A two lens field corrector for replacing the meniscus lens

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Abstract: A meniscus lens with a too low a Z-value to manufacture is replaced by a lens pair of one plano-convex and one plano-concave lens, reproducing the same corrective results as a meniscus lens, but with smaller manufacturing costs.

1 Introduction

The Z-value, which is defined by formula

$$Z=\frac{1}{2}\left|\frac{r_1}{R_1}-\frac{r_2}{R_2}\right| \quad , \qquad (1.1)$$

where r represents semi-diameter of the lens, R radii of curvature, and the lower index the surface of lens, is often used as a rough estimate of manufacturability of the lens. The limiting values change from manufacturer to manufacturer, but as a general rule of thumb, a $Z < 0.05$ is an indication that the lens is difficult to manufacture to specifications. This is due to difficulties in making sure that the second surface is properly aligned with respect to the first surface, and does not suffer from decentering or wedge errors.

Avoiding the meniscus altogether is difficult, as it is a convenient method of correcting astigmatism (and field curvature as a consequence). Also in optimizing a doublet/triplet systems, optical design sofware often converge on having at least one weak negative meniscus lens, which has led to products too difficult to manufacture to specifications.

Here I will describe a way to replace the meniscus with two lenses that have shape factor of ±1, i.e. one surface is a plane, such as stock components by most manufacturers. The outer surfaces facing away from each other are chosen as the plane surfaces, leaving the curved surfaces facing each other. The two curved surfaces and the air space between is capable of correcting comparable amounts of astigmatism as the meniscus lens while keeping the required lens shapes simple.

2 Field correction examples

To demonstrate the effect of field correction, I use a f=100mm achromatic Fraunhofer doublet as the base system. The doublet is constructed with Schott N-BK7 / N-F2 glass combination often used in low-cost achromats.

An arbitrary full field of view is 2º. The doublet corrects spherical aberration, coma, distortion and corrects color aberration for F and C wavelengths. The effect is demonstrated with ray fan plots.

For the Fraunhofer doublet without field correction, the astigmatism is slightly positive, Petzval curvature is nearly zero, sagittal field curvature is negative and tangential field curvature slightly positive.

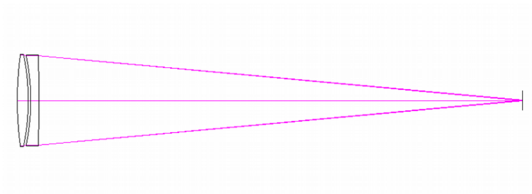

Image 1: Fraunhofer doublet.

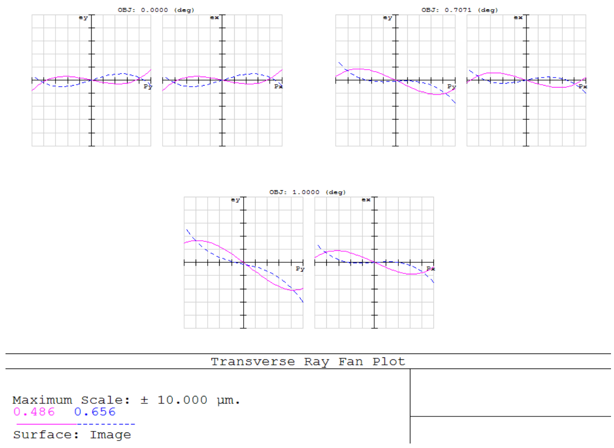

Image 2: Ray fan plots for the Fraunhofer doublet. Upper left: axial field position. Upper right: 0.7x field height. Lower center: field edge.

2.1 A singlet meniscus lens

In order to create a meniscus lens that would fix astigmatic aberrations remaining in the doublet, all variables from the doublet were removed and a plank of N-BK7 was inserted in the back focal area. Setting separation from the doublet, new back focal length and radii as variables, an optimization resulted in low negative power meniscus with greatly flattened field. It has a Z = 0.008, which is too low to be manufactured, but enough to demonstrate the image field correction.

