Glass selection and tolerance issues of a broadband IR solid immersion microscope objective with high numerical aperture

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Abbe number and partial dispersion changes in the IR region from the well know behavior in the visible range. Taken this into account high NA broadband diffraction limited IR objectives can be designed. Tolerance analyses show that it makes sense to reduce the maximum possible numerical aperture a little. This guarantees a stable manufacturing process without loss in image performance.

1 Introduction

Over the last two decades solid immersion objectives have been developed for various applications, offering the opportunity to achieve a higher resolution. For semiconductor applications hemispherical solid immersion lenses (SILs), fabricated in semiconductor materials with a high refractive index (up to n = 3.5 for silicon, for example) are commonly used. With such materials it is possible to design an objective with a numerical aperture of 3.2. An apochromatic color correction is mandatory if a broad spectral range from 1200 nm to 2000 nm is required.

2 Glass selection

In the IR region the change of the refractive index with the wavelength is weaker than in the visible range, but the requested large wavelength range of $\Delta\lambda$ = 800 nm is broader than for typical objectives designed for the visible spectrum. For N-BK7 for example, the refractive index changes about Δn=0.0091 for a wavelength range of $\Delta\lambda$ = 170 nm (480 nm to 650 nm). In the IR region the index change is about Δn=0.0104 for the required wavelength range, which is comparable to the change in the visible region. This example demonstrates that an apochromatic color correction is necessary to realize objectives with a diffraction limited resolution. To do color correction one has to thought first about how to fulfill the achromatism condition. It is known that an achromat can be built by choosing a flint type-glass (low Abbe number) for the negative lens and a crown-type glass (higher Abbe number) for the positive element. To select two glasses to build an achromat is a well-known procedure described in many text books, see [1] for example. In the visible range a typical achromat is built using N-BK7 as the crown glass and N-F2 for the flint type in the negative lens. For the IR range it make sense to define a more generalized Abbe number like

$$\nu_{\lambda_1} = \frac{n_{\lambda_1} - 1}{n_{\lambda_2} - n_{\lambda_3}}; \quad \lambda_2 < \lambda_1 < \lambda_3 \qquad (1)$$

where λ_1 denotes the reference wavelength. Following the Abbe number defined above with λ_1 = 1500 nm, λ_2 = 1200 nm and λ_3 = 1800 nm, we fond for N-BK7 a Abbe number of ν_{λ_1} = 66.49 and for N-F2 ν_{λ_1} = 66.51 which explains why this glass combination will fail to build an IR achromat. Looking to a n-ν diagram according to equation (1) shows that the most glasses which can be used for the negative element have a Abbe number in the range of ν = 60 to 80. To fulfill the achromatism condition the Abbe number for the positive lens must be in the range of 105 to 145. Therefore, CaF_2 with a Abbe number of ν = 148.3 would be a good choice for the positive lens.

To realize an objective with a diffraction limited resolution over a spectral range of $\Delta\lambda = 800$ nm in the IR region it is not sufficient to fulfill the achromatic condition, but also the secondary spectrum must be minimized. It is well-known that the secondary spectrum could only corrected if glasses with anomalous partial dispersion are used.

As for the Abbe number it is useful to define a partial dispersion referred to the infrared wavelengths.

$$P_{\lambda_3,\lambda_1} = \frac{n_{\lambda_3} - n_{\lambda_1}}{n_{\lambda_3} - n_{\lambda_2}} \qquad (2)$$

Following the equation above the partial dispersion can be calculated for the various glasses and plotted against the Abbe number as shown in figure 1.

In the visible range the partial dispersion for normal glasses follows the so-called glass line defined by $P = a + b \cdot \nu$. The secondary spectrum could only corrected using glasses with anomalous partial dispersion, meaning a deviation from the glass line. The deviation could be considered if we rewrite $P = a + b\nu + \Delta P$.

But viewing figure 1, where is the glass line? As long as the partial dispersion are determined in the same manner for all glasses it does not matter how the glass line is defined. To find a glass line which matches to the distribution shown in figure 1 the coefficients a and b have been determined with a linear regression. Because the distri-

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bution looks more or less statistically uncorrelated, this is a bad fit. Or in other words, in the IR region most of the glasses show anomalous partial dispersion. The procedure described in [2] shows how to select two proper glasses to minimize the secondary spectrum. Three suitable glasses are found to build an apochromatic doublet if CaF$_2$ are used for the positive element, S-BAH11, S-LAM61 and L-LAM69. For other glass combinations the secondary spectrum increases more and more.

