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Noncontact method for sensing thickness and refractive index of intraocular lens implants using a self-calibrating dual-confocal laser caliper

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Abstract. We present a fiber-optic dual-confocal laser caliper method for noncontact high-precision sensing and measuring thickness and refractive index of intraocular lens (IOL) implants. The principle of the method is based on sensing and measuring the confocal intensity response of the laser beam reflection from the opposite object surfaces, which provides the advanced feature of having no limitations on the object shape, thickness, and transparency. Using single-mode optical fibers and a 658-nm laser source, the thickness measurement accuracy was assessed to be as high as 5 μm. In addition, refractive index of a transparent object with thickness smaller than the working distance of the focusing lenses can be measured. The thickness and refractive index of a plano-convex IOL were measured with a high accuracy. [DOI: 10.1117/1.JBO.23.6.067004]

Keywords: laser confocal microscopy; single-mode optical fibers; intraocular lens; thickness and refractive-index measurement.

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1 Introduction

The development and use of intraocular lens (IOL) implants for refractive cataract surgery have changed the life of cataract patients and have become the most commonly performed surgical procedure since the first IOL implantation demonstrated by Ridley Harold in 1949,[1] with an estimated 3 million surgeries per year in the United States[2] and 20 million worldwide.[3] Among many physical parameters that determine key performance characteristics, safety, and quality of an IOL, the focal length (or dioptric power), modulation transfer function (MTF), scattering, astigmatism, thickness, and refractive index play a critical role. MTF, astigmatism, and dioptric power can be measured using commercially available IOL-testing equipment. Recently, our group has developed and implemented test methodologies to measure dioptric power of various IOL designs with high precision.[4–7] However, despite their significance in IOL characterization,[8] conventional techniques employed for IOL thickness and refractive-index measurements show some specific drawbacks and limitations in precise IOL testing. For instance, the use of simple mechanical devices such as vernier calipers or micrometers for IOL thickness measurement can affect the IOL optical quality caused by the contact measurement, and the lens curvature introduces additional inaccuracies for precise measurement. Commonly used refractometers are also not suitable for the IOL refractive-index testing due to the same type of contact-based measurement. Therefore, the development and implementation of alternative noncontact sensing principles and measurement methods using remote, contact-free optical, or ultrasound irradiation sources have been considered to provide safer, more effective, and higher measurement accuracy approaches.[3,7] The use of optical measurement tools is especially attractive due to the well-developed optical imaging, microscopic, and sensing techniques providing high measurement accuracy.

There have been a number of published reports on the application of optical tools for measurement of thickness,[9,10] refractive index,[11,12] or both[13–16] of transparent media or biological samples. These tools, however, impose some specific limitations for testing thickness and refractive index of IOL in terms of spatial sample alignment, testing accuracy, variations of IOL designs, and calibration requirements. Some of these approaches are based on optical interferometry[9,10,12] that will have a limited applicability for testing of both IOL thickness and refractive index due to the complex measurements, the critical spatial alignment requirement of the IOL center to the beam axis, and the availability of IOL designs with different shapes (convex, concave, etc.). Optical coherence tomography (OCT)-based methods[11,14] do not provide superior testing accuracy compared to confocal microscope method and have the OCT limitation in measuring thickness of nontransparent objects. The conventional confocal microscopy-based platforms[13,16] have also some limitations for testing IOL in terms of confocal design and calibration requirements. In this work, we present a noncontact method for precise IOL thickness and refractive-index measurement employing an advanced fiber-optic self-calibrating dual-confocal laser caliper approach. The suggested sensing method can be applied for self-calibrating thickness measurement of any IOL thickness, shape, and transparency, and for the refractive-index measurement of a lens with surface curvature providing high accurate measurements for IOL.

