Modification to the z-scan technique by widths measurements.

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Abstract- In this work we developed an automated system z-scan, which unlike the traditional technique, instead of measuring power, we measure change of Gaussian beam widths caused by the nonlinear sample, with the finality of improving the sensitivity and increasing the signal to noise ratio.

1. Introduction.

The z-scan technique is a popular method for measuring optical nonlinearities, particularly the absorption and nonlinear refractive coefficients [1]. It has been employed to measure nonlinear optical properties of semiconductors, dielectrics, organic molecules and liquid crystals. In this technique, the sample to characterize is moved along the optical axis (z direction) of a focused Gaussian laser beam, Figure 1. The high optical field intensity in the region of the focal plane induces in the sample a behavior lenslike with variable focal length [2]. A detailed study of z-scan not only provides information on the nonlinear properties of a material, also provides important information for the optimization of optical power limiting, so that material can be used as a filter or attenuator in relation to its geometry, position and optimal thickness of the sample.

Figure 1. Experimental setup of the Z-scan technique: Lens (L), Sample (S), Pin hole (PH) and photodetector (PD)
An element characterized by this technique exhibits a nonlinearity in particular in its refractive index, the curve usually exhibits a behavior as shown in Figure 2. A maximum transmittance prefocal (a peak) followed by a minimum of transmittance posfocal (a valley), indicates that the sample has a negative nonlinear refractive index, while an opposite configuration (valley-peak) indicates that the sample has a positive nonlinear refractive index. This is a very useful feature of the z-scan technique, because the sign of the non-linearity is directly extracted from the curve.

![Figure 2. Characteristics curves of z-scan. Positive refractive index (dotted line), negative refractive index (solid line).](image)

A beam is called Gaussian if it has a transverse distribution of intensity with this functional form. The width $W(z)$ is the distance of the points on the horizontal axis where the amplitude of intensity falls $1/e^2$ of its maximum value, this value grows with respect to the propagation distance ($z$ axis). A lens placed in the trajectory of a Gaussian beam tends to cause changes in the beam, in particular its width $W(z)$, as it is considered that the sample acts as a lens with variable focal length, then we expect changes in the beam dependent on the sample position. Taking the normalized transmittance as the ratio of the nonlinear intensity ($I_{NL}$) and the linear intensity ($I_L$) we find a relationship between the linear width (width occurred without the sample) and the no linear width (the width caused by the sample) therefore the transmittance measurement and the beam widths are related by the following equation:

$$T = \frac{I_{NL}}{I_L} = \frac{W_L^2}{W_{NL}^2}$$

(1)

Where $W_L$ is the linear width and $W_{NL}$ is the no linear width. Equation (1) is valid only if the following conditions are met: thin sample, detection along axis and far field. The Z-scan technique has undergone several modifications aimed to improved sensitivity, one of this techniques is called z-scan eclipsed [3], this technique instead of using an opening on the detector is replaced with a dark disk that blocks most of the beam, leaving only a ring of light (like an eclipse), using compensation methods in this technique results in a sensitivity ~ 13 times the conventional arrangement. A variation of this technique is called thermal management eclipsed [4] which has a sensitivity even higher than the above using relatively low intensities. There is also have the modification with two lasers [5], where the changes in the absorption and refractive index induced by a strong excitation pumping are measured relative to a weak pump beam. The z-scan technique with white light [6] is used to measure the nonlinear absorption spectrum, using a white light source continues, this modification is faster because the wavelength multiplexed introduced by the use of a source broadband, the differential z-
scan technique can also be found in this category [7]. There are also modifications with respect to how they manipulate measurement data [8]. Another of these improved techniques is that proposed by G. Tsigaridas [9] where directly measured changes in the width of the beam. However, each of these techniques are complex or require equipment that is not readily available. In this work is developed a simple and inexpensive technique to measure changes in width of a Gaussian beam produced by the sample using a mechanical shutter (Chopper), a series of electronic circuits and software manipulation.

2. Description of technique for measuring widths.
To measure the width of a Gaussian beam are various techniques such as the knife technique [10], the method of Gupta [11], the method of ribbons [12] among others. In this work the measurement of the width is performed by a rotating slotted disk (chopper) [13] located at the position where you want to measure. In the position in which you want to measure the width of the beam is placed the chopper rotating at constant frequency (f). Consider a Gaussian beam initially blocked by the chopper, propagating in the z axis unto a detector. When the chopper rotates the beam begins to pass freely through one of the slots in the chopper, then will be a change in detector response (change of power become voltage) from minimum to maximum, it remains at that value until the next disk blade begins to obstruct the beam and then advise a change of maximum to minimum staying at least until the beam begins to appear again for another slot; the process is repeated indefinitely thus generating a periodic signal with frequency equal to the chopper, the waveform shown in Figure 3.

![Figure 3. Periodic signal generated by the detector](image)

![Figure 4. Acquired signal and intensity distribution](image)

It is important to note that the beam width information is on the rise and fall of the pulse produced, due to the disk scans in a similar way to the knife edge technique such beam therefore the power recording by the photodetector is integrated, as shown in Figure 4. Therefore, to obtain the intensity distribution is necessary to derive this signal; however, if we are only interested in to measure the width of the beam is not necessary to perform this operation because this information can be measured directly. There are several criteria to measure the width of a Gaussian beam which will be referred as \(W(z)\) in this paper we use the criterion in which the normalized intensity decays \(1/e^2\). In a beam of Gaussian profile this will happen twice, thus establishing the width \(W(z)\) as the difference in position of the two corresponding power values (Vth1 and Vth2 indicated with dashed lines in Figure 4).

