تعیین ضریب شکست غیرخطی مرتبه پنجم با استفاده از روش روبش Z کسوفی

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چکیده- روش روبش Z کسوفی نسخه اصلاح‌شده روش روبش Z دریچه بسته است که در آن روزنه با یک دیسک کدر جایگزین شده است. در این روش اختلاف بیشینه و کمینه عبور بهنجار به‌طور قابل‌توجهی افزایش می‌یابد و در نتیجه حساسیت اندازه‌گیری بسیار بیشتری نسبت به روش دریچه بسته را فراهم می‌کند. در این مقاله روش روبش Z کسوفی به عنوان یک روش بسیار مؤثر برای تعیین ضریب شکست غیرخطی مرتبه پنجم مواد پیشنهاد می‌گردد و حساسیت دو روش دریچه بسته و کسوفی برای غیرخطیت مرتبه پنجم مقایسه می‌گردد. در حالی که برای روش دریچه بسته رابطه‌ای تحلیلی برای عبور بهنجار شده قابل استخراج است، این امر برای روش کسوفی امکان‌پذیر نیست. درنتیجه یک رابطه تجربی برای تعیین ضریب شکست غیرخطی مرتبه پنجم از داده‌های روش کسوفی پیشنهاد می‌شود. این رابطه تجربی اختلاف بیشینه و کمینه عبور بهنجار، تغییر فاز غیرخطی مرتبه پنجم، و میزان پوشانندگی دیسک را به هم مرتبط می‌سازد و نشان می‌دهد که افزایش قطر دیسک حساسیت اندازه‌گیری را بهبود می‌بخشد. رابطه تجربی پیشنهاد شده این امکان را برای محققان اپتیک غیرخطی فراهم می‌کند تا با اندازه‌گیری عبور بهنجار شده در روش روبش Z کسوفی بتوانند ضریب شکست غیرخطی مرتبه پنجم برای مواد غیرخطی ضعیف را به راحتی و با دقت بسیار زیاد تعیین کنند.

کلیدواژه- روش روبش Z ، روبش Z کسوفی، خواص اپتیکی غیرخطی، ضریب شکست غیرخطی.

Using Eclipsing Z-scan technique for determining the fifth order nonlinear refractive index

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Abstract- By replacing the aperture in the closed aperture (CA) Z-scan with an opaque disk, the modified version of Z-scan namely the eclipsing Z-scan (EZ-scan) significantly enhances the peak-valley transmittance difference yielding a much greater measurement sensitivity than that observed with CA Z-scan at the similar conditions. This paper introduces the EZ-scan technique as a highly effective method for determining the fifth-order nonlinear (NL) refractive index of materials. The study highlights the higher sensitivity of the EZ-scan method for precise measurements and compares the sensitivity of CA Z-scan and EZ-scan. While an analytical relation for normalized transmittance can be derived for CA Z-scan, this is not feasible for the EZ-scan technique. Instead, an empirical relationship is proposed to determine the fifth-order NL refractive index from EZ-scan measurements. The proposed relation links the peak-valley transmittance difference, the fifth-order NL phase shift, and the disk obscureness, demonstrating that increased disk diameter improves sensitivity. This advancement provides a valuable tool for researchers in NL optics to determine the fifth order NL refractive index easily and precisely once the normalized transmittance of the EZ-scan is measured.

Keywords: Z-scan technique, Eclipsing Z-scan, Nonlinear optical properties, Nonlinear refractive index

1. Introduction

The nonlinear (NL) refractive index is an intensity-dependent property of materials that causes a change in the refractive index due to intense light-matter interaction. This variation in refractive index can give rise to various phenomena, including self-phase modulation, cross-phase modulation, self-focusing, and self-defocusing, each of which holds significant practical relevance. These NL optical effects have enabled advancements in applications such as optical limiting and all-optical switching, a key component in photonic communication systems and signal processing [1].

Among various methods proposed for determining the NL refractive index, the Z-scan technique stands out due to its simplicity and high precision, making it a widely preferred approach in NL optical studies [2, 3]. In the closed aperture (CA) Z-scan version the sample is scanned along the propagation direction of a tightly focused laser beam while the power transmitted through a small aperture placed after the sample is measured as a function of the sample position. The resulting signal typically exhibits a characteristic valley-peak pattern for a positive NL refractive index or a peak-valley sequence for a negative NL refractive index.

In the eclipsing Z-scan (EZ-scan) technique, the aperture is replaced by an opaque disk, and the power transmitted around the disk is measured as a function of the sample position [4-6]. Since the intensity of a Gaussian beam decreases away from its center, changes in power transmitted around the disk are highly sensitive to variations in the beam size. Consequently, the sensitivity of the EZ-scan technique is much greater than that of the CA Z-scan method [7].

In this work, an empirical relationship is proposed to determine the fifth-order NL refractive index by measuring the maximum and minimum transmittance values of the EZ-scan signal.

