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SURFACE PROFILE MEASUREMENT OF 3D-PRINTED TRANSPARENT OBJECTS USING NONLINEAR OPTICS

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ABSTRACT: In Additive Manufacturing (AM), it is necessary to measure the surface profile of 3D-printed transparent objects in noninvasive manner, which remained, however, practically difficult to date. Nonlinear optical responses of transparent materials have been utilized in short-wavelength light generation, optical phase/intensity modulators, and non-destructive inspection of the sample characteristics. In this research, we introduced nonlinear optics to surface profile measurement of 3D-printed micro-optic structures. For in-depth understanding of third harmonic generation mechanisms, the harmonic conversion efficiency was measured with different input polarization states, incident angles, and focal depths in the transparent materials including Sapphire and Si wafers. Our results can be utilized in surface inspection required in various industrial and scientific applications, including 3D-profile measurement of printed optical components and waveguides.

KEYWORDS: additive manufacturing; third harmonic generation; femtosecond laser; sapphire

INTRODUCTION

Optical harmonic generation of transparent materials has been widely used in short-wavelength light generation, optical modulation, and non-destructive study of the sample characteristics (Saleh, Teich et al. 1991, Park, Kim et al. 2011, Kauranen and Zayats 2012, Garmire 2013). In Additive manufacturing (AM), it is necessary to measure the surface profile of 3D-printed transparent objects in noninvasive manner, which remained, however, practically difficult to date and nonlinear optical phenomenon of transparent object offers a good way to help overcome the problems of noninvasive metrology (Alles, Pasternak et al. 2007).

Among optical harmonic generation phenomena, second harmonic generation (SHG) and third harmonic generation (THG) have been widely used. Second harmonic generation (SHG) is very sensitive to characteristics of heterointerfaces, however, the third harmonic generation (THG) occurs in all materials, even though the crystal has a center of inversion symmetry (Tsang 1995). THG signal can be used for non-destructive study of the sample characteristics (Kunwar, Toivonen et al. 2016, Yi, Lee et al. 2017), which is a good way to measure the surface profile of 3D-printed transparent objects. To use the THG signal to measure the surface profile of 3D-printed transparent...
objects, it is necessary to study the third harmonic generation characteristics and mechanisms depending on different states of incident femtosecond laser beam. When a laser beam focuses onto a nonlinear crystal, the polarization state and intensity of the outgoing beam are dependent on the polarization state of the incident beam and the position of the focused spot inside the sample (Tsang 1995, Saeta and Miller 2001, Madden, Hall et al. 2011). Besides the application of noninvasive metrology of transparent objects, these phenomena give other good prospective scientific and industrial applications. For example, the polarization dependence of harmonic generation will determine the quality and efficiency of micro fabrication, and it can help distinguish the nonlinear phenomenon from other phenomena occurring inside the measured targets. By controlling the position of focused spot inside the sample and choosing a suitable orientation of the crystal with respect to the light beam, phase matching can be realized, which have effects on the laser microfabrication as well (Baldacchini 2015).

In this paper, firstly, we used a typical nonlinear object, sapphire to study the femtosecond laser-sapphire interaction phenomena and general measurement methods based on THG. In the experiment, THG strength was measured with different input polarization states, incident angles, and focal depths in the sapphire, then we moved to other transparent objects like Si and 3D-printed polymer structures to demonstrate the possibilities of noninvasive metrology of surface profile of 3D-printed transparent objects.

**THG MEASUREMENT OF TRANSPARENT OBJECTS**

**Experimental setup for THG measurement**

The experimental setup for studying THG from transparent objects is shown in Figure 1. The femtosecond laser source has a center wavelength of 1560 nm with a repetition rate of 80 MHz, the light pulses typically exhibit a duration of less than 100 fs with the average power of more than 350 mW. The transmitted signals then can be detected with EMCCD, which can greatly amplify the number of resulting electrons produced by the incident light and can be used to detect THG signal well.