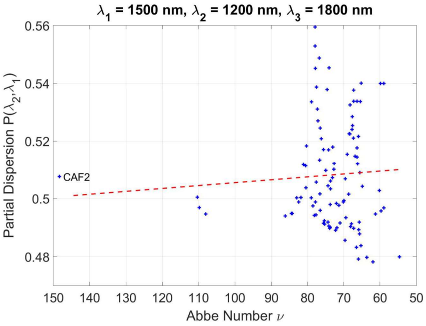

Fig. 1 *Distribution of the partial dispersion of SCHOTT glasses and CaF$_2$, the dashed line refers to the glass line described in the text.*

To avoid this problem it is common to design apochromatic objectives by selecting glasses that form a triangle in the P-ν diagram . Following the procedure described in [2] and using the IR P-ν-diagramm (fig. 1) glass combinations could be found to fulfill the achromatic condition. For example: CaF$_2$, LF5 and N-SF11.

It is obvious that for an objective with a high NA more than three lenses are necessary. Therefore, it seems that there is a wide margin to play around with the glasses to control the chromatic aberrations. Looking on the chromatic aberrations during the optimization process it is not the aim to fulfill the apochromatic condition exactly, but to ensure that the focal shifts of all wavelengths are close to the diffraction limited depth of focus. The above discussed behavior of the glasses in the IR region helps to select proper glasses during the optimization process.

3 Tolerance aspects

The first idea was to design an objective with a numerical aperture as high as possible, limited only by the space needed for the mechanical mount of the front lens. Following the ideas regarding the glass selection described above results to an objective containing 15 lenses plus the solid immersion lens (SIL) resulting to NA = 3.2. Tolerance analyses based on the today's available high end manufacturing technologies [3] have been done, considering air spaces and a shifting element as compensators. First, the tolerance calculation has been done without the SIL. The results show that the Strehl ratio will decrease form SR = 0.99 (design value) to $SR = 0.95$. Due to the landing process the SIL will get some scratches after a certain time and must be replaced. Therefore, the objective must have a mechanical interface enabling the replacement of the SIL by the end-user. The tolerance calculations show that a replaceable SIL will introduce additional wave front errors, resulting that the Strehl ratio drops to $SR = 0.83$.

The maximum resolution defined by the value of the numerical aperture could only achieve if the residual aberrations after the manufacturing process are sufficient low. Having this in mind the objective has been redesigned for a numerical aperture of = 2.9. Taking the same tolerance values the $NA = 2.9$ objective in combination with a replaceable SIL results to a decrease of the Strehl ration to SR = 0.95.

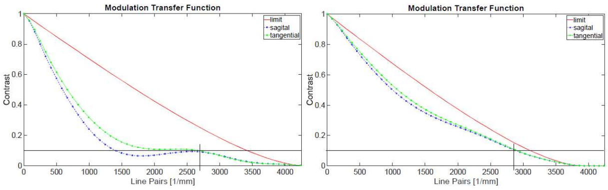

Fig. 2 *MTF curves: Left objective with NA=3.2, SR=0.83, right NA= 2.9, SR=0.95, calculated for λ=1500 nm.*

To demonstrate the advantage of a slightly reduce aperture if the manufacturing tolerances would be considered, figure 2 shows the MTF curves of the two discussed systems. The MTF curves have been calculated based on the diffraction theory describing the optical path differences using a set of 36 Zernike coefficients. If assumed that a 10% contrast would be sufficient to get a meaningful CCD image, figure 2 shows that the SIL objective with $NA = 2.9$ and a Strehl ratio of $SR = 0.95$ can resolve 2870 line pairs per millimeter, as opposed to the SIL objective with $NA = 3.2$ and a Strehl ration of $SR = 0.83$ can only resolve 2650 lp/mm.

4 Conclusion

Taken the change of the glass behavior in the IR region regarding the Abbe number and the partial dispersion into account high NA broadband objectives can be deigned which show a poly chromatic Strehl ratio of SR = 0.99 To guarantee a stable manufacturing process it make sense to reduce the NA a little without any loss in image performance.

References

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