Object tilt—a source of systematic error in transmission deflectometry

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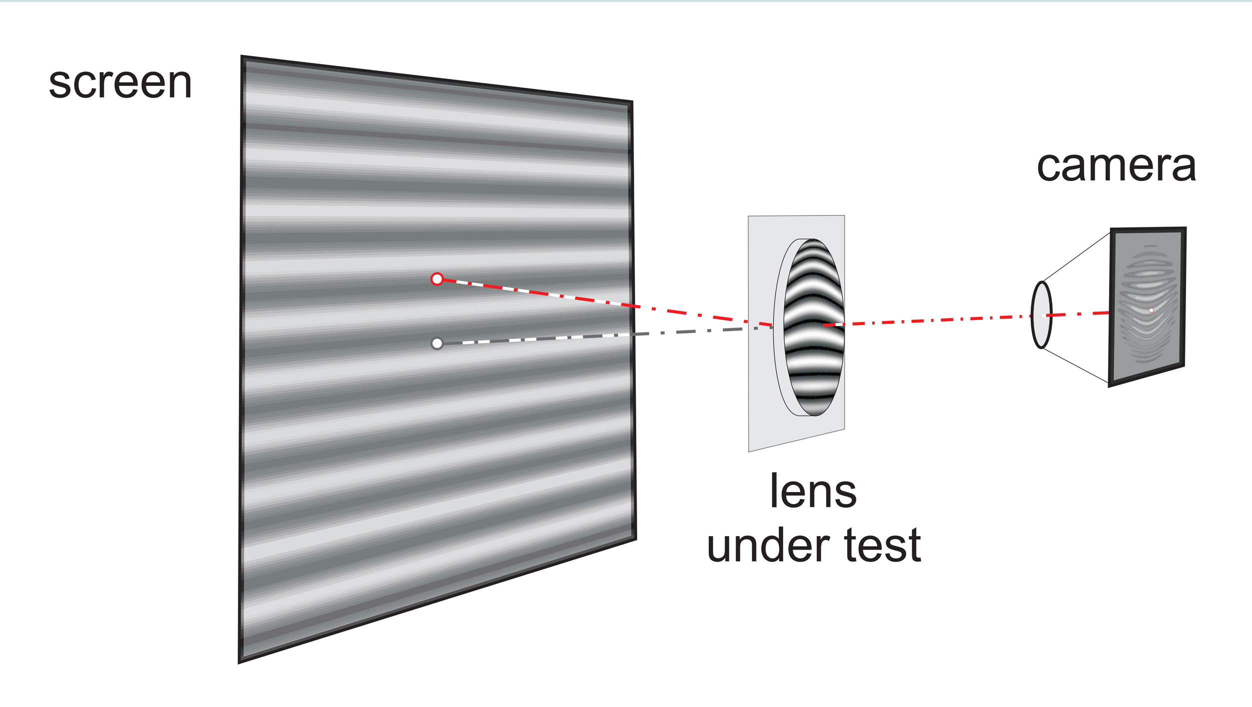

Fig. 1 *Phase-measuring deflectometry in transmission. Due to the optical power of the lens under test, the camera observes a different phase of the pattern.*

We apply **phase-measuring deflectometry** (PMD) [1] to measure the optical properties of lenses in **transmission.** Whereas the measurement of the refractive power of weak lenses yields very good results [2], **locating the optical axis** is far more challenging—especially for weak lenses. In this case the result strongly depends on the position of the object under test in the measurement setup.

The major **source of error** turns out to be the **tilt of the object**. For spherical lenses, we can derive an **explicit relation** between object tilt and (virtual) decentration.

Locating the optical axis

The optical axis of a lens is identical to the ray of light that is **not deflected** by the lens. Thus, the first idea to locate the optical axis with transmission PMD is to identify the point where the **phase is not changed** by the object under test. The result is depicted in Fig. 2.

