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Chromatic aberration theory in modern metrology

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Chromatic confocal sensors

The working principle of chromatic confocal sensors is derived from confocal microscopy. A fiber optic tree coupler is used in backward direction to connect a polychromatic LED light source and a spectrometer to a single fiber leading to the measuring head. Light leaving the optical fiber enters a hyperchromatic objective which focuses every wavelength onto another plane (Fig. 1). Only the wavelength focused onto the object surface is reflected into the optical fiber which acts as a pinhole. All other wavelengths are defocused and only a small percentage of their intensity is coupled back into the fiber. Using the spectrometer one is able to calculate the object distance by measuring the wavelength of maximal intensity.

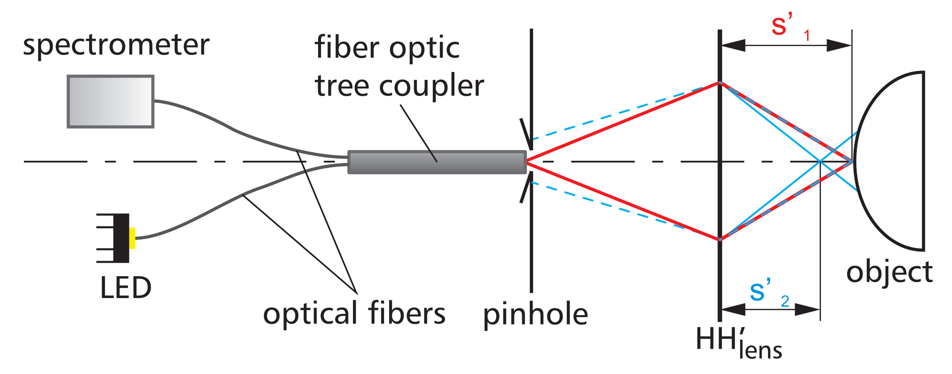

Fig. 1. Functional principle of chromatic confocal sensors

Hyperchromatic optical systems

While typical optical systems are corrected for chromatic aberration, hyperchromatic objectives are designed for large longitudinal chromatic aberration. With n_i being the refractive index of the lens element i and being its refractive power for the reference wavelength $_0$, we can define the Abbe number as

$$ {}_{i,\ 0} \qquad \frac{n_i(\ {}_0)\quad 1}{n_i(\ {}_1)\quad n_i(\ {}_2)}. \tag{1}$$

The difference in working distance between the two wavelengths $_1$ and $_2$ can be calculated using the equation [1,2]:

$$ s \quad s(\ {}_1) \quad s(\ {}_2) \quad s(\ {}_0)\frac{s'^2_l}{{}^2_l} \ {}^{l}_{i\ 1} \quad {}^2_i \frac{{}_i}{{}_{i,\ 0}}. \tag{2}$$

The influence of each element is determined by the paraxial height ratio of the marginal ray $_i \quad h_i / h_1$.

Measurement of tilted surfaces

When measuring tilted surfaces one has to consider the influence of the tilt angle on the available intensity at the spectrometer. Assuming a perfectly aligned optical system without aberrations, the completely reflected intensity is coupled back into the fiber for the tilt angle =0. Due to the law of reflection the image space numerical aperture of the optical system has to be larger than sin(2) to make sure that enough intensity reaches the spectrometer (Fig. 2).

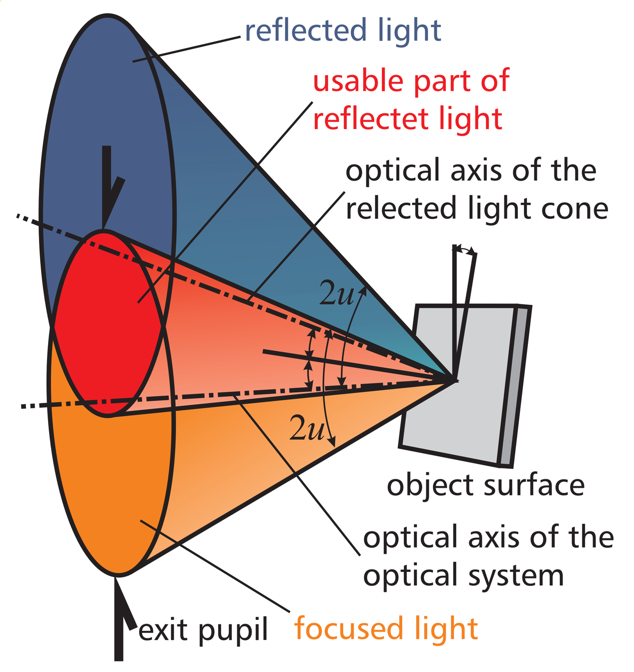

Fig. 2. Only the part of the reflected intensity overlapping with the exit pupil (marked red) can produce a signal, while the remaining amount shown in blue is blocked by the stop of the optical system.

