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Inclusion Analysis and Absorption Measurement in Nonlinear Crystals

Laura L. Smith

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Disclaimer

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ABSTRACT

Yttrium calcium oxyborate (YCOB) is a newly developed nonlinear optical crystal used for second harmonic generation in the Mercury laser. As with any new crystal, optical characterization of the material properties needs to be fully investigated. We are developing two new techniques to detect inclusions and measure optical absorption. With the side illuminating detection examination (SIDE) method, we hope to identify and map the size, density, and the morphology of inclusions. The multi-pass absorption technique (MPAT) will be used to help determine the absorption coefficient of various finished crystalline pieces at near-infrared wavelengths.

I. INTRODUCTION

The National Ignition Facility (NIF) plays an important role in the future of fusion energy. NIF will be able to demonstrate energy gain and fusion ignition with 192 laser beams directed towards a target about the size of a BB. While NIF will demonstrate the science of fusion ignition, the Mercury laser showcases the next generation of laser technology that will enable commercialization of fusion energy production. It is designed as a high average power repetitively pulsed diode-pumped solid-state laser. The goal is to produce 100-J, 5-10 ns pulses at 10 Hz at wavelength of 1047 nm. The Mercury laser is a prototype of a potential inertial confinement fusion (ICF) power plant driver. Within the Mercury laser, frequency conversion plays an intricate role in producing the ideal laser wavelength output. YCOB or DKDP crystals are used to achieve high average power second harmonic generation (SHG). YCOB crystals are ideal for frequency conversion because they have a low optical absorption, high nonlinear coupling (3x), and high thermal conductivity (3x) compared to DKDP. The crystals are grown with the Czochralski method temperatures above 1500°C. The manufacturer, Crystal Photonics, has gradually been improving the quality of the crystals by changing the stoichiometry, rotation rate and the pulling rate. Qualitative observation of YCOB crystals has identified inclusions (1-10 microns diameter) that appear throughout the boule. Using the SIDE method, we hope to measure the size, density, and morphology of the inclusions. Using these measurements and knowledge of the existing growth conditions, Crystal Photonics can adjust the crystal growth parameters to reduce the number and size of the inclusions in the YCOB crystals. MPAT will be used to measure the absorption of a variety of crystals at different wavelengths. Although there are other techniques to measure small optical absorption, we hope to verify that this technique will improve the accuracy and consistency of existing measurements.

II. THEORY

2.1 SIDE

The SIDE method uses dark field microscopy to detect the inclusions. The fixture holding the crystals has LED light coming into one edge of the crystal, there are three mirrors positioned on the three other sides of the mount (See figure 1). Since the diode light is propagating transversely across the crystal bulk, only light scattered from defects such as scratches and inclusions, will be redirected out of the plane of propagation and onto the detector.

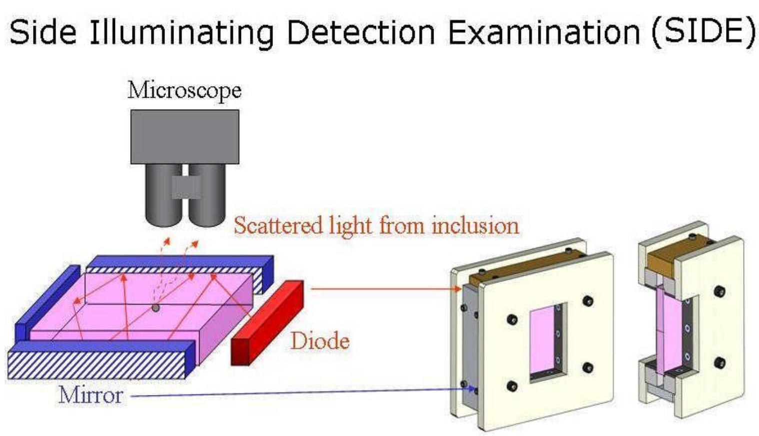

Figure 1. Schematic of the SIDE apparatus.

2.2 MPAT

The MPAT is used to measure the absorption coefficient of different crystals. The increased optical path length increases the absorption signal so that even a crystal with a small absorption coefficient can be measured accurately. The setup consists of a collimated laser, three mirrors, a Faraday isolator, and a detector. As seen in Figure 2, the collimated beam will travel through the Faraday isolator, towards two parallel six inch mirrors. The laser light will make multiple passes between the mirrors. The beam will come out of the parallel mirrors and is retro-reflected through a third mirror back to the polarizer. It will then be directed to the detector by the polarizer where a measurement will be made. A measurement will be taken with and with out the test part in-between the mirrors at Brewster's angle, giving a measurement of the differential loss.