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2 Experimental Sensing Approach

We developed a fiber-optic-based dual-confocal laser sensing system shown in Fig. 1.[17] As for other similar sensor methods, the measurement accuracy is the key characteristic that is highly dependent on the alignment of laser beams and the calibration of distances between the optical components. Below, we present a step-by-step procedure for setting up and the alignment of the proposed dual-confocal laser caliper system.[18]

As a laser source, we used a solid-state diode laser with a center wavelength at 658 nm, an output power of 25 mW, and a beam diameter of 8.0 mm. The laser characteristics affect the overall performance of the confocal microscope sensor; the wavelength is directly related to the resolution, the larger beam diameter compared to a typical 1-mm diameter of He–Ne laser enables a high laser-to-fiber coupling efficiency due to the reduced size of the focused beam spot that is moved toward matching to the relatively small input area of the single-mode fibers used, and the laser low coherence reduces instability of the output power due to the coherent interference between the optical elements. The laser beam is launched into a 50:50 single-mode fiber coupler, and it is divided into two arms (O1 and O2, Fig. 1), which are configured as two identical fiber-optic confocal microscopes. The fiber coupler consists of single-mode fibers with a 5-μm core diameter.

Instead of using a single lens for the confocal microscope, we employed a collimating and focusing lens pair configuration that provides broader capabilities for precise collimating, focusing, and alignment of the confocal laser beams. Without using the focusing lenses (LF1 and LF2, Fig. 1), laser outputs from both arms of the fiber coupler are collimated using identical 10× (NA = 0.25) microscope objective lenses, LC1 and LC2. By mounting the fiber-lens assemblies on tilting and translational mechanical stages, two collimated laser outputs were aligned to face each other on the same beam axis. This was performed by maximizing the measured laser intensity at the detector. The measured intensity was 7.4 mW, which provides 59% of overall laser-to-fiber coupling efficiency, when assumed only a half of the intensity will be delivered to the detector through 50:50 fiber coupler.

Following the alignment of beam axes, a total-reflectance flat mirror was placed at the target position (T, Fig. 1), the reflective surface facing the collimating lens LC1. The mirror was adjusted to be normal to the beam axis, which was again performed by maximizing the intensity at the detector. This is to ensure the next step: the alignment of the focusing objective lens LF1 to the beam axis. Now, placing the LF1 at a position that is a focal length away from the mirror, we can detect the confocal reflection signal from the mirror, and then by maximizing the signal intensity the optimal alignment can be achieved.

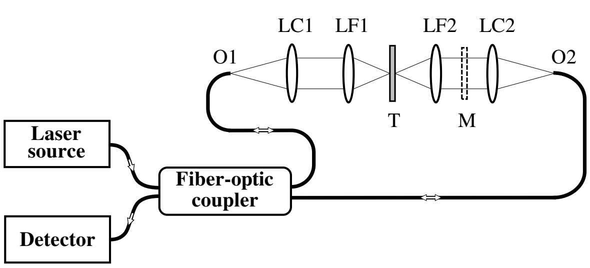

Fig. 1 Schematic diagram of the noncontact fiber-optic dual-confocal laser caliper setup.

This procedure was repeated for the other confocal microscope, by placing the mirror facing the opposite side and placing the focusing lens LF2. The distance between the two confocal microscopes, eventually the distance between LF1 and LF2, depends on the working distance (WD) of LF1 (identical lens is used for LF2) and the thickness of the object to be measured. For example, when 20× lenses (NA = 0.40, WD = 3.3 mm) were used, the distance between LF1 and LF2 must be >7.6 mm (1 mm + 3.3 mm + 3.3 mm) to measure a thickness of about 1 mm. The most convenient method is to place two lenses as far apart as possible within the travel limit of the mechanical stage on which a measurement sample will be mounted; however, the farther they are apart the more time it takes for measurements.

The operating principle of the dual-confocal laser caliper is straightforward (Fig. 2). Let us assume the distance between LF1 and LF2 is L. We placed a thin plate (OBJECT, Fig. 2) with parallel surface, which also has a certain degree of reflectivity on both surfaces, between LF1 and LF2. The thickness of the plate, t_0, is known with high accuracy. The surface of the plate can be adjusted to be normal to the beam axis using the same procedure as described in the previous paragraph. The plate is mounted on a mechanical translational stage that moves along the beam axis (x-axis, Fig. 2). Limiting the travel distance of the plate from close proximity of LF1 and to that of LF2, confocal reflection signals were recorded while the plate was moved from left to right. A silicon photodiode combined with an analog-to-digital converter was used as a detector. If the plate is not transparent, there will be one peak when the left surface of the plate is at x_{10} (x_1, Fig. 2), where the left surface of the plate is a focal length of LF1 (F_1) away from the lens. Another peak will be observed at x_{20} (x_2, Fig. 2), when the right surface of the plate is a focal length of LF2 (F_2) away from the lens. Now, the distance L between LF1 and LF2 can be expressed as a function of other parameters described above

$$L = F_1 + |x_{20} - x_{10}| + t_0 + F_2. \tag{1}$$

If we repeat the same procedure using an object with unknown thickness (t_s), the two peaks will be observed at x_1 and x_2. Equation (1) is now expressed as

$$L = F_1 + |x_{20} - x_{10}| + t_s + F_2. \tag{2}$$

By comparing Eqs. (1) and (2), we obtain an expression for the unknown thickness t_s in terms of known and measured parameters