Design procedure

1) Analytical calculations are based on (2) to determine the minimum number of lenses. The result is influenced by the available spectral band, the required numerical aperture, and the intended longitudinal aberration.

2) LensView™ is used to search for appropriate starting systems with the necessary number of lenses, the required numerical aperture, and a small field angle.

3) The optical glasses are changed step-by-step to achieve the hyperchromatic effect: In order to get a high longitudinal aberration, the glasses of the positive lenses have to be substituted by glasses with small Abbe Number while the negative lenses have be made out of low dispersive materials. After each change of an optical glass a monochromatic optimization is performed.

4) Optimization process: The systems longitudinal chromatic aberration should be about the value calculated with (2). In ZEMAX™ the main optimization can be performed defining at least 3, better 5, different wavelengths in the multi-configurations editor and making the image distance for all but one wavelengths variable. At the same time the longitudinal chromatic aberration can be influenced by defining the AXCL value in the merit function editor.

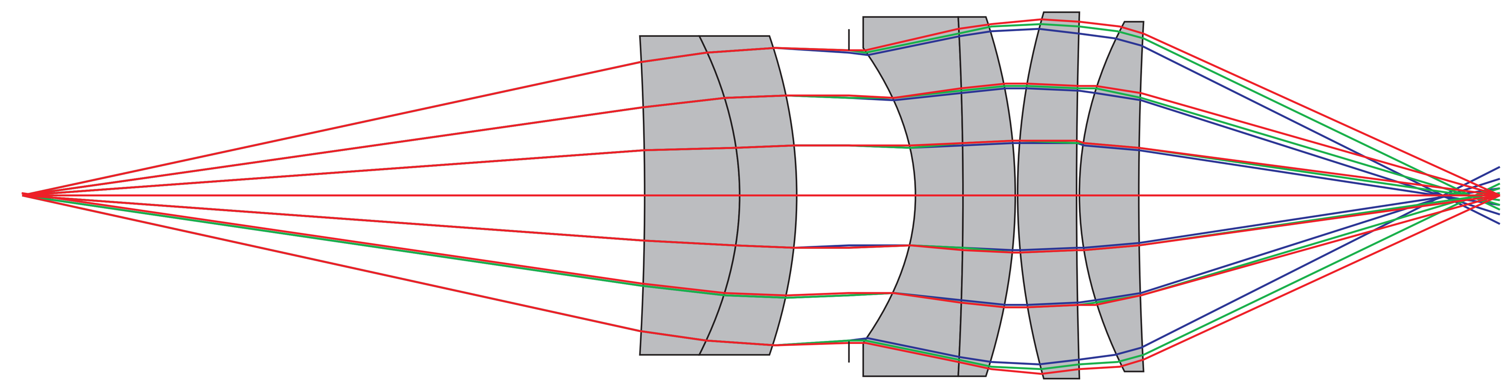

Fig. 3. Preliminary stage of a chromatic confocal objective lens

Results

Using the described design procedure, we were able to design a chromatic confocal objective lens (Fig. 3) capable of measuring at large working distances and showing relatively large tilt tolerances. The system has been designed for usage of a spectral bandwidth from 430nm to 630nm.