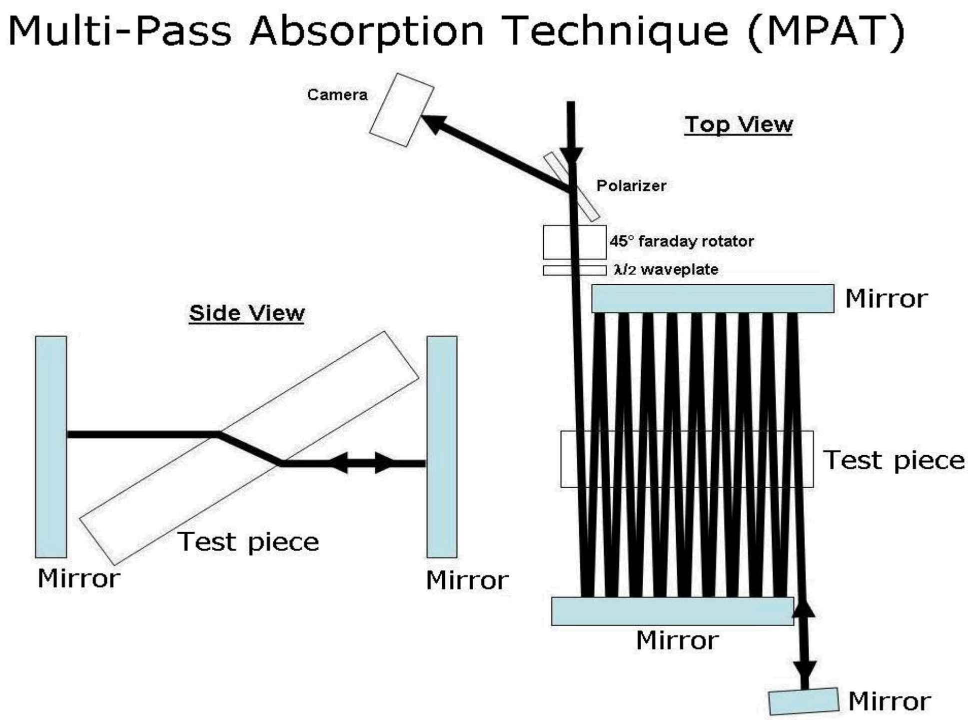

Figure 2. MPAT setup. The test samples are 1.5 cm by 6 cm.

MPAT relies on measuring the difference of the returned signal with and without the test part. It assumes that the return signal is reduced exclusively from absorption of the light multi-passed through the test part. As a result, the test part must be well polished in order to minimize surface scattering. Furthermore, the light must be s-polarized and the test part should be rotated at Brewster's angle

$$R_{\parallel} = \frac{\tan^2(\theta_i - \theta_t)}{\tan^2(\theta_i + \theta_t)} \quad . \qquad [1]$$

The measurement with and without the crystal will help eliminate errors (mirror loss as a example) within the system. Calculations to determine the amount of spacing between the mirrors and the angle at which the beam must come in order to have sufficient passes between the two mirrors were made in preparation for the setup. The crystal has a higher index of refraction than air, therefore when the light enters the crystal it is bent towards the normal. This causes a slight displacement, which needs to be accounted for when calculating the number of passes that can be achieved. As seen in Figure 3, the original length z is shortened to z\` because of the displacement. To calculate z\` three components are involved,

$$z` = d + z_2 + z_3 \,. \qquad [2]$$

Mirror spacing, s and test part thickness, T are related by (See Figure 3b)