2. Theory of Z-scan

In the Z-scan technique, the NL sample acts as a diffractive plane. Consequently, the electric field distribution on a plane positioned sufficiently far from the sample can be determined using the Fraunhofer diffraction integral.

$$E_a(z,r)=\frac{1}{i\lambda d}\int_0^{\infty} J_0\left(\frac{krr'}{d}\right)E_e(z,r')2\pi r'dr' \qquad (5)$$

where $E_e = E_{in}\exp(i\Delta\Phi)$ is the electric field on the exit surface of the sample, E_{in} is the electric field incident on sample, $\Delta\Phi = kL\Delta n$ is the NL phase change along the sample, $k=2\pi/\lambda$ is the wavenumber, λ is the laser wavelength, L is the sample thickness, $\Delta n = n_2 I$ with n_2 the third order NL refractive index or $\Delta n = n_4 I^2$ with n_4 the fifth order NL refractive index and I is the intensity.

The normalized transmittance through an aperture can then be defined as

$$T(z)=\frac{\int_0^{r_a}\left|E(r,z,\Delta\Phi)\right|^2 rdr}{\int_0^{r_a}\left|E(r,z,\Delta\Phi=0)\right|^2 rdr} \qquad (6)$$

where r_a is the aperture radius.

Similar to Eq. (2), the normalized transmittance for EZ-scan can be defined by integrating the intensity from the edge of the obscuring disk to infinity.

$$T(z)=\frac{\int_{r_d}^{\infty}\left|E(r,z,\Delta\Phi)\right|^2 rdr}{\int_{r_a}^{\infty}\left|E(r,z,\Delta\Phi=0)\right|^2 rdr} \qquad (7)$$

where r_d is the disk radius.

Employing Eqs. (6) and (7), the normalized transmittance is obtained for CA Z-scan and EZ-scan by substituting $\Delta\Phi = kLn_2 I$ in the case of third order nonlinearity or $\Delta\Phi = kLn_4 I^2$ in the case of fifth order nonlinearity.

Further calculations reveal a relationship between the NL phase change and the peak-valley transmittance difference in the Z-scan technique when using a Gaussian laser beam. In CA Z-scan, for a medium with third-order nonlinearity $\Delta T_{pv} = 0.406(1-S_a)^{0.25}\left|\Delta\Phi_0\right|$ and for a medium with fifth order nonlinearity $\Delta T_{pv} = 0.21(1-S_a)^{0.25}\left|\Delta\Phi_0\right|$ where $\Delta T_{pv} = T_{\max} - T_{\min}$ denotes the peak-valley transmittance difference, S_a is the aperture transmittance given by $S_a = \left[1-\exp(-2w^2/r_a^2)\right]$ and w is the beam radius on the aperture plane.

In the EZ-scan performed for a medium with third order nonlinearity $\Delta T_{pv} = 0.68(1-S_d)^{-0.44}\left|\Delta\Phi_0\right|$ where $S_d = \left[1-\exp(-2w^2/r_d^2)\right]$ denotes the disk obscureness.

3. Results and discussions

Figure 1 compares the normalized transmittance measured by CA Z-scan and EZ-scan for a fifth-order NL phase change of 0.1 rad. The red curve represents the CA Z-scan signal with a small aperture transmitting 1% of the laser beam power, while the blue curve corresponds to the EZ-scan signal, where a large opaque disk blocks 99% of the beam power.

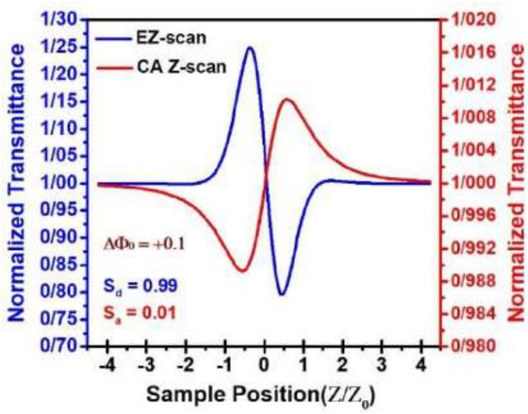

Fig. 1. Normalized Transmittance assuming a fifth order phase change of 0.1 rad. Red curve indicates the CA Z-scan signal and blue curve represents the EZ-scan signal.

As shown, the peak-valley transmittance difference in EZ-scan is approximately 25 times greater than that in CA Z-scan, resulting in significantly higher sensitivity for determining the NL refractive index. To establish an empirical relationship between the peak-valley transmittance difference, fifth-order NL phase change, and disk obscureness, the normalized transmittance was computed using Eq. (3) for varying phase changes and disk obscureness. Figure 2 illustrates the EZ-scan normalized transmittance for a fifth-order NL phase change of 0.15 rad, considering disk obscureness of S=0.95, 0.98, 0.99 and 0.995. The results demonstrate that as the disk obscureness increases, the peak-valley transmittance difference becomes more pronounced, thereby improving the sensitivity of the technique.