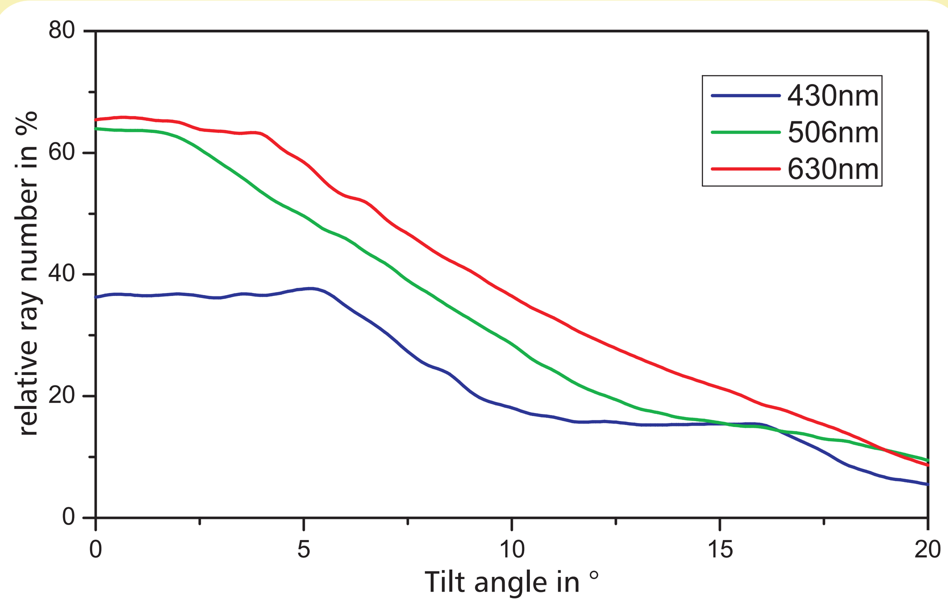

Fig. 4. Influence of the tilt angle on the number of rays reflected onto the core of the optical fibre.

In order to determine the intensity coupled back into the fiber under consideration of aberrations, a Monte Carlo tolerance analysis with 200 runs has been performed for the final design. The 10th worst system has been converted to a non-sequential ZEMAX-model, assuming that 95% of the manufactured systems will show a better performance.

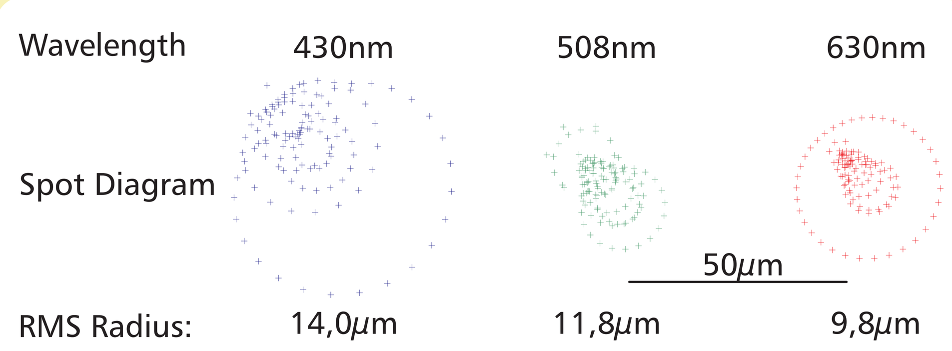

Fig. 5. Monochromatic spot diagrams of the Monte Carlo toleranced system. For each wavelength spots are calculated on the best image plane.

The spot diagrams in Fig. 5 show that spherical aberration could not be corrected for all wavelengths. The reflected intensity coupled back into the fiber is analysed in two different figures: While influence of the tilt angle is shown in Fig. 4, the spectral response of the system is presented in Fig. 6.

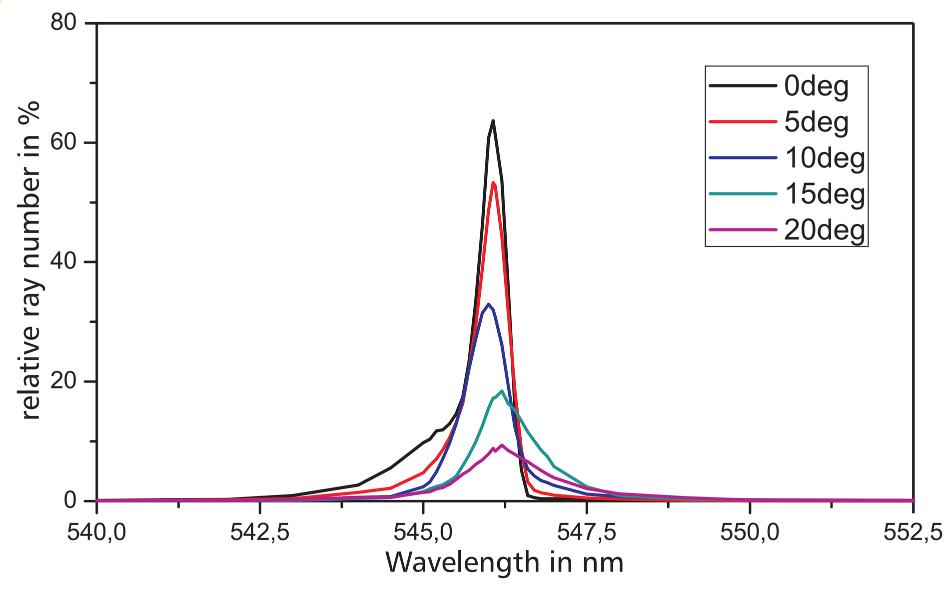

Fig. 6. Influence of the wavelength on the number of rays reflected onto the core of the optical fibre with mirror position optimized for =546nm.

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