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Nonlinear Refractive Index Measurement On Pure And Nd Doped YAG Ceramic By Dual Arm Z-Scan Technique

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Abstract. Transparent ceramics gain much attention as an alternative medium for high power ultra-short lasers because of its superior thermal properties over single crystals. Measurement of nonlinear refractive index is essential to understand the limit of such material for ultra-short laser generation. Dual arm Z-scan technique was employed to measure n_2 for single crystal and ceramic at the same time to avoid any uncertainty due to different measuring times.

Keywords: Transparent ceramics, Z-scan technique, Nonlinear measurement.
PACS: 42.65.-k, 78.20.-e, 78.20.Ci, 81.05.Je

INTRODUCTION

Femtosecond laser gained significant progress after its first demonstration in Kerr lens mode-locked (KLM) Ti:Sapphire laser [1]. Yttrium aluminium garnet (YAG) crystals gained attraction for ultra-short lasers because of its superior thermo-mechanical properties. Recently, 35 fs pulses were generated in Yb:YAG laser by Kerr lens mode-locked technique [2]. Transparent polycrystalline ceramics of YAG received more interest in the past few years because of its ease of processing and fabrication over YAG single crystals and its exceptional physical properties. Also, doped YAG ceramics find interest in ultrashort laser generation because of its interesting optical properties. One of the optical parameters that controls pulse broadening in ultra-short laser generation is the irradiance-dependent nonlinear refractive index (n_2) defined as $n(I) = n_0+n_2I$ where n_0 is the linear refractive index and I is the irradiance. Self-phase modulation (SPM) and B-integral parameter that plays an important role in high power lasers is dependent on n_2. This makes n_2 as a necessary parameter to be measured especially for the laser materials such as YAG ceramics used for femtosecond lasers [3]. Nonlinear refractive index on YAG ceramics was earlier measured using nanosecond laser [4].

After the invention of Z- scan technique [5], it was widely accepted as a reliable technique to measure nonlinear refraction (NLR) and nonlinear absorption (NLA) both for liquids and solid samples because of its experimental simplicity and capability of determining both nonlinear parameters utilizing a single beam. Closed aperture (CA) Z-scan and open aperture (OA) Z- scan are used to measure the nonlinear refraction (NLR) and nonlinear absorption (NLA) respectively. Due to error imbedded in the characterization of the pulse irradiance, these nonlinear experiments usually bear a large relative measurement error (e.g. ~25%) for Z-scan measurements based on the errors in measuring the spot size, pulse width of the pulse [6]. Therefore, it is difficult to extract the very small differences in the nonlinearities between two samples, which are measured at different times.

In this paper, we report a very precise measurement, to differentiate the n_2 of pure and Nd doped YAG ceramics and single crystals using a relatively newly developed dual-arm Z-scan technique within ~5% of our measurement uncertainty [6].

EXPERIMENTAL PROCEDURE

The single crystal and transparent ceramic of pure and Nd doped YAG were used for the measurement.

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Both the undoped ceramic and crystal are of same thickness (1 mm); similar case for Nd doped samples (1.48 mm). Samples were polished under the same conditions to achieve the same pitch, flatness and roughness (within rms value of 1 nm). The excitation pulse was generated from an optical parametric generator / amplifier (TOPAS-C, Light Conversion, Ltd.) pumped by an amplified Ti:Sapphire laser system (CPA 2110, Clark-MXR, Inc.) which outputs ~ 1 mJ of ~150 fs (FWHM) pulses at a 1kHz repetition rate. The pulsewidth at 1300 nm is 120 fs (FWHM), measured by second harmonic autocorrelation technique. The setup is composed by two identical parallel single-beam Z-scan arms constructed by matched optics. Single crystal and ceramic samples, mounted on the same stage, are translated parallelly through the focus of the each Z-scan arm. The pulse energy, arm path length and z position on each arm is matched, so that the irradiance is equalized at each z position. This is confirmed by performing dual-arm Z-scan on two matched cells filled with carbon disulfide (CS_2). The beam waist, w_0, at the focus is 22 μm (HW $1/e^2$ M), measured by performing closed aperture on CS_2 and open aperture Z-scan on GaAs wafer. The Rayleigh range, z_0, of the beam in the sample is 2.12 mm, calculated by $z_0=n\pi w_0^2/\lambda$, where n is the refractive index of the sample and λ is the wavelength. After the irradiance is matched at each Z-position, we mounted the samples in each Z-scan arm (crystal in one arm and corresponding ceramic sample in another arm) and perform Z-scans simultaneously at different input pulse energies.

