching performance when Fe and Mg doping concentration were 0.8 %M. In particular, 1.2FM$_2$PP shows the maximum switching effect and the best parameters among the prepared samples. Thus, the results offer the possibility of developing an all-photonic switching device. The device had high MD of 86.5% and SC of 8.8 dB at minimum ST of 47 ms.

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