

Superapochromat: Design, Glass Selection, and Tolerance Analysis Using a 100x Microscope Objective as an Example

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Designing objectives for a broad wavelength range the spectral behavior, especially the partial dispersion, of the various glasses plays an important role. Taken this into account a diffraction limited high-aperture microscope objective with 100x magnification that shows a chromatic focal shift less than 75 nm over a wavelength range from 400 nm to 850 nm can be realized.

1 Introduction

In optical metrology, particularly in the semiconductor industry, multispectral analysis methods have recently been used. The aim is to acquire measurement data across a wide wavelength range as fast as possible, without the necessity to refocus for individual wavelength ranges. In conjunction with high spatial resolution, this requires large-aperture microscope objectives with a very low chromatic focal shift (CFS), covering a spectral range that extends well beyond the typical range of apochromats, which is about 436 nm to 656 nm. Objectives corrected for a significantly wider spectral range are often referred to as superapochromats.

2 Superachromat

The term superachromat was first introduced by Herzberger in the 1960s (see [1] for example). To figure out how an superachromat will works, we start with the design of a apochromat with three thin lenses. Following the explanation in textbooks like [2] the following three conditions are found:

$$\varphi = \sum_i \varphi_i \quad \sum_i \frac{\varphi_i}{\nu_i} = 0$$

$$\sum_i \frac{\varphi_i}{\nu_i} P_{gF}(i) = 0 \quad \text{with } P_{gF} = \frac{n_g - n_F}{n_F - n_C}$$

The apochromat shows three zero-crossings for the chromatic focal shift. A superapochromat requires a fourth zero-crossing. To achieve this, a fourth relationship is added to the above system of equations.

$$\sum_i \frac{\varphi_i}{\nu_i} P_{Fd}(i) = 0 \quad \text{with } P_{Fd} = \frac{n_g - n_d}{n_F - n_C}$$

With this now four conditions, a system of equations can be formulated that allows to determine the individual lens powers based on the choice of glass materials. But how to choose the glasses?

3 Glass Selson

If we consider only the chromatic conditions in the above equations for a system of three thin lenses, A, B, and C, the following condition must be satisfied.

$$D = \begin{vmatrix} 1 & 1 & 1 \\ P_{Fd}(A) & P_{Fd}(B) & P_{Fd}(C) \\ P_{gF}(A) & P_{gF}(B) & P_{gF}(C) \end{vmatrix} = 0$$

After solving the determinant and rearranging the terms with respect to $P_{gF}(B)$, we obtain

$$P_{gF}(B) = \frac{P_{gF}(C)P_{Fd}(A) - P_{Fd}(C)P_{gF}(A)}{P_{Fd}(A) - P_{Fd}(C)} + \frac{P_{gF}(A) - P_{gF}(C)}{P_{Fd}(A) - P_{Fd}(C)} \cdot P_{Fd}(B)$$

which describes a straight line in a P_{gF}/P_{Fd} -diagram.

Using the well-known triangle construction, i.e. select three glasses that form a triangle in the P/ν -diagram [2], a combination of N-PK51/K10/SF4 will be found to build a cemented triplet. This lens will show the typical apochromatic character of the color focal shift, but it is not a superapochromat. If K10 is replaced with N-SK2, the partial dispersion of N-PK51/N-SK2/SF4 lies on a straight line in the P_{gF}/P_{Fd} -diagram, which is not valid for N-PK51/K10/SF4, shown in Fig 1.

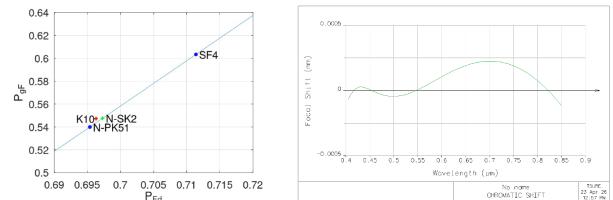


Fig. 1 Left: P_{gF}/P_{Fd} -diagram, Right: Chromatic focal shift of the N-PK51/N-SK2/SF4 triplet, with four zero-pass points

Using the above described method to take the positions of the various glasses within the P_{gF}/P_{Fd} -diagram into account, it is possible to design a

diffraction-limited 100x microscope objective with a chromatic focal shift less than 75 nm over a wavelength range of 400 nm to 900 nm.