RESULTS AND DISCUSSIONS

The closed-aperture Z-scan traces of the two samples, the single crystal and the transparent ceramic of undoped YAG (1 mm thick), are shown in Fig.1 with different input energies. No open-aperture signal (i.e. no NLA) is observed for all the samples. The positive sign of n_2 is verified by the Z-scan traces featured by a pre-focal valley followed by a post-focal peak. By fitting the Z-scan (Fig. 1) traces using Gaussian decomposition method [7], the n_2 value is estimated to be $8 \pm 2\times10^{-16}$ cm^2/W for both the single crystal and ceramic. Note that both samples show exactly the same shape of Z-scan traces, indicating very close value of n_2.

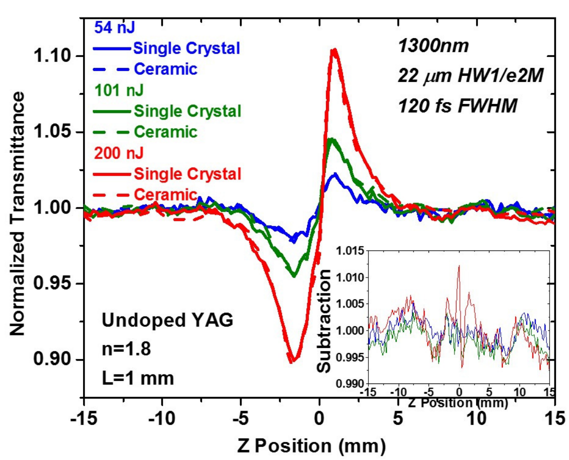

FIGURE 1. Closed aperture Z-scan traces of undoped YAG single crystal and ceramic at different laser energies.

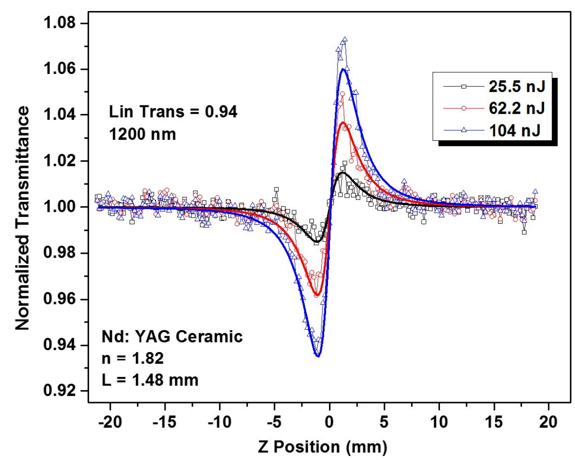

FIGURE 2. Closed aperture Z-scan traces of Nd doped YAG transparent ceramic at different laser energies.

Similarly, the measurement was carried out for 1% Nd doped crystal and ceramic (1.48 mm thick) at 1200 nm wavelength and the recorded Z - traces at different laser energies are shown in Fig. 2. The average value of n_2 for doped ceramic was found to be 6.5 x 10^{-16} cm^2/W. The subtraction of the Z-scan traces at each energy, which cancels the correlated noise between two Z-scan arms, shows no discriminable nonlinear signal difference above the noise floor, as shown in the inset of Fig.1. Given the signal noise ratio of the subtraction curve, we estimate the n_2 difference between the two samples is less than 5%. The value of n_2 in esu can be converted by the equation: $n_2(esu) = cn_0n_2(m^2/W)/40\pi$, where n_0 is the refractive index of the material (here 1.82) and c is the speed of light in m/s. From this formula, n_2 (esu) of pure and doped YAG ceramic is found to be 3.34 x 10^{-13} esu and 2.82 x 10^{-13} esu respectively. These values are similar to the reported value for YAG ceramic measured by nanosecond laser at 532 nm [4]. The difference in both these values lie within the percentage of uncertainty in the experiments which is around 25 % in our case.

It can be seen that the Nd doped sample also shows the same value considering the percentage of uncertainty in our experiments as mentioned in the introduction. Also it is to be noted that the measurements for the doped samples were carried out in a separate time. Under the given experimental conditions, the ceramic and single crystals of both pure and doped YAG show same value of n_2. Considering the thickness of the grain boundary (< 10 nm) of these ceramics, contribution of grain boundary volume on such nonlinear parameters can be considerably low which makes both the crystal and ceramic look the same. In addition, the size of the beam waist (~ 22 μm) is few orders larger than the thickness of the grain boundary. This can be a limitation to precisely measure the irradiance dependent refractive index on the grain and the boundaries separately.

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