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Measurement of Thermooptic Coefficient in Lead Sulfide Using Laser Single-Beam Scanning Technique

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Abstract

In this work, the single beam scanning technique was employed to express the nonlinear interaction between laser radiation and semiconductor material (lead sulfide) as well as to determine the thermooptic coefficient of the material (lead sulfide). Direct measurement, low cost and reliability are the main features of this technique. The value of the thermooptic coefficient was determined to be -5.8x10^{-5}K^{-1} for PbS thin film. Due to authors review, this is the first attempt in Iraq to measure such parameter in semiconductor thin films.

قياس المعامل الحراري البصري لكبريتيد الرصاص باستخدام تقنية المسح بحزمة الليزر المنفردة

الخلاصة

في هذا البحث، أستخدمت تقنية المسح بحزمة الليزر المنفردة لتوضيح التفاعل اللاخطي ما بين الليزر والمادة شبه الموصلة (كبريتيد الرصاص) وكذلك لتحديد قيمة المعامل الحراري البصري للمادة نفسها. من أهم ما يميز هذه التقنية هو أنها توفر طريقة مباشرة للقياس تكون واطئة الكلفة وذات موثوقية بالقياس. بلغت قيمة المعامل الحراري البصري لعينة كبريتيد الرصاص المصنعة على شكل غشاء رقيق (-5.8x10^{-5}K^{-1}). استناداً للمراجعة التي أجراها الباحثون، فإن هذه محاولة أولى على مستوى العراق لقياس هذا المعامل في الأغشية الرقيقة شبه الموصلة.

Introduction

The laser-material interaction is mainly determined by reflectance, absorptance and transmittance of the material at the wavelength of laser radiation. Absorbing a portion of the incident laser energy by the free and bounded electrons in the atoms of materials leads these electrons to gain energy and translate to higher electronic levels. These electrons loose the gained energy fast throughout the collisions occurred during times of 10^{-14}-10^{-12}s [1-3]. Figure (1) shows the mechanisms of interaction between the incident photon energy and the treated material concerned in this work (lead sulfide).

As the material absorbs energy from a Gaussian-distributed light beam, a local heating is induced in the material. The refractive index of the material may uniformly change due to the formation of thermal lens resulted from the generated heat. The radial distribution of temperature inside bulk medium causes an identical radial distribution in the refractive index. This makes material behaves like lens in the propagation path of the light incident beam. The bulk medium density degrades as its temperature

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increases. As the degradation is negative, the thermal lens formed is a divergent lens [4-8].

In 1962, an analytical study, including the intensity variation of a Gaussian-distributed light beam passing through a thermal lens, was presented [9]. In 1964, the first study dealing with the effect of the thermal lens on the light propagation in bulk media was presented [10] and it included the computation of focal length of the thermal lens. Both studies were based on an approach supposing that thermal lens had a parabola-shaped variation in refractive index and it can be considered as an ideal lens. Despite this approach had presented an acceptable description for the behavior of the thermal lens as a light beam passes through, it could not determine the parameters of such behavior precisely. In addition, advances in high sensitive and fast response electrooptic devices had stimulated to think how to protect such devices from high-intensity light beams. This imposed much intensive studies on the optical limitations considered in such protection. These limitations are based on the nonlinear optical properties of the material [11].

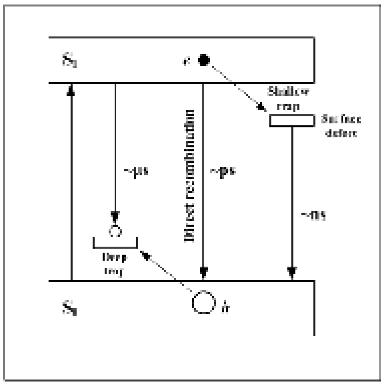

Figure (1) the mechanisms of interaction between the incident photon energy and the treated material concerned in lead sulfide

An experimental method for measuring the nonlinear optical parameters of a bulk material was developed. In this method, a sample is scanned with a light beam and changes in beam parameters, if any, due to passing through the bulk medium are measured to determine the related changes in the nonlinear parameters of the bulk medium [12-14]. Regarding to our search, there were very limited studies interesting the determination of nonlinear parameters in semiconductors by single-beam scanning technique. The most common used methods are based on the continuous comparison with a reference beam to trace the changes occurred in the light beam, which is known as dual-beam scanning technique. However using dual-beam scanning technique submits more reliable results, it requires more sophisticated experimental setup than using single beam.

