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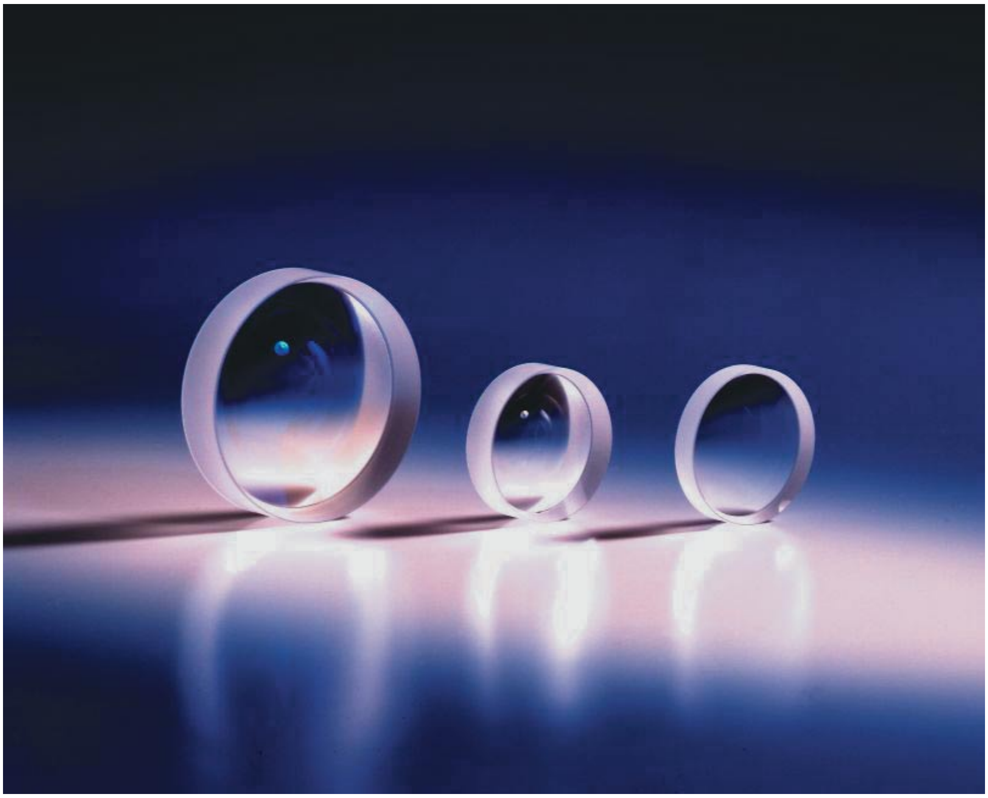

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Technical Report

Noncontact measurement of central lens thickness

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1. Introduction

The production of high-quality optical lenses from glass or polymer materials is subject to tight specification tolerances. Critical lens parameters such as central thickness have to be monitored frequently, during the production process. A noncontact, fast and precise optical measuring setup based upon a confocal chromatic probe can be used to measure central lens thickness ranging from 30 µm up to 25 mm. The only parameters that have to be known up front are the radius of curvature of one lens surface, and the material used. The following will present this measurement technique, illustrating it with some actual examples.

2. Measurement principle

The central thickness of a lens can be determined by measuring the distances S_1 and S_2 from a fixed reference point to the vertex of both top and bottom side of the lens. The difference between these two distances yields the central thickness.

