Measuring optical nonlinearities using a heterodyne Z-Scan technique

I. Guedes*, L. Misoguti, L. de Boni, S. C. Zilio
Departamento de Física e Ciência dos Materiais, Instituto de Física de São Carlos,
Caixa Postal 369, 13560-970 São Carlos, SP, Brazil
+55 (16) 3373-8085 ext 238, guedes@if.sc.usp.br

Abstract

We present a heterodyne Z-Scan technique to obtain resonant nonlinearities ($n_2$) of Kerr-like media. From phase measurements we determine both signal and magnitude of $n_2$. Results are presented for a GdAlO$_3$ sample.

Introduction

Since it was introduced, the Z-Scan technique [1] has extensively been used in determining optical nonlinearities in several materials. Here we will describe an alternative scheme based on the use of a heterodyne Z-Scan technique. We modulate the incoming radiation and measure both its amplitude and phase at far field position. Besides its inherent simplicity, the present method has a special attractive of providing reliable values of nonlinear refractive indexes from phase curves no matter noisy is the Z-Scan signature.

Experimental Setup

The experimental setup used is relatively simple. We use the second-harmonic ($\lambda = 532$ nm) of a diode pumped Nd:YVO$_4$ cw laser as the exciting source. The beam passes through an electro-optic modulator (EOM) driven by a function generator that allows us to add a few (~10%) percent of sinusoidal amplitude modulation ranging from 10 to 300 Hz. The modulated beam is then focused onto the sample with a 12-cm-focal length lens. The energy transmitted through a small aperture placed at the far field is measured with a Si detector plugged into a dual-phase lock-in amplifier triggered by the modulation signal.

Results and Discussions

To demonstrate the feasibility of the heterodyne Z-Scan technique we used a well-characterized 1.5 mm-thick GdAlO$_3$ sample (linear absorption $\alpha = 4.1$ cm$^{-1}$), which is known to present an electronic Kerr nonlinearity ($n_2 \approx 18 \times 10^{-5}$ cm$^2$/kW @ 532 nm, $T_1 = 12$ ms) and negligible thermal effects. We consider a cubic nonlinearity and a small nonlinear phase change. When the aperture at the far field is small, the measured normalized Z-scan transmittance is given by [1]

$$T(z, \Delta \Phi_0) = \frac{I(z, \Delta \Phi_0)}{I(z,0)} = 1 - \frac{4\Delta \Phi_0(t)x}{(x^2 + 1)(x^2 + 9)}$$

(1)

where $x = z/z_0$, $z_0 = k w_0^2/2$ is the diffraction length of the beam, $w_0$ is the beam waist at the focus, $k = 2\pi/\lambda$ is the wave vector, $\lambda$ is the wavelength, and $\Delta \Phi_0$ is the on-axis phase shift at the focus, given as: $\Delta \Phi_0 = k \Delta n_0(t) L_{eff}$, with $L_{eff} = (1 - e^{-\alpha L})/\alpha$ being the sample’s effective length and $\Delta n_0(t)$ the dynamic refractive index change that can be evaluated assuming a Debye relaxation equation of the form: $\tau \frac{d\Delta n_0}{dt} + \Delta n_0 = n_2 I(t)$, where $\tau$ is the relaxation time and $n_2$ is the nonlinear refractive index. The modulation of the laser beam is approximately given by $I(t) = I_0 [1 + \Gamma_m \sin(\omega_m t)]$, where $\Gamma_m$ is the modulation amplitude, $\omega_m$ is the modulation frequency and $I_0$ is the on-axis irradiance at the focus. By solving Debye’s equation one obtains

$$\Delta n_0(t) = n_2 I_0 \left[ 1 + \frac{\Gamma_m}{\sqrt{1 + \delta^2}} \sin(\omega_m t - \alpha) \right]$$

(2)

where $\delta = \omega_m \tau$ and $\alpha = \tan^{-1} \delta$. The on-axis irradiance measured by the detector is obtained by substituting Eq. (2) into Eq. (1), resulting in:

$$I(z, t) = I_0 [1 - A(x) B] + I_0 \Gamma_m F(z, \delta) \sin(\omega_m t + \varphi)$$

(3)
with

\[
\varphi = \tan^{-1} \left[ \frac{A(x)B\delta}{(1 + \delta^2) - A(x)B(2 + \delta^2)} \right]
\]

(4)

\[F(z, \delta) = 1 - A(x)B \frac{2 + \delta^2}{1 + \delta^2}\]

(5)

\[A(x) = \frac{4x}{(x^2 + 1)(x^2 + 9)}\]

(6)

and \(B = k_n I_0 L_{\text{eff}}\). The DC term on the right-hand side of Eq. (3) corresponds to a background signal, while the second term corresponds to the modulation signal and is out of phase by \(\varphi\). The above set of equations was obtained by neglecting terms in \(G_m^2\) and \(B^2\). The dual phase lock-in gives directly the amplitude and phase of the modulation. By scanning the sample position along the \(z\)-direction, the amplitude can be normalized to the one obtained for \(|z| >> z_0\) such that the values of \(G_m\) and \(I_0\) are eliminated. Figure 1 shows the results obtained for the GdAlO\(_3\) sample at \(\delta = 2.64\). Although the amplitude signal is fairly noisy due to internal and surface imperfections, the phase signal is virtually noise free and could be used as an important tool in the characterization of resonant \(n_2\) and \(\tau\) of saturable absorbers and thermal nonlinearities. In other words, the linear noise present in both in phase and in quadrature signals are cancelled out when the phase between them is recorded. The parameters used are: \(\tau = 12\) ms, \(w_0 = 20\) \(\mu\)m, \(I_0 = 0.445\) kW/cm\(^2\) and \(n_2 = 19.4 \times 10^{-5}\) cm\(^2\)/KW.

Fig. 1. Normalized amplitude (a) and phase (b) of the modulation for the GdAlO\(_3\) sample. The squares correspond to the experimental points while solid lines are the curves obtained using Eqs. (4) and (5).

Conclusions

Summing up we have presented an alternative based on the use of an heterodyne Z-Scan technique. By modulating the incoming laser, we demonstrate that the optical nonlinearity can be obtained from phase measurements instead of the magnitude ones which is related to the conventional Z-Scan signature. The former was shown to be noiseless, providing reliable values of nonlinear coefficients.

Acknowledgements

This work was supported by the FAPESP, CNPq and Capes from Brazil. I.Guedes acknowledges support from DF/UFC and CNPQ.

References