The temperature-dependent variation of refractive index in a bulk medium is termed as "thermooptic parameter" and it has distinct importance when studying the thermal effects on the nonlinear properties of optical materials. It is a fact that single-beam scanning technique usually requires super-precise lasers [15-16], but the increasing development of methods and techniques employed for such studies tends towards measuring and determining the thermooptic parameter [13,17].

Thermooptic parameter of a bulk material is defined as [18]:

$$\frac{dn}{dT} = \frac{lk}{fP_{abs}}\Delta X \qquad (1)$$

where l is the wavelength of laser beam used for scanning, P_{abs} is the power absorbed by the material, k is the thermal conductivity of material, DX is the difference between maximum and minimum normalized transmission of laser beam and f is a function describes the propagation of laser beam transmitted through the sample and passing through a spatial aperture and is given by [19]:

$$f = m(1-S)^{0.25} \qquad (2)$$

where m is a tabulated constant for most materials and is equal to 0.406 for PbS [19], and S is the transmitted portion of laser beam through an aperture placed after the sample along the linear axis of the setup.

In order to determine the value of DX, an assumption that the nonlinear effects due to the absorption of laser beam energy have started to occur in the bulk medium. The value of DX can be given as a function of the change in phase (Df_0) and linear beam transmission (S) as:

$$\Delta X = f|\Delta f_0| \approx 0.406(1-S)^{0.25}|\Delta f_0| \quad (3)$$

The laser power absorbed by the sample (P_{abs}) is determined by the difference between the total incident power (P_{in}) and the transmitted power (P_{trans}) and can be given by a relation derived from Beer-Lambert law as:

$$P_{abs} = P_{in} - P_{trans} = P_{in}[1-e^{-aL}] \quad (4)$$

where a is the absorption coefficient of the sample at the wavelength of laser beam and L is the sample thickness.

The normalized transmittance $X(z)$ is defined as:

$$X(z) = \frac{\int P_t(z)\Delta f(z)dz}{S\int P_{in}(z)dz} \qquad (5)$$

where

$$\Delta f(z) = \Delta f_0 \exp\left[-\frac{2r^2}{w^2(z)}\right] \qquad (6)$$

Experiment

In this work, two samples of lead sulfide (thin film and powder) were used as the nonlinear media. Thin films of high purity (99.999) lead sulfide were deposited on glass slides of 250nm thickness. The deposition was performed by thermal evaporation system under vacuum of 10^{-6} torr. Also, lead sulfide powder of grain sizes 50-150nm, placed in a quartz cell, was used as a powder sample. The PbS powder was prepared chemically via colloid procedure of the dodecyl benzene sulfonic acid sodium (DBS) solution added to $P(NO_3)_2$ solution to obtain such sub-microscale and nanoscale grain sizes [20]. The two forms (film and powder) were used to introduce the effect of material state on the nonlinear parameters.

As shown in Fig. (2), we used a 632.8nm He-Ne laser with 9mW output power as a scanning laser beam source with suitable optical system (lenses) required for focusing (L1, 7.5cm) and collimating (L2, 10cm). The transmitted laser beam was limited spatially by an aperture (A) mounted between the sample (S) and the second lens (L2). High-sensitivity photodetector (PD) was used to measure the incident and transmitted laser power before and after passing the sample. The sample (S) was mounted on a micrometer in order to move precisely as needed for scanning-beam technique. All the set-up components were mounted on an optical bench to ensure the alignment necessary in such precise experiments.