$$\tan(\theta_i) = \frac{z_2 + z_3}{s - T} \,. \qquad [3]$$

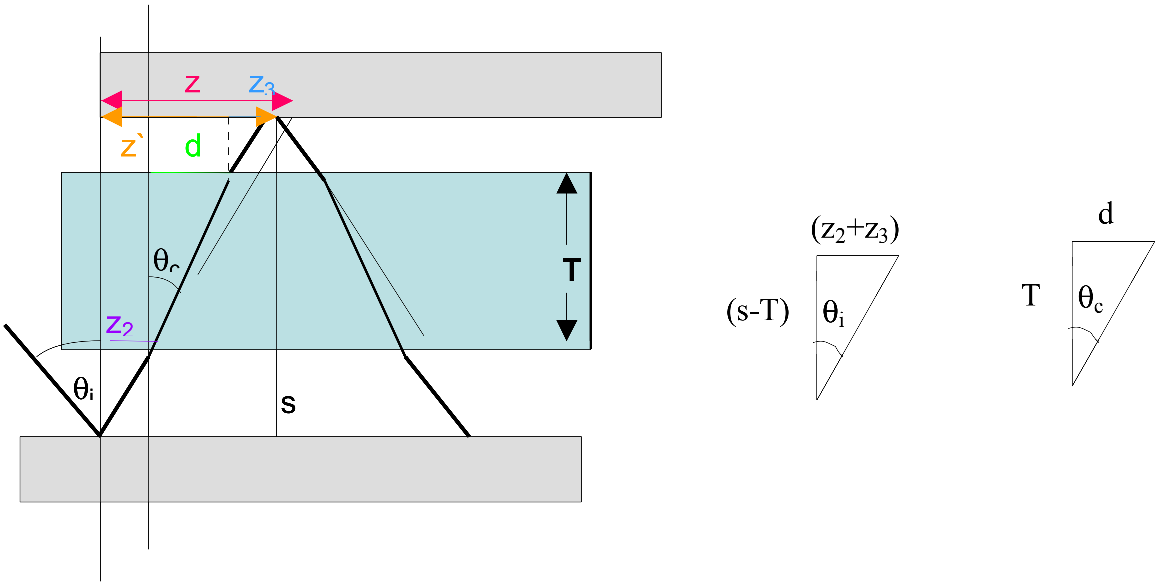

Figure 3. Shows the path that a beam takes while entering and exiting a higher and lower index of refraction.

where θ_i is the angle of incident. The displacement d is calculate using the angle of incident inside the crystal, θ_c

$$\tan\theta_c = \frac{d}{T}. \qquad [4]$$

The number of passes M, is related the mirror size, B and z` by,

$$\frac{M}{B} = z`. \qquad [5]$$

Combining the equations [2]-[5] produces

$$\frac{M}{B} = (s-T)\tan(\theta_i) + T\tan(\theta_c)\,. \qquad [6]$$

Solving for θ_i along with Snell's law gives us the equation

$$\tan^{-1}\left[\frac{m}{(s-T)B} + \frac{T\tan(\sin^{-1}(\frac{n_1\sin(\theta_i)}{n_2}))}{s-T}\right] = \theta_i\,, \qquad [7]$$

where n_1 and n_2 are the index of refractions of air and the test part respectively. The final equation was solved in Matlab, making the number of passes and the mirror spacing parameters to calculate the angle of incidence. The results were used to help setup the system as shown in Figure 4.