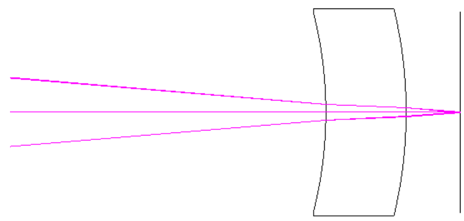

Image 3: A meniscus lens inserted near the focal plane.

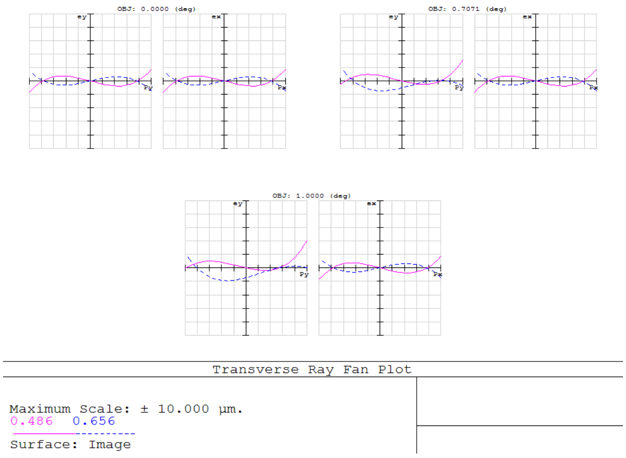

Image 4: Ray fan plots with a meniscus lens.

2.2 Proposed two lens corrector

The singlet meniscus is now replaced with a plano-convex and a plano-concave lens, with curved surfaces facing each other. After optimization of the surface curvatures, their separation and position in the main doublet image space, the following layout resulted. The lenses were replaced with the closest fit catalog lenses (with a total cost of less than EUR 40,00 at the time of writing) and reoptimized. Material for both lenses is Schott N-BK7.

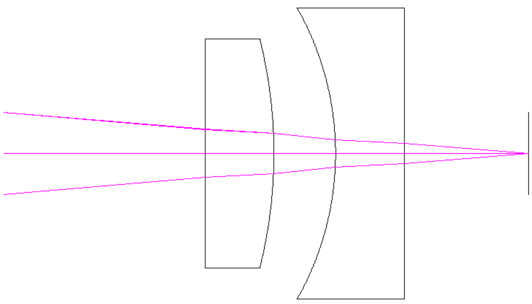

Image 5: A two lens corrector. The shapes correspond to products from multiple manufacturers.

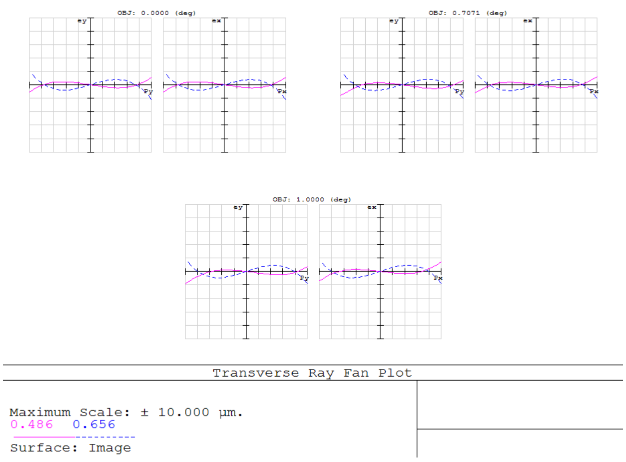

Image 6: Ray fan plots for the two lens corrector.

3 Aberration control

The improvement of the image is based on defocusing[1] the system from the paraxial focus after the field curvatures have been adjusted to balance around a flat image plane.