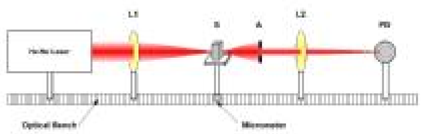

Figure (2) the experimental set-up of this work. **L1** and **L2** are lenses, **S** is the sample, **A** is the aperture and **PD** is the photodetector

Results and Discussion

Figure (3) shows the variation of the transmitted power through the PbS sample (film/powder) with the incident power. It is clear that the variation starts linear then convert to a different-slope region. This can be considered as the main motivation of this work since we observed the nonlinearity in this variation. Such behavior means the existence of some retardation against passing laser beam and the value at which the linear behavior converts into nonlinear represents a threshold for the optical limitation effect to begin [13,20]. This effect is completely different from that of single-crystal material [14].

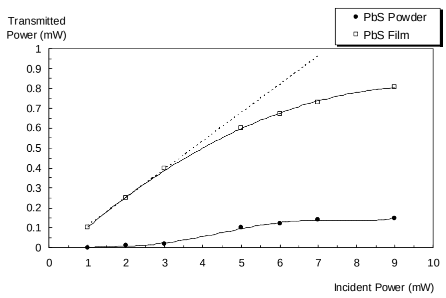

Figure (3) the variation of the transmitted power through the PbS sample (film/powder) with the incident power

The increasing of incident laser power induces the lattices of crystalline structure to vibrate more around their steady-state points. Hence, the probability of collisions between the incident photons and these molecules increases and then the interaction rate increases too. As the kinetic energy of the molecules is changed, the temperature of material is necessarily changed and hence the refractive index would also change. This change in refractive index with temperature is an important parameter in all studies related to the optical nonlinearities of materials and their devices, which are worthy to be studied for more understanding of the laser-material interaction.

As the grain sizes in thin film sample are much smaller than those in powder, the occurrence of nonlinear effects in thin films is more probable than in powders because the collisions have higher rates. We expected that such nonlinear behavior requires high power light beam (laser) to occur, but the optical nonlinearity of the material itself is the main parameter that determines this behavior. Most materials have small nonlinearity, so they may express such properties just at high power densities ($>10^5 W/cm^2$) of the irradiating light. Some materials have strong optical nonlinearity that even low power densities may induce them to appear. In this experiment, the irradiation power density is more than $200 W/cm^2$, that means transferring about $10^6 W/cm^3$ along the 200nm PbS film.

Agreeing with Beer-Lambert law, the PbS film sample transmits the laser beam more than the powder sample does. As well, the absorbed power in the latter is more than the film sample, so we expect the laser-material interaction being more observable in the powder sample as more optical power is consumed inside the sample. However, the next measurements would confirm or refuse this hypothesis.

In order to express the effect of incident power on the transmittance of the sample, three different powers (1, 5 and 9mW) were used. Figure (4) explains the transmittance of the PbS film sample moving along the set-up axis (z-displacement) towards and away from the focus of the lens L1. No doubt that increasing the incident power leads to increase the transmitted portion of laser beam through the sample. However, the sample has a maximum transmittance at the position of the highest power density.

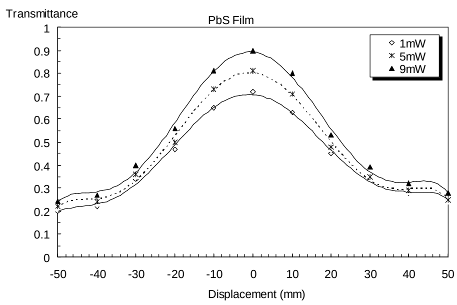

Figure (4) the transmittance of the PbS film sample moving along the set-up axis (z-displacement) towards and away from the focus of the lens **L1**

There is only one position at which the power density being the maximum, the focus of the lens, where z=0. Looking at figure (5), which is similar to figure (4) but for the powder sample, we see that the film sample is more homogenous than the powder due to the smaller thickness. Also, the effect of the incident power on the transmittance of the sample is larger in film sample since it increased by 25% as the incident power scaled from 1mW to 9mW, whereas it increased by only 8.1% in case of powder of the same range of incident power scaling. Long path length and scattering are the main effects trying to attenuate the transmission of laser light through the powder sample [9].

