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Improved Z-scan adjustment to thermal nonlinearities by including nonlinear absorption

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ABSTRACT

We propose a modified mathematical model of thermal optical nonlinearities which allow us to obtain the nonlinear refraction index and the nonlinear absorption coefficient with only one measurement. This modification is motivated by the influence that nonlinear absorption has on the measurement of the nonlinear refraction index at far field, when the material presents a large nonlinearity. This model, where nonlinear absorption is considered to adjust the curves of nonlinear refraction index obtained by Z-scan technique, has the best agreement with experimental data. The model is validated with two ionic liquids and the organic material÷ *Eysenhardtia polystachya*, in thin media. We present these results after comparing our proposed model to other reported models.

1. Introduction

Strong electromagnetic fields interacting with matter give origin to nonlinear optics phenomena (NLO). Therefore, the optical properties of the material change. These properties play an important role to design optoelectronics devices [1].

There are different techniques to study the nonlinear properties of materials (refraction and absorption) such as nonlinear interferometry [2], degenerate four wave mixing [3], mixture quasi-degenerate three-wave [4], elliptical rotation [5], measurements of wave front distortion [6], the Z-scan technique [7], among others. Z-scan is one of the most used techniques due to its simplicity and accuracy. It has been used to characterize some materials like gold and silver nanoparticles [8,9], hybrid materials [10,11], liquid crystals [12], and organic dyes such as *Hibiscus sabdariffa* [13,14]. With this technique, it is possible to obtain the sign and magnitude of the nonlinear refractive index (n_2) with the experimental setup at far field and with closed aperture. Furthermore, the nonlinear absorption (β) is measured at near field and with open aperture. The technique consists in displacing the sample along the optical axis (z direction) of a focused laser beam, generally with Gaussian distribution, and detecting the transmitted power at far field or at near field. The Gaussian decomposition method is the most used [15,16], this one gives an analytical expression for the normalized transmittance. Samad et al. [17] used the Huygens-Fresnel principle to obtain an analytical expression of the on-axis far-field; this model considers a big phase shift as in the model proposed by Kwak et al. [18], where an expression for the transmittance is obtained using the free aberration approximation of Gaussian beam. Reynoso et al. [19] considered the nonlinear thin media as a photoinduced lens, where the focal length is represented by a constant (a_m) multiplied by high power beam radius ($\omega(z)^m$), where m represents the nonlinear phenomena in the material. Severiano et al. [20] proposed a model for thick media based on Reynoso et al. [19] model. However, all these models do not consider the nonlinear absorption, which is present in thermal nonlinearities and it has influence on the Z-scan curves. Most of the models only propose the measuring of nonlinear refractive effects; nevertheless, it is not possible to separate experimentally the nonlinear absorption and nonlinear refractive effects. For this reason, in this paper we introduce a modification, which includes nonlinear absorption in the expression of the model of the focal length of the reference [20]. This modification allows us to have a better understanding of the nonlinear physical phenomena present in a material, and determine the nonlinear absorption and the nonlinear refraction with only one measurement at far field. This new expression to focal length is compared with other models such as Pálfalvi et al. [21], Sheik-Bahae et al. [22], Gordon et al. [23], Sheldon [24], and Garcia et al. [25]. Additionally, there are not reports about the *Eysenhardtia polystachya* nonlinear optical properties.

In Section 2, the description of model by Severiano et al. [20] and the development of the new focal length photoinduced are presented.

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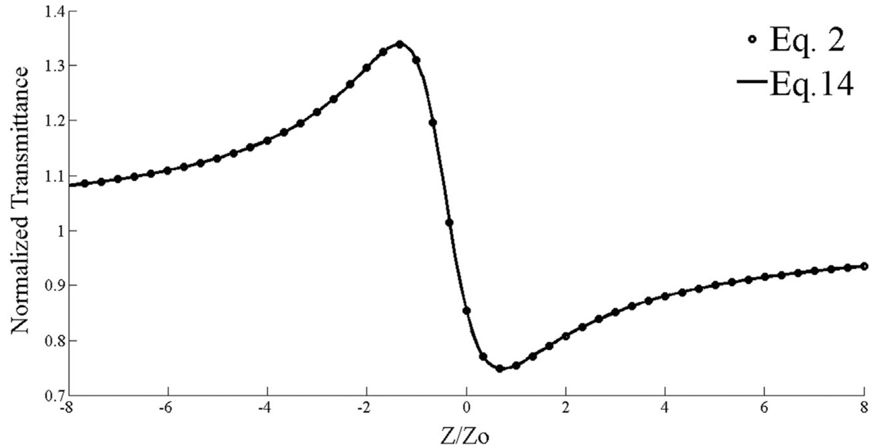

Fig. 1. Z-scan curve obtained with Eqs. (2) and (14) with β=0.