For this distance measurement, the chromatic longitudinal aberration of a special optical probe can be used (see figure 1). Spectrally broadband light is coupled into a fiber that guides it − via a fiber coupler − to a special optical probe with a distinct chromatic aberration along the optical axis. The light that comes from the fiber end face is thus focused wavelength-dependently onto the surface to be measured, where it leaves a spot of a few microns in diameter. However, a perfectly focused image of the fiber core is only observed at one single wavelength λ_1. The retro-reflected light of this same color, only, is perfectly focused back onto the fiber end face, where it is efficiently coupled into the fiber. Other wavelengths are suppressed significantly because of the blurred image they generate at the fiber end face. Via the fiber coupler, the reflected light is guided to a spectrometer. The measured spectrum exhibits a sharp peak at λ_1. By calibration, distance S_1 between probe and lens surface can then be derived from the wavelength found. The focal lengths of $\lambda_{\min}$ and $\lambda_{\max}$ (the shortest and the longest wavelength that the probe can handle) determine its working range. It can therefore be varied within a broad range by choosing optical heads with different levels of longitudinal chromatic aberration.

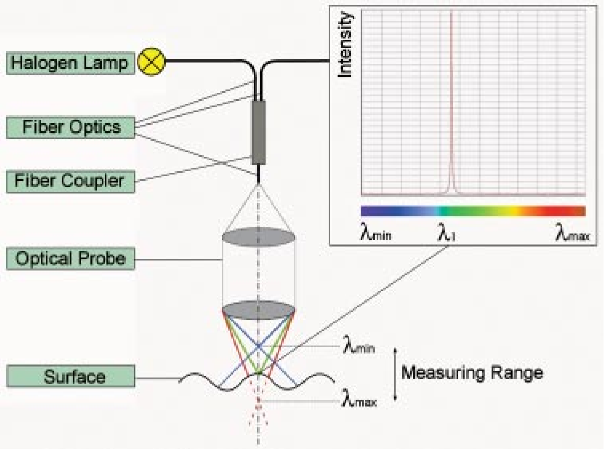

Figure 1. Principle of the chromatically encoded confocal measurement.

If two surfaces (or interfaces) of a transparent material are located within the probe's working range, then two different wavelengths λ_1 and λ_2 will render a sharp image, each on one of the surfaces, respectively (figure 2). Correspondingly, two peaks can be seen in the spectrum. They correspond with the distances S_1 and S_2 to the two surfaces.

In this geometry, it has to be considered that light reflected from the lower surface is refracted at the upper surface upon entering and leaving the transparent material. For a correct measurement of the distance S_2, the refractive properties of the upper surface must thus be taken into account.

The geometrical light path is illustrated in figure 2 for the special − though recurrent − case of two parallel surfaces, showing two single rays coming from the optical probe. The incident ray 2 hits the upper surface at an angle α. Refraction neglected ($n = 1$), the ray would intersect with the optical axis in a distance S_0 from the probe. However, due to refraction ($n > 1$), the ray travels on from the first surface at a smaller angle β and intersects with the optical axis at a bigger distance S_2. This follows Snell's law of refraction, taking into account, though, that the refractive index n is a function of wavelength λ:

$$\sin\alpha / \sin\beta = n(\lambda). \qquad (1)$$

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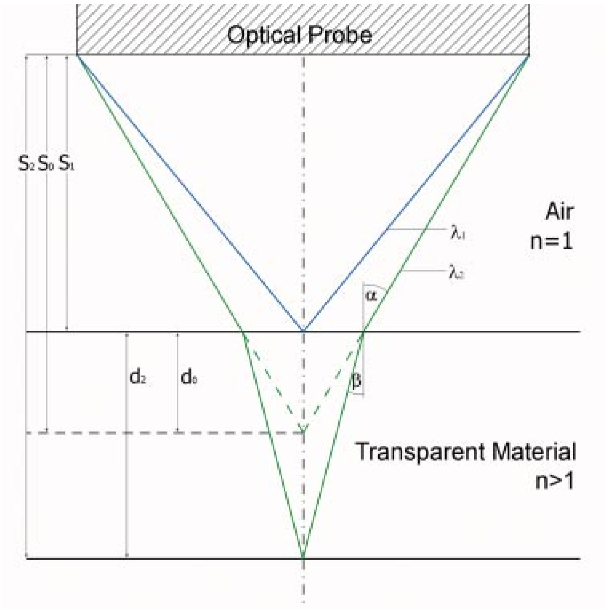

Figure 2. Ray path in a layer with flat parallel surfaces.