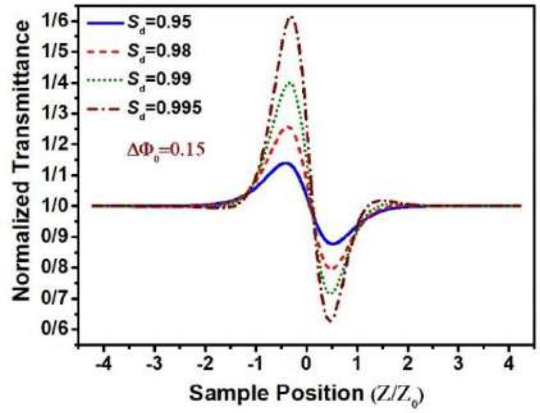

Fig. 2. EZ-scan normalized transmittance for different disk obscureness.

Figure 3 illustrates the EZ-scan normalized transmittance for varying fifth order NL phase change considering a large opaque disk blocking 99% of the laser beam power. As anticipated, the peak-valley transmittance difference increases with increasing the fifth order NL phase change.

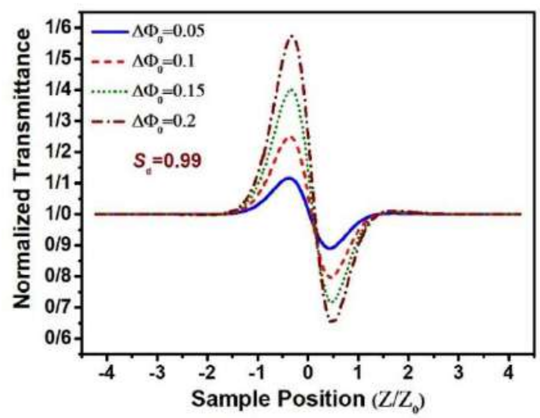

Fig. 3. EZ-scan normalized transmittance for different fifth order NL phase change.

Fig. 4 exhibits the Peak-valley transmittance different versus disk obscureness assuming a fifth order NL phase change of 0.05 rad.

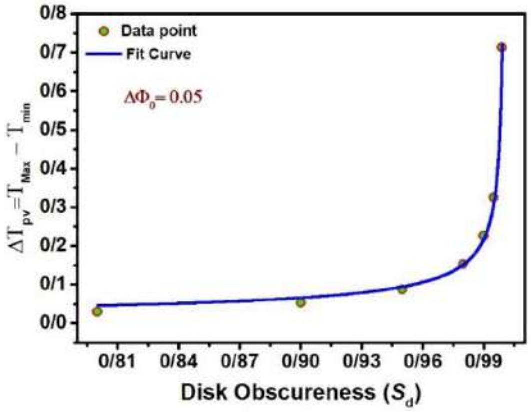

Fig. 4. Peak-valley transmittance different versus disk obscureness.

The circles in Fig. 4 show the calculated data points and the solid blue line represents the fitted curve described by $\Delta T_{pv} = 0.4(1-S)^{-0.52}\left|\Delta\Phi_0\right|$.

Further investigation reveals that the proposed empirical relation remains valid for larger NL phase change up to approximately 0.2 rad for large disk obscureness in the range of $0.9 \le S_d \le 0.995$.

Fig. 5 illustrates the Peak-valley transmittance different versus NL phase change for different disk obscureness of 0.98, 0.99 and 0.995. The straight lines represent the linear fit given by the proposed relation $\Delta T_{pv} = 0.4(1-S)^{-0.52}\left|\Delta\Phi_0\right|$ confirming its validity within the range of investigation.

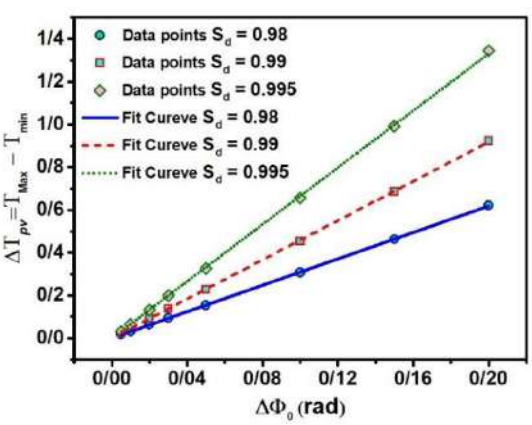

Fig. 5. Peak-valley transmittance different versus fifth order NL phase change for different disk obscureness.

4. Conclusion

The normalized transmittance for two versions of Z-scan, namely CA Z-scan and EZ-scan, was calculated and compared for fifth-order nonlinearity. The results indicate that the measurement sensitivity of EZ-scan is at least 25 times greater than that of CA Z-scan. While an analytical relation for the normalized transmittance as a function of sample position can be derived for CA Z-scan, this is not possible for EZ-scan. Therefore, we proposed an empirical relation that enables the determination of the fifth-order NL refractive index once the normalized transmittance for EZ-scan with a known disk radius is measured.

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