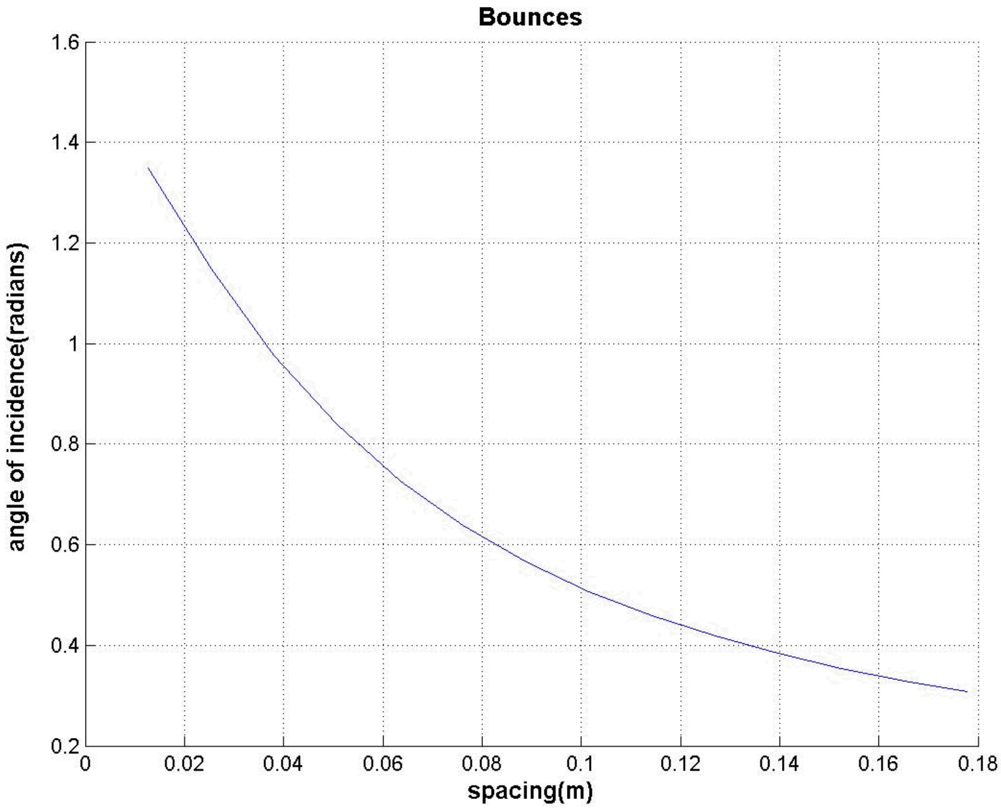

Figure 4. This graph shows the amount of spacing and the angle of incidence needed to achieve 18 bounces without a crystal in position.

To calculate the absorption, the optical path length first needs to be calculated. The equation for a single-pass optical path length is

$$L = t / \cos[\sin^{-1}(\sin\theta_i / n_2)], \qquad [8]$$

where L is the optical path length and α is the absorption coefficient.

III. DATA

3.1 SIDE

The original apparatus is made of white Teflon but this decreases the contrast. Black electrical tape was placed on the back surface to help eliminate reflections; the white line that appears in the picture is the gap between the tape, and not a crack. Figure 5 demonstrates the effectiveness of the SIDE apparatus. With the flashlight, minimal defects can be seen on the surface. With the LED light, dust particles and impurities on the surface can be seen clearly.

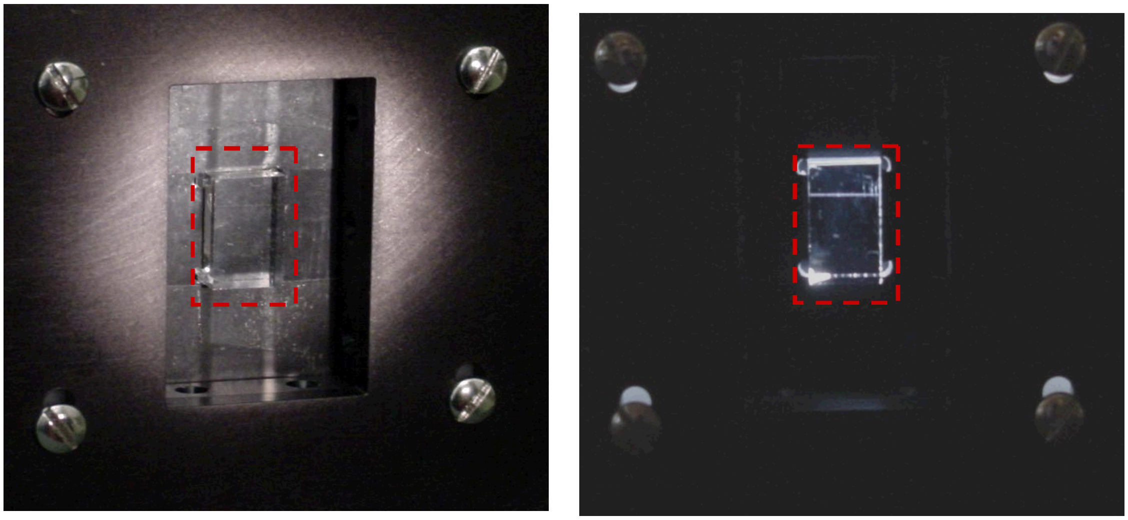

Figure 5. SIDE apparatus with flashlight illumination (left side) and with LED light illumination (right side) on the YCOB sample for defect inspection. The red box indicates the location of the YCOB crystal.