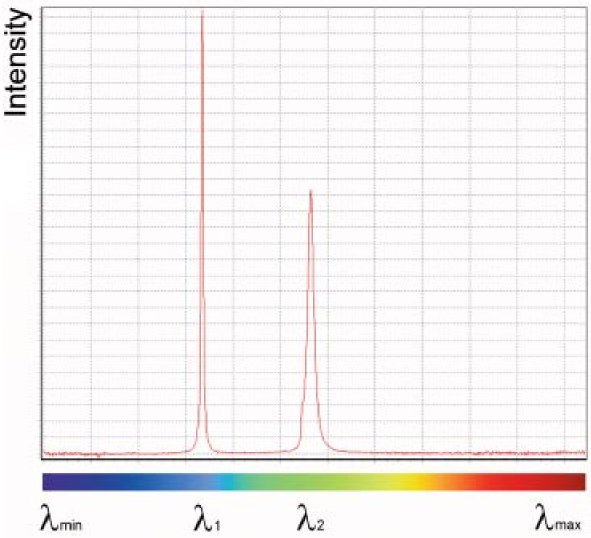

Figure 3. Spectrum from a layer-thickness measurement.

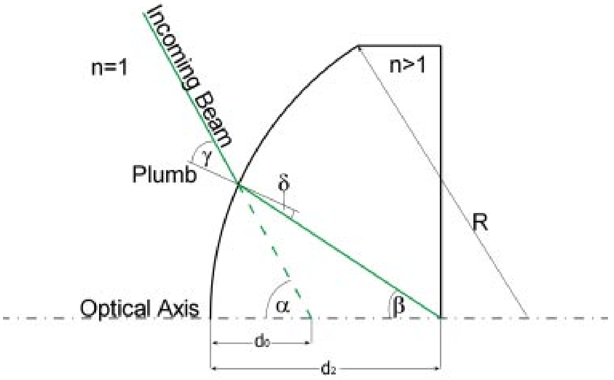

Figure 4. Ray path in a lens.

Furthermore:

$$\frac{s_2-s_1}{s_0-s_1}=\frac{d_2}{d_0}=\frac{\tan\alpha}{\tan\beta}=\frac{\sin\alpha}{\sin\beta}\cdot\frac{\cos\beta}{\cos\alpha}=n\cdot\frac{\cos\beta}{\cos\alpha}\,. \tag{2}$$

The true thickness d_w can be determined from the measured thickness d_g by integration over all of the bundle of rays, weighted statistically with a factor of $g(\alpha)$ that corresponds to the share of all individual rays in the beam's complete intensity and their representation in the measurement process.

$$d_w = d_g\cdot n(\lambda)\int\limits_0^{\alpha_{\max}}\frac{\cos\left(\arcsin\left[\dfrac{\sin\alpha}{n(\lambda)}\right]\right)}{\cos\alpha}\,g(\alpha)\,d_\alpha\,. \tag{3}$$

For a given optical head, the integral can be represented as a function K of wavelength and numerical aperture $NA = \sin\alpha_{\max}$. Equation (3) is then reduced to

$$d_w = d_g\cdot n(\lambda)\;K(\lambda,\,NA). \tag{4}$$

Wavelength λ in equation (4) is a function of the working range; it corresponds to wavelength λ_2 of the second peak in the spectrum of the reflected light (see figure 3). It can be determined by a wavelength calibration of the spectrometer.

In the case of a lens with a curved upper surface (radius of curvature R), generally the angle α between an incoming ray and the optical axis does not correspond with the angle γ between the ray's direction of incidence and the plumb line at the upper surface. The situation is illustrated in figure 4. Also, the refracted ray's angle δ with that plumb line does not correspond with the angle β towards the optical axis any more.