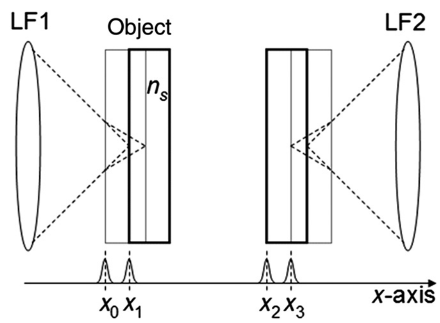

Fig. 2 Operating principle of the noncontact dual-confocal thickness measurement method. Dashed-lines are for illustration of laser focused through lenses.

$$t_s = t_0 + |x_{20} - x_{10}| - |x_2 - x_1|. \tag{3}$$

Equation (3) suggests that we can measure the thickness of any unknown object, which has well-defined reflecting surfaces on both sides, after calibrating the distance between optical components using a plate of known thickness. This method does not require precise determination of focal lengths of lenses and the distance between them, and therefore, the possible errors are reduced.

Two additional peaks will be observed when a transparent object with a thickness smaller than the WD of focusing lenses is used. As can be seen from Fig. 2, there is a backreflection from the right surface of the object at x_0. This is due to the focusing through the transparent object. However, x_0 is not t_1 away from x_1, since the refractive index of the object (n_s) increases the effective focal length of LF1. If we designate the distance between x_0 and x_1 as d, the refractive index of the object can be calculated using other parameters[13]

$$n_s = [NA^2 + (1 - NA^2)(t_s/d)^2]^{1/2}. \tag{4}$$

Another peak observed at x_3 can also be used for the calculation by letting d represent the distance between x_2 and x_3. This is valid only when the measured object has inversion symmetry.

The IOL thickness measurement requires an additional alignment. Unlike a parallel plate, the IOL not only needs to be placed normal to the beam axis but also the center of the IOL must coincide with the beam axis since the center is the thickest portion regardless if it is planoconvex or double-convex. Thickness measurement of negative-power IOL is also possible; however, it will not be discussed in this study. After the alignment of two collimating lenses, LC1 and LC2, a flat total-reflectance mirror (M) was placed to be normal to the beam axis (see Fig. 1). The position of the mirror M is approximately a focal length of the IOL away from T. Using one portion of the dual-confocal setup (O1), the dioptric power of the IOL is measured by placing the IOL at T. This method not only provides a high-precision measurement of the IOL dioptric power but also ensures the IOL alignment to the beam axis.[5] After the power measurement, the mirror is removed and the two focusing lenses are placed back at LF1 and LF2. The rest of the measurement procedure is the same as that for a plate. Refractive index can also be measured when the thickness of the IOL is smaller than the WD of the lenses; however, the measured values using $(x_1 - x_0)$ and $(x_3 - x_2)$ are different when a planoconvex IOL is used.

3 Results and Discussions

Figure 3 shows a confocal reflection signal measured for a 1-mm standard metal plate using 20× objective lenses. The values x_{10} and x_{20}, as defined in the previous section, were 0.1927 and 0.9565 mm, respectively. The full-width at half-maximum (FWHM) of a peak was 15 μm and the precision of the mechanical translational stage was 0.1 μm. FWHM of our setup was larger than the theoretically predicted value of 3.5 μm, which is calculated using an expression for the axial response of a confocal microscope $(\Delta z)_{1/2}$[19]

$$(\Delta z)_{1/2} = 0.442\lambda/(1 - \cos\alpha), \tag{5}$$

where λ is the laser wavelength and $\sin\alpha$ is the numerical aperture of the focusing lens. The setup showed a lower axial resolution compared to the theoretically predicted value since the setup was operated under the fiber-dominated mode for increased coupling efficiency by using a larger NA (0.25) of the collimating lens compared to that of the optical fiber NA (0.12).[20]