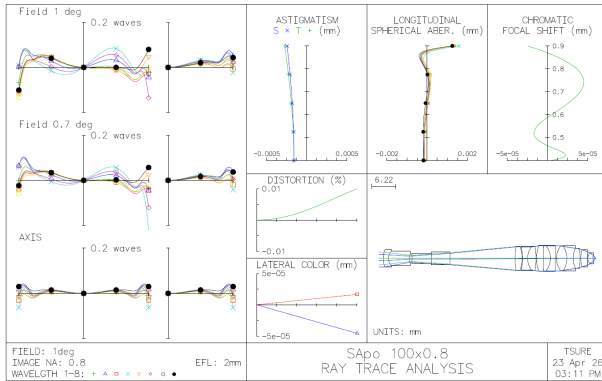


Fig. 2 Overview of the optical performance of a 100x microscope objective. The four zero-pass points of the CFS indicates the superapochromatic behaviour.

4 Glass Tolerances

From the glass manufacturers, one only gets n_d and ν_d as tolerance specifications. But are these two values sufficient to determine the influence of the tolerances for a wider wavelength range? Buchdahl [3] introduced the so-called chromatic coordinate,

$$\omega(\lambda) = \frac{\lambda - \lambda_0}{1 + 2.5(\lambda - \lambda_0)}$$

which can be used to represent the refractive index as a power series $n(\omega) = n_0 + a_1\omega + a_2\omega^2 + a_3\omega^3$. To describe the wavelength-dependent change of the refractive index, it is sufficient to consider only the linear term, $n(\omega) \simeq n_0 + a_1(\omega)$. Then a_1 can be written as

$$a_1 = \frac{n_0 - 1}{\nu(\omega_{bl} - \omega_{red})}$$

If the Abbe number now changes to $\nu' = (1 + \epsilon)\nu$, the following relationship can be formulated for the wavelength-dependent change of the refractive index:

$$\Delta n(\lambda) = \frac{(n_0 - 1)\epsilon\omega(\lambda)}{\nu(1 + \epsilon)(\omega_{rot} - \omega_{bl})}$$

Thus, by specifying the Abbe tolerance, the spectral behavior of the refractive index changes can be analyzed. The accuracy in the visible spectral range is better than 10^{-4} for a wide range of glasses. The following two figures show some examples of the change in the refractive index according to the Buchdahl model compared with data measured by SCHOTT. The behavior of most glass melts can be described quite well with the Buchdahl model, as shown in Fig.(3) for two melts, N-LASF45 and N-LAK22. However, there are now and then melts that show a different behavior, especially outside the usual wavelength range of 435 nm to 654 nm, especially in the short-wavelength range, see Fig(4).

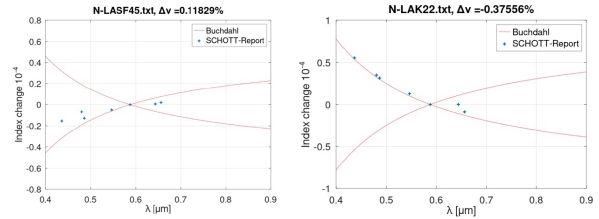


Fig. 3 Representation of the measured refractive index change compared to the Buchdahl model

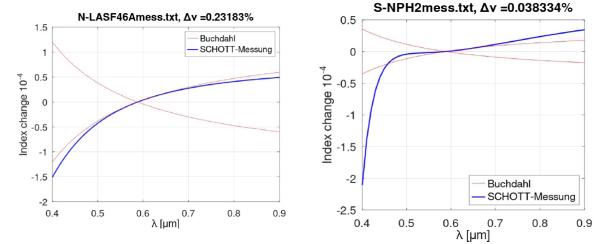


Fig. 4 Representation of the measured refractive index change compared to the Buchdahl model, left N-LASF46A, right S-NPH2

This Buchdahl-Model is the way how the optic design software OSLO do the glass tolerancing. A detailed tolerance analysis shows that even with the use of glasses with the tightest tolerance level of the Abbe number, a chromatic focal shift of $CFS = 485$ nm would occur. By using a air space as a compensator, a chromatic focal shift of $CFS = 120$ nm is to be expected on a statistical average, using a second compensator $CFS = 90$ nm can be achieved.

5 Conclusion

If one takes the model described above into account to choose the glasses, diffraction-limited microscope objectives with a chromatic focal shift < 100 nm in the wavelength range of $\lambda = 400$ nm to 850 nm are feasible. The tolerance analysis shows that typical glass tolerances can be compensated by using two air spaces as compensators. Overall, a complex, iterative adjustment process is necessary. There is a residual risk for the production of such lenses, as one cannot be 100% sure that the glass melts behave as assumed in the tolerance analysis with a glass model according to the Buchdahl-Model.

References

- [1] M. Herzberger and N. R. McClure, "The design of sperachromatic lenses", Appl. Opt **2**, 553-560 (1963).
- [2] R. Kinkslake: *Lens Design Fundamentals*, 2nd Edition, SPIEE Press, (2010).
- [3] H. A. Buchdahl, "Optical Aberration Coefficients", Oxford University Press, (1954).