Although, the uniformity of transmittance encouraged us to develop the study towards the measurement of one of the nonlinear parameters; the thermooptic coefficient.

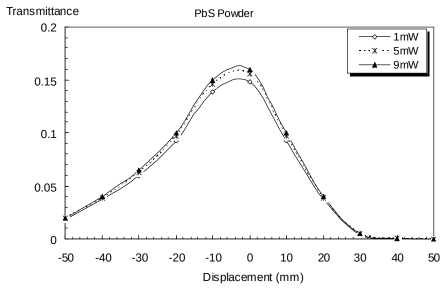

Figure (5) the transmittance of the PbS powder sample moving along the set-up axis (z-displacement) towards and away from the focus of the lens **L1**

As shown previously, the thermooptic coefficient is a function of the difference between the maximum and minimum normalized transmittance (*DX*). So, we plotted in figure (6) the normalized transmittance of both PbS samples (film and powder) versus the displacement (z) in order to determine the behavior and values of the term *DX* required in Eq. (1). The normalization in transmittance - in case of powder sample - is more apparent than that of film sample because the latter sample (PbS film) is more sensitive to the incident power and the occurrence of the nonlinear interactions. We determine that the difference between maximum and minimum of the normalized transmittance is 0.64 and 0.89 for PbS film and powder, respectively.

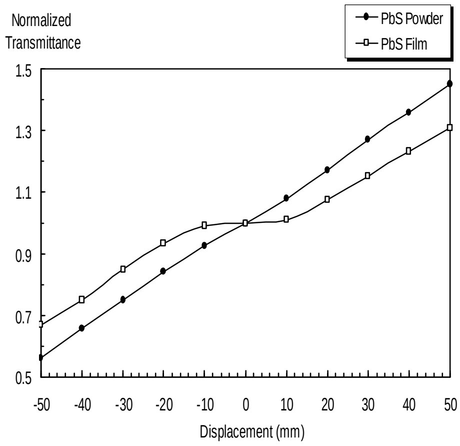

Figure (6) the normalized transmittance of both PbS samples (film and powder) versus the z-displacement

Figure (7) shows the nonlinear variation of the term *DX* with the incident power for both PbS samples (film and powder) and it is clear that the variation in the normalized transmittance of the powder sample is much smaller than that of film sample. However, the behavior in the film sample is more symmetric. This supports the assumption stating that the nonlinear interaction is much probable in the PbS film than in powder. Accordingly, the computed value of the thermooptic coefficient (dn/dT) is $5.6\times10^{-5}K^{-1}$ for thin film samples.

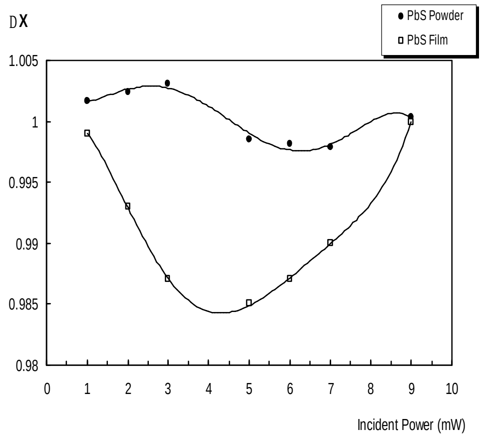

Figure (7) the nonlinear variation of the term *DX* with the incident power for both PbS samples (film and powder)

Conclusions

According to the results obtained in this work, an effective, reliable and simple measurement of the thermooptic coefficient of lead sulfide (PbS) was presented. The measurement is based on single-beam scanning technique to measure the transmittance of the sample under test. The He-Ne laser is good candidate as a light beam due to its low cost and high directionality as well as the availability of the suitable high efficient photodetectors. Also, we conclude that lead sulfide (PbS) semiconductor is a nonlinear material due to its high thermooptic coefficient, which is dependent of the state of sample. This study encourages extending the use of such materials in the advanced applications related to nonlinear optics.

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