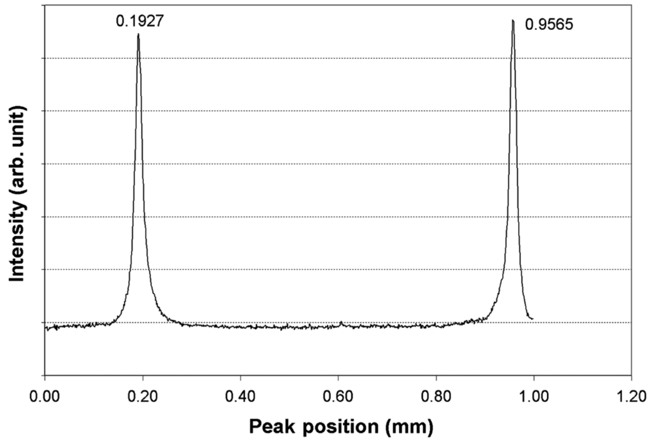

Fig. 3 Confocal reflection intensities for the thickness measurement of a standard 1-mm plate using 20× objective lens.

Figure 4 shows data measured for a thin glass plate using 20× objective lenses. The thickness of the glass plate was 1.00 mm as measured with a vernier caliper as one of the standard techniques listed in Sec. 1 using a mechanical tool to measure the IOL thickness providing an accuracy of 10 μm. Four peaks were observed as the thickness of the plate is smaller than the WD of the lens. The intensity peaks at x_0, x_1, x_2, and x_3 are measured to be 0.1415, 0.7967, 1.5406, and 2.1976 mm, respectively. The thickness and refractive index of the glass plate can be calculated using Eqs. (3) and (4): t_s is 1.0199 mm and n_s is 1.482. Both results match well to the known values. Calculated values of d using $(x_1 - x_0)$ and $(x_3 - x_2)$ were 0.6552 and 0.6570 mm, respectively. The difference is 1.8 μm, and it is well within the experimental error. The intensity peaks at x_0 and x_3 were smaller than those at x_1 and x_2, because the direct reflection from the front surface is stronger than that from the back surface.

Figure 5 shows data measured for a planoconvex IOL using 20× objective lenses, planar surface facing LF1. The thickness of the IOL was 0.76 mm when measured with a vernier caliper.

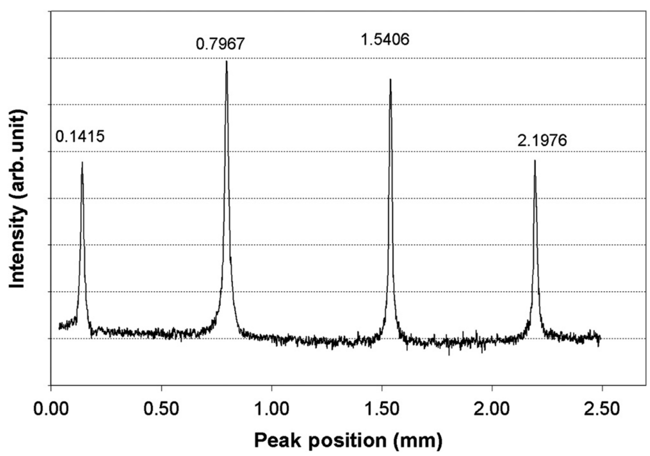

Fig. 4 Confocal reflection intensities for the thickness measurement of a glass plate using 20× objective lens.

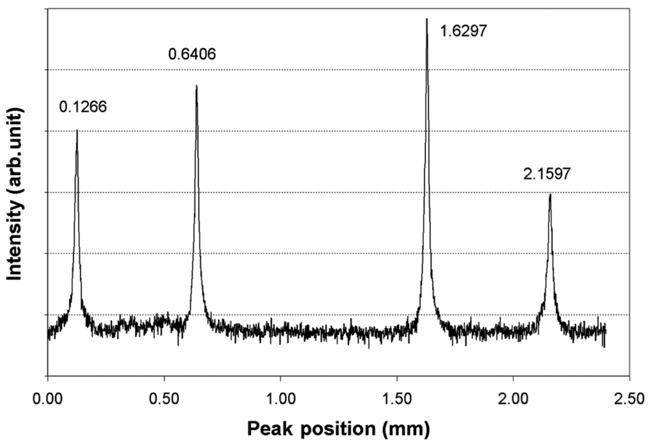

Fig. 5 Confocal reflection intensities for the thickness measurement of an IOL using 20× objective lens.