Thus, to calculate the value of \(W(z)\) through a data acquisition card, a computer, the time \(\Delta t\) time it takes for the signal change of Vth1 to Vth2 is measured and put into the following equation [9]

\[
W = k \tan \left( \frac{2\pi f \Delta t}{n} \right)
\]

Where \(k\) is the distance between the center of rotation of the chopper to the center of the beam, \(f\) the rotation frequency and \(n\) the number of chopper blades.
3. Implementation of the technique.
The experimental setup is implemented with a PIN photodetector SM1PD1A de Thorlabs, a own designed trans-resistance amplifier, a single mode JDS 1145P 30mW HeNe, a lens with focal length of 5cm, a data acquisition card model USB1208FS, a own designed motorized displacement platform; all components are arranged a shown in Figure 5. The sample is displaced around the focus of the lens registering the width changes using the technique described above for each sample.

![Figure 5](image)

**Figure 5.** Experimental setup: L (lens), Sample (S), Chopper (Ch), photodetector (PD), electronic circuit (EC), data acquisition card (DAQ).

The sample is fixed on a base that moves along an endless screw driven by a stepper motor that is controlled by the computer through data acquisition card. The whole process is implemented in Labview, Figure 6 shows the control panel. In order to carry out $z$-scan measurements is only necessary to enter the desired values for scanning and file names in which data produced under the program will be saved.

![Figure 6](image)

**Figure 6.** Front panel of the $z$-scan program.
The algorithm of the z scan program is the following:

i) To acquire N edges of Vph see figure 4, ii) From each edge to calculate the width using eq (2) and to obtain an average width, iii) to move the platform $\Delta z$ (left or right), iv) to repeat i) to iii) until the distance to scan has been completed v) to display on the PC screen (bottom of figure 6) the measurements on a graph (screen 3) in addition to the graphical results are also displayed Vph (screen 1), and the time it takes to Vph to change from Vht1 to Vth2 (screen 2) according to Figure 4.

4. Test and results.

The scans were carried out for thin samples i.e., samples whose thickness is much smaller than the Rayleigh range for a piece of blue acetate (mica) 0.1 mm thick and bacteriorhodopsin film of 0.008mm. A comparison between traditional and our proposal technique was carried out in order to verify that the sensitivity was improved, two scans were performed for each sample using the same components (laser, lens, detector, amplifier, data acquisition board, platform and distribution) and equal number of samples average, the distance from the laser output to the lens is 50cm and the distance of the lens to the photodetector is 50cm. The curves obtained with both techniques are shown in Figure 8. The power used for the blue acetate was 25 mW while for bacteriorhodopsin was 3mW.

![Figure 8. Z-scan curves for different materials. (a) Mica, (b) Bacteriorhodopsin film.](image)

It can be seen that the curves are very similar, however it should be noticed that the traditional detection there exist fluctuations, while than with widths measurements does not exist, which indicates that the signal to noise ratio was effectively improved. To reaffirm this conclusion it was carried out a scan for a sample of bacteriorhodopsin with the power of the laser attenuated to 500µW power. The resulting curve is shown in Figure 9.

![Figure 9. Z-scan curve for bacteriorhodopsin to a power of 500µW](image)
As you can see fluctuations in the traditional technique measurements are quite large, but with the detection of width variations in the shape of the curve is quite clear. Scans were also made for liquid samples, tincture of benzalkonium and blue antiseptic mouthwash, deposited in a cuvette with a thickness of 3mm, these are thick samples, compare the curves shown in Figure 10. Unlike the previous curves are truly significant changes in extent and shape of the curve. These differences are due to the samples did not meet the condition of thin sample.

![Comparison of results between the traditional technique and width measurement. (a) blue antiseptic mouthwash (b) tincture of benzalkonium](image)

**Figure 10.** Comparison of results between the traditional technique and width measurement. (a) blue antiseptic mouthwash (b) tincture of benzalkonium

In order to calculate and compare the value of SNR of each technique, were carried out experimental measurements. The experiment is to acquire a number of values of voltage (for the pinhole) or width (for the chopper), in a certain position with a laser power of 120µW for five minutes. The result is two signals corresponding to each technique, variations of these signals indicate the measurement uncertainty and from these we can calculate the SNR of each technique. We found that the SNR with wide measurement technique is 100 times larger than traditional technique.

### 5. Conclusions.

We developed an automated z-scan with a conventional detection system (detecting changes in intensity) and a detection system which consists of measuring directly the changes in the widths produced by the sample. Scans were carried out for different samples with the conventional technique and our modification of it, we can see that in fact the form of detection was used to measure the transmittance through the variations in width, allows sharper curves particularly those carried out with lower power, which indicates that the signal to noise ratio was improved. Our system is limited by the size of the spot, because if it is large enough for that the blades of the chopper did not fully cover, the waveform will be distorted and the results of the measurements will be wrong, this is a problem when working with samples that are very dispersive or cause very large changes in beam size, however, is solved by placing a lens whose area is large enough to cover the spot size.

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