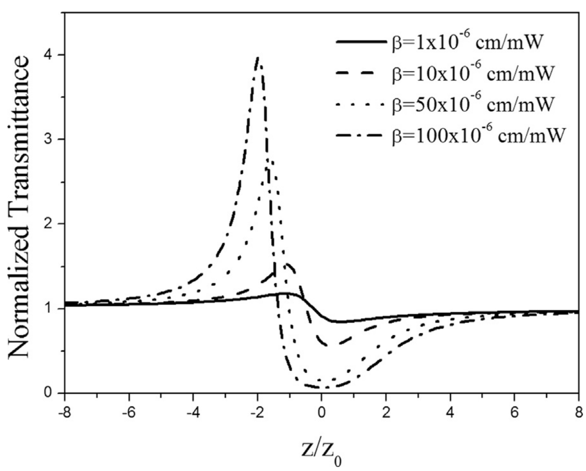

Fig. 2. Z-scan curve obtained with Eq. (14) with β≠0.

In Section 3, the model was validated by comparing two results of ionic liquid, one of them is previously reported. In Section 4, we describe the *Eysenhardtia polystachya* optical properties, and the adjustments of the experimental results by considering the models described in Section 2 and comparing with the models of Refs. [21–25]. Finally, the conclusions of this work are presented.

2. Mathematical model

Our mathematical model is based on irradiance detection on axis at far field. We considered a thin media and the formation of photo-induced lens due to nonlinear self-focusing effect. The light transmittance across the media depends on focal photoinduced lens (*F(z)*) as well as Rayleigh distance z_O. *F(z)* depends on the radius of the beam at some power "*m*" [19],

$$F(z) = a_m \omega^m, \tag{1}$$

where a_m is a constant with the adequate units. m is a real number that describes the type of nonlinearity of the material [20]. The beam parameters are ω is the radius of the beam, ω_O is the beam waist, $z_O = \pi\omega_O{}^2/\lambda$ is the Rayleigh distance, where λ is the wavelength of the beam.

This model was extended by considering the thick media as a set of thin lenses separated by a distance d, immersed in the nonlinear medium of refractive index n_O. The focal length $f\,(z)$ for each of these lenses is affected due to the properties of the Gaussian beam within the material. The normalized transmittance of the Z-scan curves can be numerically calculated by knowing the Gaussian beam waist and using ABCD matrices for each unit defined in [20]. In this model, the thin media is considered less than $1.5z_O$. If the media has a different thickness, it is considered as a thick media.

For a thermal nonlinear media (m=2), the focal length is

$$F_{Ther}(z) = \frac{\pi\kappa}{(dn/dT)P\alpha d}\omega^2. \tag{2}$$

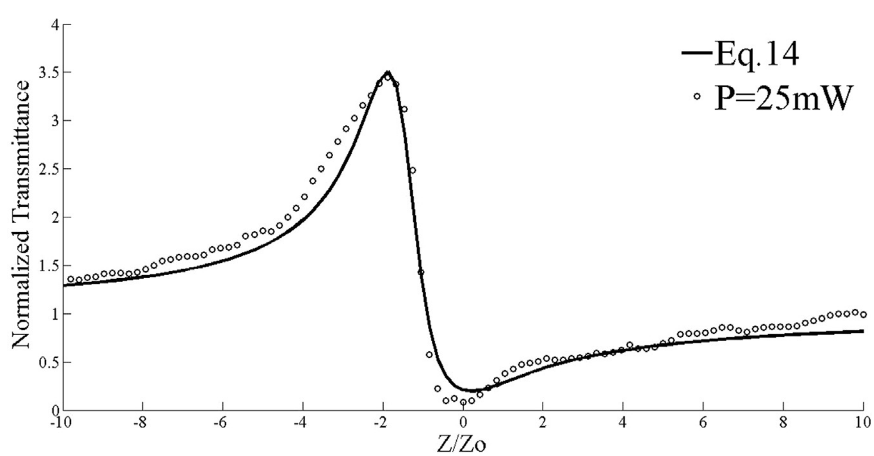

Fig. 3. Z-scan curves with power of: 25 mW by ionic liquid [BMIM][BF_4].