3.2 MPAT

Initial measurements were taken with various angles to determine if the system was correctly polarized (Figure 6). The experimental data in Figure 6 agrees with the general shape of a reflectivity curve for different index of refraction using equation 1. The experimental data lies between the calculated curves for index of refraction of 1.455 and 1.517. Figure 6 inset shows that the Brewster angle of the test part corresponds to an index of 1.455, which is appropriate since the test part was fused silica with a index of 1.46 at 1047nm. The deviation of the experimental data from the calculated reflectivity curve is partially due to the fact that the absorption signal changes with the angle of rotation due to its the optical path length dependence.

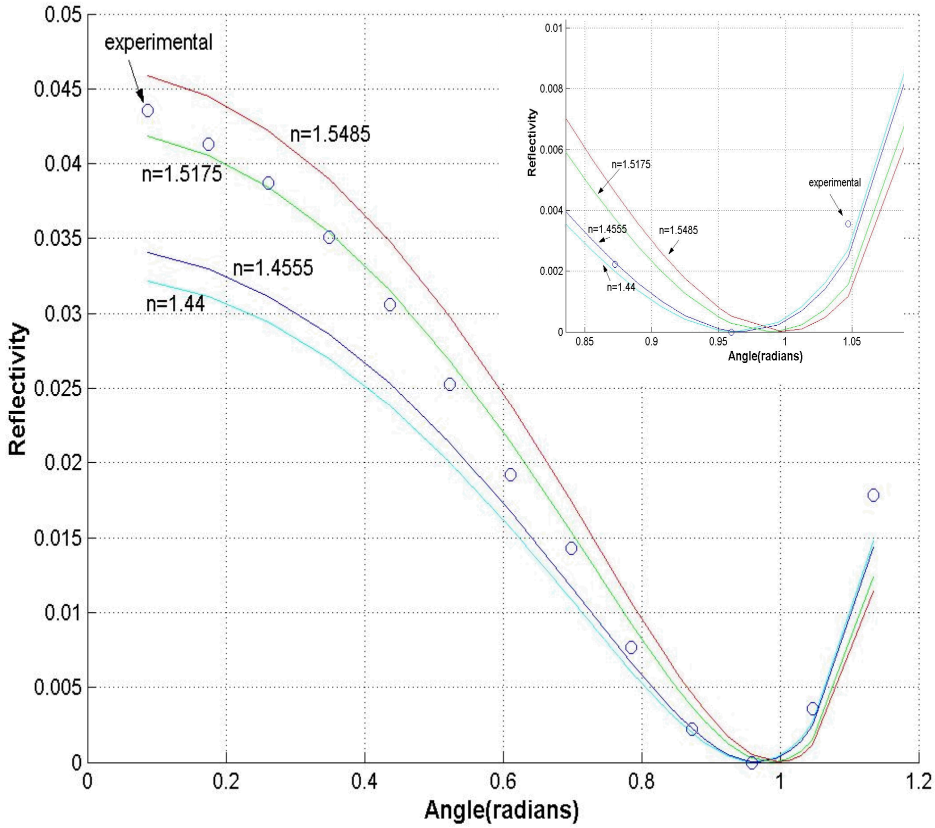

Figure 6. Reflectivity vs. test sample rotational angle for experimental data (open circle) and theoretical calculation (lines) with different index of refraction.

IV. DISCUSSION

A limitation with the SIDE method is that the light appears to only illuminate gross defects (> 10 μm) within the crystal. Nevertheless, the LED light is far more superior to regular lighting for optics inspection. It can also show dust particles and residual scratches on the surface. Its compactness and the speed in which it can be used to visually inspect optic make it a very useful tool. However, it is likely that small inclusions will scatter at angles too shallow to detect in the current configuration.

Initial measurements with fused silica test part shown that additional signal losses are present in the MPAT system. There seems to be other objects causing additional absorption other than from the test part. One source of absorption could be from the poor mirror surfaces. When the test sample is placed in position, the beam path will not travel the same path as when there was no test sample, this causes systematic errors if the mirror reflectivity is not uniform. A second problem was the beam was cut off by the optics; in particularly, the faraday rotator aperture was not large enough for the retro-reflected beam. Significant improvement is expected with replacement of the above parts.

V. CONCLUSION

The SIDE method as currently configured cannot be used because the inclusions in the YCOB crystal are extremely small. However, it would be a great tool for crystals that have larger defects. The MPAT system is working properly in principal. However, our current configure lacked of accuracy and reliability to measure small absorption coefficients (10^{-3}/cm). Some of the existing shortcomings will be overcome with better optics, i.e. dielectric coated mirrors and large aperture faraday rotators.

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