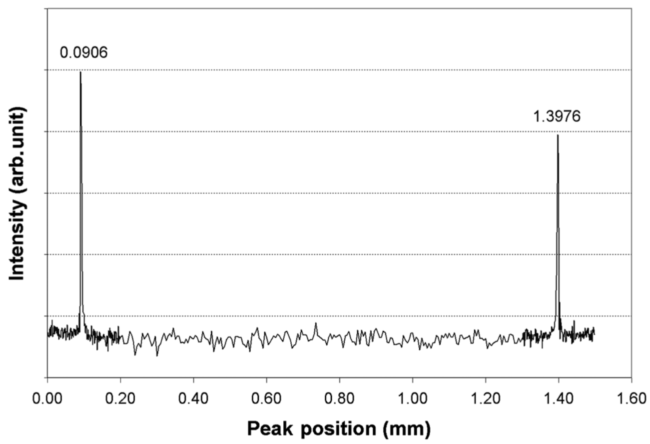

Fig. 7 Confocal reflection intensities for the thickness measurement of an IOL using 60× objective lens.

Four peaks at x_0, x_1, x_2, and x_3 are measured to be 0.1266, 0.6406, 1.6297, and 2.1597 mm, respectively. The thickness and the refractive index calculated using Eqs. (3) and (4) were 0.7747 and 1.438, respectively. Both results match well to the known values. The calculated values of d using (x_1–x_0) and (x_3–x_2) were 0.5140 and 0.5300 mm, respectively. The difference is 16 μm, which is larger than the difference measured from the glass plate. It is because the reflections measured from LF1 (peaks at x_0 and x_1) are through the planar surface; however, the reflections measured from LF2 (peaks at x_2 and x_3) are through the convex surface. Additional focusing effect from the convex surface has decreased the effective focus of LF2, thus, the peak was observed when the object was closer to LF2, giving the larger value of (x_3–x_2) than (x_1–x_0). We used (x_1–x_0) as d for the calculation of refractive index. The intensity at x_3 is also smaller than that at x_0. We assumed the convex surface is locally flat when it is at the laser focus (focal spot diameter is 1.5 μm). The IOL dioptric power measured during the alignment was 26.7 D.

For comparison, the measurement was performed using 60× objective lenses. Figure 6 shows the measured data for a standard 1-mm metal plate. x_{10} and x_{20} were 0.1365 and 1.2136 mm, respectively. Because of high NA of the lenses, FWHM was reduced to 5 μm. Figure 7 shows data measured for the same IOL. The intensity peaks at x_1 and x_2 are measured to be 0.0906 and 1.3976 mm, respectively. The calculated IOL thickness was 0.7700 mm, which is closer to the value measured with a vernier caliper than when it was measured with 20× lenses. Since the WD of 60× objective lens is only 0.28 mm, the refractive index could not be measured. Objective lenses with high NA and long WD such as infinity-corrected lenses could be used when the measurement of refractive index while maintaining high accuracy is necessary.

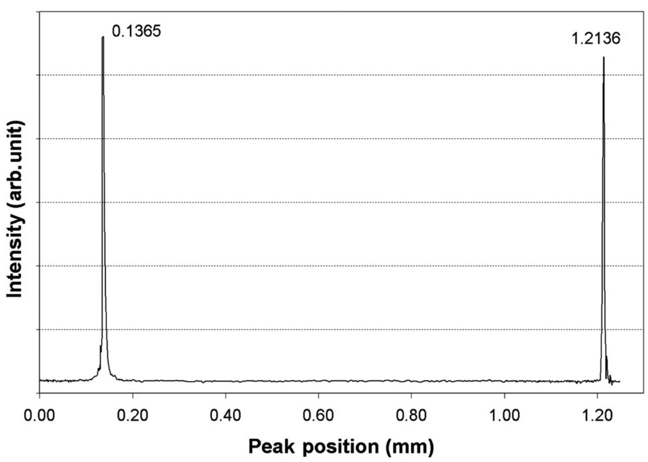

Fig. 6 Confocal reflection intensities for the thickness measurement of a standard 1-mm plate using 60× objective lens.