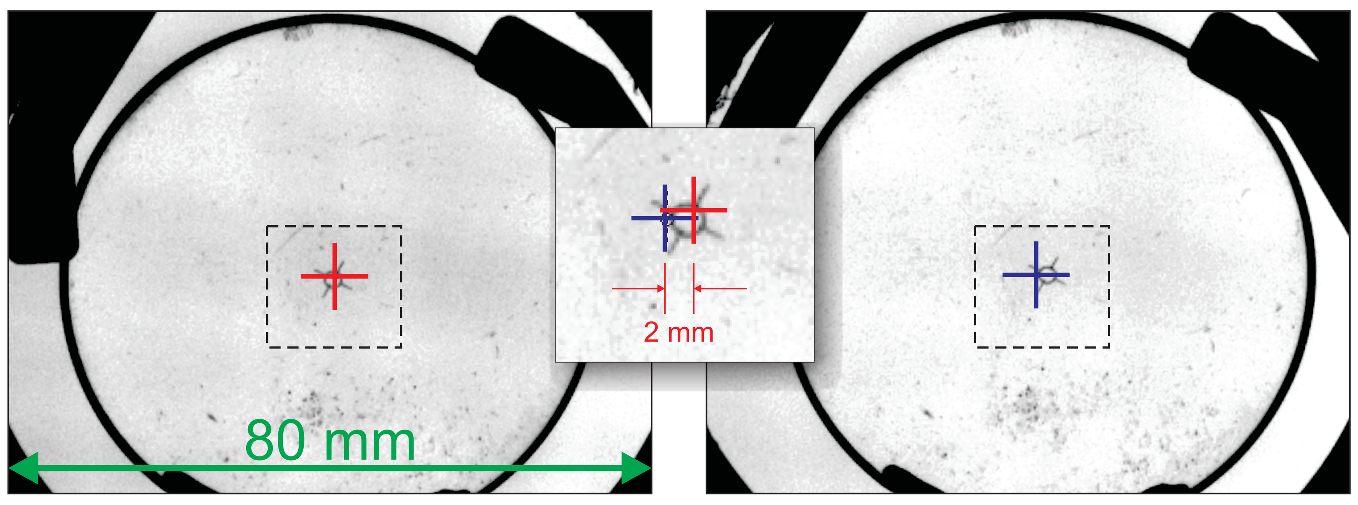

Fig. 2 *Points with minimal phase change. Left: Orthogonal observation. Right: Observation with an angle of approx. 10°. The identified optical axes differ by approx. 2 mm. (lens curvatures r_1=76.9mm, r_2 = 93.0mm).*

It is possible to find a ray that is not deflected, but this ray is **not necessarily the optical axis**. While the object is the same for both ray fields, they experience completely **different wedge angles** (see Fig. 3). As we do not know the interaction points, it is very difficult to reconstruct the transparent object even from multiple views. From one view alone, this location **error is unavoidable**.