The main aberrations that affect the image field are astigmatism, Petzval curvature, and sagittal and tangential field curvatures. The meniscus lens effectively removes astigmatism, but this only moves the sagittal, tangential and Petzval field curvatures closer to each other instead of balancing around some flat image plane.

The Petzval curvature represents the fundamental field curvature, but the medial field curvature (located between sagittal and tangential field curvatures) is a better image quality indicator.

$$\Delta W_{20} = -W_{220} H^2 - \frac{1}{2} W_{222} H^2 \quad , \qquad (3.1)$$

where ΔW_{20} is the amount of defocus needed for medial focus, W_{220} is field curvature and W_{222} astigmatism.

Field curvatures (in this case) exhibit order T-M-S-P[1] (or tangential, medial, sagittal and petzval, respectively) when viewed from the direction of the propagation of light. Optical components with positive power create positive (inwardly curved) field curvatures, whereas negative components create negative (outwardly curved) field curvatures.

The two free surfaces in the two lens corrector adjusts the field curvature by overcompensating the field aberration in gradually reducing amounts, until the medial field curvature is close to zero, while keeping the correctors optical power as small as possible.

3.1 Prescriptions and wavefront coefficients

Table 1 below lists the prescriptions for the above systems.

Table 2 lists the wavefront aberrations. It demonstrates that while the meniscus lens performs well in reducing astigmatism, the lens pair not only outperforms it, it also bends the field curvature slightly backwards, around a flat image plane. The lens pair also produces the effect much closer to the original focal length.

Material	Fraunhofer (*f=100mm*) Radius	Thickness	Meniscus (*f=107.6mm*) Radius	Thickness	Lens pair (*f=102.4mm*) Radius	Thickness
N-BK7	56.325	2.202				
	-36.854	0.500				
N-F2	-36.537	1.667				
	-169.670	96.864		95.057		84.312
N-BK7			-7.270	1.500	inf	3.000
			-8.357	1.026	-20.670	2.680
N-BK7					-12.900	3.000
					inf	5.379

Table 1: Prescriptions of the three systems. Note the varying focal length due to insertion of a negative power unit.

Aberrations		Fraunhofer	Meniscus	Two lens
Spherical aberrration	W040	-0.1171	-0.1226	-0.0729
Coma	W131	0.047	-0.0548	0.0549
Astigmatism	W222	0.228	0.0309	0.0136
Tangential field curvature	W220T	0.4191	0.0767	-0.0105
Medial field curvature	W220M	0.3051	0.0613	-0.0173
Sagittal field curvature	W220S	0.1911	0.0459	-0.0242
Petzval field curvature	W220P	0.0771	0.0304	-0.031

Table 2: Wavefront aberrations. The medial field curvature lies between the sagittal and tangential field curvatures, and represents the best image quality.

4 Conclusion

Here I have suggested an alternative method of reproducing the effects of a meniscus lens that eliminates meniscus manufacturing difficulties. The resulting two-lens unit increases optomechanical complexity, but enables the use of simpler lenses that in most cases can be purchased from manufacturer catalogs. The lens pair can correct equivalent or greater amount of astigmatism and field curvatures than a meniscus lens. The low negative power of the single material component introduces low enough new color aberration that it can be ignored.

5 Discussion

Unlike a singlet meniscus lens, the two lenses can be achromatized.

Due to very low optical power, the unit can be inserted anywhere in an existing system.

The mechanical tolerance of the separation of the two lenses is found to be very strict, removing some of the optomechanical benefits of using the unit instead of a single meniscus. But since two problems are rarely equal, exchanging meniscus manufacturing difficulties to supposed machining difficulty may very well be a sound choice. In some cases, a spacer ring fitting perfectly to the contours of the lens surfaces may be designed directly from the CAD file output of the optical design software and 3D printed in quantity and with very low cost.

1 J. E. Greivenkamp, "Field Guide to Geometrical Optics", SPIE, ISBN-13 9780819452948, 2003