However, the true central thickness d_w can be determined from the measured thickness d_g, in analogy with the case of a flat upper surface. Only, the radius of curvature R of the upper lens surface must be considered as an additional parameter:

$$d_w = d_g\cdot n(\lambda)\;K(\lambda, NA, R). \tag{5}$$

The special case of a flat upper surface discussed above is contained in this equation with $R\rightarrow\infty$.

2.1 Sensor concept

The measurement principle described above has been employed in the new sensor CHRocodile. The device consists of a white light source, a fiber coupler, a spectrometer, control electronics and a compact measuring head, according to the optical probe illustrated above. The light is guided through a glass fiber (length up to 25 m) to the measuring head, which has been implemented as a strictly passive optical device without electronics or moving parts. A broad choice of measuring heads with working ranges reaching from 100 µm up to 25 mm and distance resolutions down

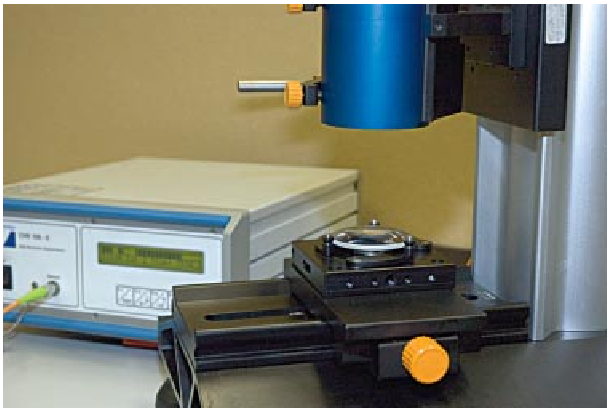

Figure 5. Measurement setup for measuring the central thickness of lenses.

to 3 nm allow for solving a multitude of measurement tasks with excellent reproducibility. Due to the high repetition rate of 4 kHz, very short measurement times are feasible, particularly within in-line applications of the sensor.

2.2 Measuring lens thickness

For thickness measurement, a lens is placed in a position aligned with the probe's optical axis (figure 5). The radius of curvature of the upper lens surface has to be entered, and the lens material must be selected from a database, from which the system obtains the material's exact refractive index. As soon as the measurement procedure has been carried out, the system immediately displays the central thickness of the lens.

All common lens shapes (concave, planar-convex, aspherical) and lens materials (glass, polymers, and others) for the visible wavelength range can be measured. Even measuring coated lens surfaces is possible. The measurement system is insensitive to temperature variations and vibrations, leaving the measurement suited for industrial production environments, without difficulties.

2.3 Measuring thin layers

Applying a special probe, the sensor can be operated as a white light interferometer for measuring thin transparent layers with an optical thickness of 2 to 250 µm. This is especially attractive for applications like e.g. measuring foils or varnish (liquid or solid). Also, the simultaneous thickness measurement at several transparent layers in layer stacks is possible.

2.4 Distance measurement

By the simple turn of a switch, the device can be operated as a high-resolution distance sensor, just as described in section 1. Using optical probes with a high numerical aperture allows for measuring polished, rough, highly reflective or opaque surfaces, at a slope of up to 30° to the probe's optical axis, yielding a high lateral resolution of 2 µm. Because of the high measurement repetition rate, this makes it possible to build up scanning 3D systems for noncontact measurement of topographies, profiles and layer thickness. Typical applications are quality and production control within the glass, polymer, semiconductor and automotive industries, both in the laboratory and in industrial production.

3. Summary

The measurement technique introduced here offers a means for noncontact, fast and precise thickness measuring of transparent samples. Unlike many other optical measurement procedures, it is very robust against external influences, and it can easily be operated, too. Therefore, it is a true alternative versus tactile metrology and avoids typical disadvantages like damage to the sample. This leads to considerable time and cost advantages, particularly with respect to sensitive components like optical lenses.

4. References

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