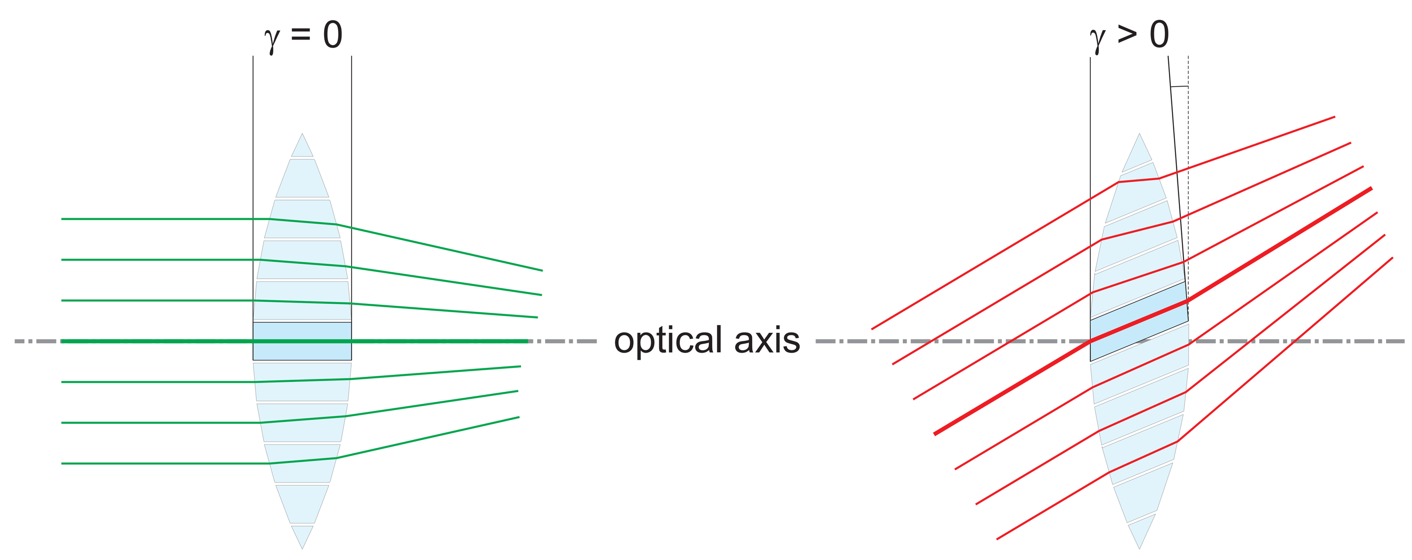

Fig. 3 *A lens can be modeled as a combination of wedges. Depending on the angle of the rays, we have to consider different wedge angles. For example, the center ray will be deflected by a tilted object.*

Error estimation & Conclusion

To **quantify** the location error we calculate the effect for a spherical lens. We are looking for the ray that is not deflected when hitting the lens under a certain angle alpha.

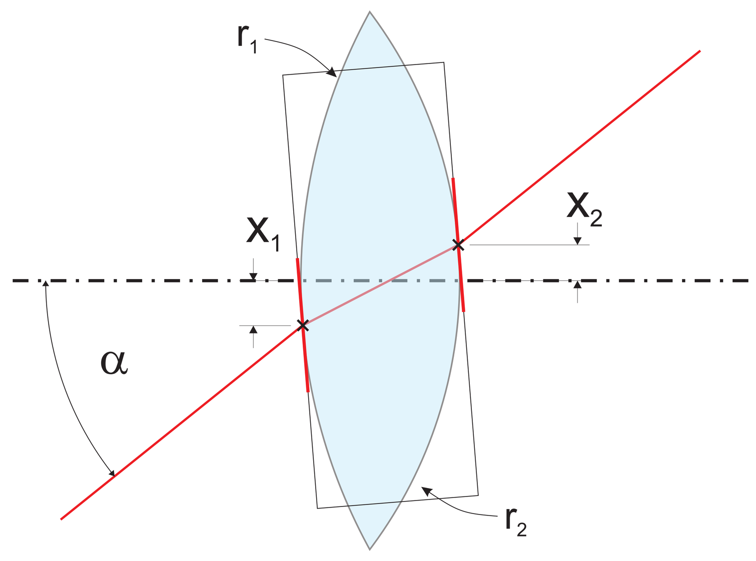

Fig. 4 *The "wrong" optical axis is given by that ray, which does not change its direction. It is refracted by parallel fractions of the two surfaces that have the same optical effect as a tilted planar glass.(The offset of the ray can be neglected).*

The **resulting error** x_1 of the axis-location and the **observation angle** α are connected by this equation:

$$\alpha = \left(\frac{n-1}{r_1} + \frac{n}{d}\left(1 - \frac{r_2}{r_1}\right)\right) x_1$$

d is the center thickness and *n* is the refractive index of the glass. The location errors of the two sides are connected by the simple equation $x_1 r_2 = x_2 r_1$.
For the example above (Fig. 2) the equation leads to an error x_1 of 1.9 mm for a tilt of 10° which **corresponds very well to the observation**.

For applications in the eyeglass industry, the typical tolerance for the location of the optical axis is ±1 mm. Therefore, the **required accuracy** for this measurement is about **±0.1 mm**.

The above considerations show that even for the worst case of a weak lens of 1 D (Fig. 2), this accuracy can be achieved if the **lens orientation** inside the sensor is controlled within a range of **±0.5°**. This is feasible by using appropriate mounting. Thus, this measuring technique is suited for practical applications.

[1] M.C. Knauer, J. Kaminski, G. Häusler: "Phase Measuring Deflectometry: a new approach to measure specular free-form surfaces", Proc. SPIE 5457, pp. 366-376 (2004)
[2] M.C. Knauer, C. Richter, G. Häusler: "Measuring the refractive power with deflectometry in transmission" Proc. 109. DGaO, A24 (2008)

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