A few general factors that could limit the measurement accuracy of the presented method are discussed as follows.

1. An essential factor that can significantly affect the measurement accuracy is the precise optical alignment of the dual-confocal laser caliper setup. As described in details in the previous section, by performing a rigorous alignment procedure, we eliminated any potential measurement inaccuracies caused by misalignment. A further improvement of accuracy over the alignment procedure would be required when a detector with higher sensitivity and optomechanical stages with higher precision are used. However, a quantitative description of potential errors induced from misalignment cannot be addressed. The overly time-consuming procedure is not necessary once the experimental setup is established, and therefore, the measurement of IOL thickness, refractive index, and dioptric power is repeatable at the calibrated and measured accuracy. An additional advantage of the proposed measurement approach is related to the system's potential for eliminating any remaining possible misalignment and error from the setup. Shanna and Shappard demonstrated how the maximum axial response signal can be changed due to the misalignment of the optical fiber versus the beam axis.[21] The authors indicated that a maximum signal can be detected when the target is slightly out of focus of the focusing objective lens in case of using a weakly guiding step-index optical fiber, which can be associated with an error in determining F_1 and F_2 when they were measured by detecting confocal signals. In addition, Dabbs and Glass showed that the axial response

of the confocal microscope depends not only on the distance between the target and focusing lens but also on the distance between the fiber and collimating lens.[17] Therefore, there can be significant errors in F_1 and F_2 if they are determined solely by confocal signals. However, the proposed test method eliminates the necessity of measuring F_1 and F_2 during the calibrating procedure using a standard thickness sample, and thus, any remaining measurement errors due to the alignment procedure are canceled out.

2. In general, the axial resolution of an optical microscope system, whether it is a widefield microscope or a confocal laser scanning microscope, is less than the lateral resolution of the same system. Thus, the measurement accuracy of the proposed test method is inherently limited. We can improve the performance using a shorter wavelength laser and a higher NA objective lens [see Eq. (5)], although an accuracy in submicrometer range is hardly achievable unless some ultrahigh-resolution techniques for breaking the diffraction limit in the subwavelength nanometric range such as confocal nanoscopy are employed.[22]
3. The accuracy limit due to the resolution of mechanical translational stages does not play a significant role because it is smaller than the FWHM of axial confocal signal. Moreover, the possible error caused by the translational stages is not an accumulative value, and therefore, the measurement accuracy remains unchanged regardless of the thickness of the sample. This advanced feature is valid for the proposed test method as it eliminates one source of inaccuracy, L, by self-calibrating the measurement setup using a standard thickness plate. In addition, some errors induced by the thermal expansion of the standard plate made of stainless steel are also possible. However, the linear thermal expansion coefficient of stainless steel is $17.3 \times 10^{-6}\ (\mathrm{K})^{-1}$ at room temperature, which indicates that the error due to thermal expansion is negligible compared to the errors induced by the axial resolution of confocal microscopes.

4 Conclusions

In conclusion, we presented a fiber-optic dual-confocal sensing method for noncontact high-precision measurement of thickness of an object with reflective surfaces. The method is proved to be specifically useful for the thickness measurement of IOL implants, where contact-free measurement is highly desirable. We have successfully measured the IOL thickness with accuracy as high as 5 μm, when single-mode fibers, 60× objective lenses, and 658-nm laser source were used. Since the alignment of optical components is critical in the proposed method, we developed a step-by-step procedure for the optical alignment to reduce any possible errors due to the misalignment. The measured IOL thickness using our method was 0.7700 mm, which agrees well with the value measured by the conventional mechanical methods. In addition, refractive index of an IOL is also measured using 20× objective lenses, and the measured value was 1.438. The method is not only limited to the thickness and refractive-index measurement of thin transparent object but it can also be effectively employed to objects with any thickness and transparency if the thickness is within the travel limit of translational stage and the object has measurable backreflection at the surfaces. Furthermore, due to the high precision of the noncontact method, measurements can be performed without any physical contact on the sample, which ensures that the sample can be preserved in its original conditions. In addition, fragile or soft material, and tissue can also be used for the thickness measurement.

Disclosures

The authors have no relevant financial interests in this article and no potential conflicts of interest to disclose.

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