![Schematic illustration of experimental setup](image)

**Figure 1. Schematic illustration of experimental setup**

**THG dependency check to different incident polarization, focus position and tilt angles**

To study the THG characteristics and mechanisms of transparent objects depending on different
states of incident femtosecond, a typical nonlinear object, sapphire, was used. In the experiment, the sample was moved along the direction of the incident femtosecond laser beam so that can help us distinguish surface and bulk contributions to THG in sapphire wafers and study the effect of different focused spot locations inside the ample on the THG yield. By adjusting the objective lens tilt angles, we can check the incident laser angle effects on the strength of THG signal. Half wave plate was used for controlling of the polarization state of the incident laser beam and can help check the polarization dependence characteristics of THG. In the experiments, we firstly checked the THG signal based on the incident femtosecond laser with different polarization states by adjusting half wave plate. The laser was focused on the bottom surfaces of the sapphire wafers with different cut axis. We checked the a-plane, c-plane, r-plane and m-plane, respectively. There were clear and similar periodical patterns in a-, r- and m-planes, however, we cannot find such patterns in c-plane. As shown in Figure 2, polarization dependence check of THG in sapphire can help distinguish the nonlinear phenomenon from other phenomena occurring inside the sapphire and test the material characteristics like structural symmetry.

![Figure 2. Polarization dependence check of THG at sapphire wafers with different cut axis: (left) a-plane sapphire; (right) c-plane sapphire](image)

When the laser beam struck on different positions of the sapphire wafers, there were different strengths of the THG signal. Figure 3 shows that the third harmonic generation happened at the sapphire-air interfaces of different planes. When the focus point moved from the bottom surface of the sapphire to the up surface, the THG signal became weaker and weaker, and then disappeared, and the signal came out again when the focus point began to reach to up surface of the sapphire. This method can help distinguish surface and bulk contributions to THG in sapphire wafers. When the incident laser was not normal to the wafer surface and had a tilt angle, the THG signal decreased at the wafers. It shows tilt angle is also a factor to consider when try to obtain high THG signal, as shown in Figure 4. We also checked other transparent objects like Si wafer with the same setup and measurement methods and found that it is possible to detect THG and use the THG signal to measure the profile of transparent objects noninvasively. In-depth understanding of the characteristics and mechanisms of THG from Si wafers will be done in the future work.
Figure 3. THG signal intensities of different focus point positions

Figure 4. Effects of tilt angle on THG signal intensity

THG measurement for measuring 3D profiles of 3D-printed objects

Because THG has the strongest strength at interfaces, it can be used to measure surface profile of 3D-printed transparent objects. Figure 5 shows that the THG signal can be detected at interfaces of the printed cylinder. In the experiment, the cylinders were fabricated by two-photon polymerization using SU-8. The designed diameter of the cylinder was 40 um and the height was 60 um. By checking the THG peaks, it is possible to measure the surface profile of the 3D-printed cylinder noninvasively.

Figure 5. Detection of THG signal at two-photon polymerized micro cylinders: (a)microscopic image of printed cylinders; (b)schematic illustration of THG from the targets; (c) THG signal of different focus positions along Z directions

CONCLUSION

We have observed the third harmonic generation signal at sapphire wafers with different cut axis to study the femtosecond laser-sapphire interaction phenomena and general measurement methods based on THG and found the THG signal intensity was dependent on the polarization states of
incident femtosecond laser beam. Polarization dependence of THG can help distinguish the nonlinear phenomenon from other phenomena occurring inside the sapphire and test the material characteristics like structural symmetry in the future application of 3D-printing, it can determine the quality and efficiency of micromachining as well. The incident beam focus locations at different depth planes and the different adjusted tilt angles have effects on harmonic generation as well. Different focus locations can be used for in-depth understanding of surface and bulk contributions to third-harmonic generation and obtaining an efficient THG conversion and measuring the profile of transparent objects noninvasively. With this experiment method and setup, by measuring different points of the 3D-printed transparent objects, noninvasive measurement of the surface profile of 3D-printed transparent objects can be realized.

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