Optimal lens arrangement in high numerical aperture objectives.

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Abstract

Demand for High NA objective lenses with diffraction limited image quality is growing. This demand translates in design more complex optical system with many optical components. In order to optimize an optical system lens components structure new design methodology based on functional separation lens group in high numerical aperture (NA) objective was developed. For this purpose all lens component were divided on the three lens group: front group, middle group and output lens group. The front lens group includes front lens (thick meniscus for dry type of objective or thick Plano-convex lens for immersion objective) and several aplanatic shape meniscus lenses. The middle lens group included several cemented lens components (doublets or triplets) and output lens group includes "Double Gauss" lens system or combination of cemented doublet with one or two singlet lenses. The total number of lenses in such types of optical system can reach 15-16 or even more. Design an optimal composition (optical components arrangement) for high numerical aperture objective lens will be discussed. Quantitative related parameter for optimal objective lens components structure will be proposed.

1. Introduction

Most of the advanced high quality dry type objectives have NA greater then 0.9 (usually NA=0.95). For immersion type of objectives NA= 1.3 with object in the water and NA=1.4 with object in the oil. The optical systems with such NA level usually have high order aberration and as result of this effect the image contrast is reduced. The advanced high NA objectives should be very well corrected to avoid resolution loss which is result of low image contrast. For this purpose the front part of objective should reduce NA from 0.95 (1.3) to level 0.1. This is necessary because middle lens group of the objective work most effectively with low NA beams. Usually middle lens group consist of 2-3 (depends on aberration correction level) cemented lens components (doublets or triplets). The output objective lens group for immersion objective usually consists of "Double Gauss" lens group. This is because in immersion objective front lens is plano-convex and as result Petzval sum need to be corrected. The "Double Gauss" lens group used for this purpose. For "Dry" type of objective lens instead "Double Gauss" lens group in output objective part more simple optical components (singlet lens or cemented doublet) with negative optical power usually used.

2. Basic front lens group structure and working condition.

The objective front lens group consist of front lens and one or several aplanatic meniscus. The main advantage of aplanatic meniscus lenses lies in the fact that they do not introduce spherical aberration, coma and satisfied of SIN condition. Figure 1 illustrates an aplanatic meniscus lens. Point A is object, point A' is image of point A. S is distance from first lens surface to object, S' is distance from first lens surface to the point A'.

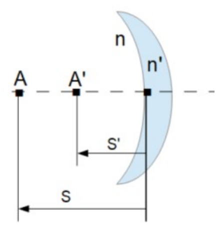

Fig. 1 Aplanatic meniscus lens

Dependence dimensions S and S' from lens parameter shown in formulae (1) and (2)

$$S=R\,(1+\frac{n'}{n});\ (1)$$

$$S'=R\,(1+\frac{n}{n'});\ (2)$$

Where **n** and **n'** is refractive indexes and **R** is lens surface radius. The main advantage of this aplanatic lens is large working distance (WD=R) and large linear magnification (V=n'). The disadvantage of this aplanatic surface is residual astigmatism and chromatic aberration. This aplanatic meniscus lens introduces residual astigmatism (Xs'-Xm') shown in formulae (3)

$$Xs'-Xm'=\frac{VL^2SX^2}{Y(X-S)\propto}S_{III};\ (3)$$

Where V is linear magnification; L is object size; X is chief plane distance to object; α is aperture ray angle; S_{III} is astigmatic Seidel sum [1]. To avoid residual astigmatism aplanatic surface radius optimize for better aberration correction. This mean in real objective lens surface has not precisely aplanatic shape but surface shape should be optimal to minimize all aberration including also astigmatism. Figure 2 illustrates front parts of typical high NA objective lens. This particular group includes front Plano-convex lens, two meniscus and single lens with positive power. The front lens is strong positive power component and usually it's made from high refractive index flint glass. This lens decrease NA at most.

Functions of meniscus lenses consist in further NA reduction and compensation of chromatic aberration which appears in front lens due to use heavy flint glass. If input NA of aperture ray equal 0.9-0.95, output NA need to be decreased to level 0.05-0.15.

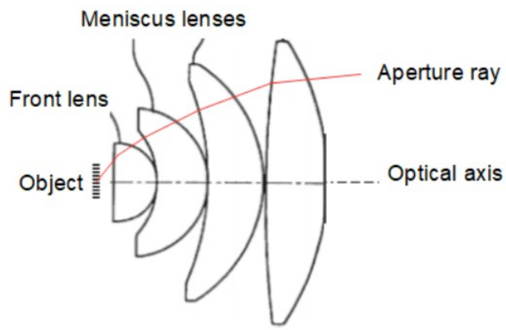

Fig. 2 High NA objective front lens group

For immersion type of objective frontal meniscus lens has flat first surface and as result of this large Petzval curve will introduces. This fact required to use additional lens group in following part of objective.

3. Middle lens group

Middle part of the high NA objective includes several group of cemented doublet and sometimes for better aberration correction cemented triplet (e. g. objective lenses with apochromatic correction). This part of objective works with low NA beams. Figure 3 represent high NA objective optical schematic [2,3].

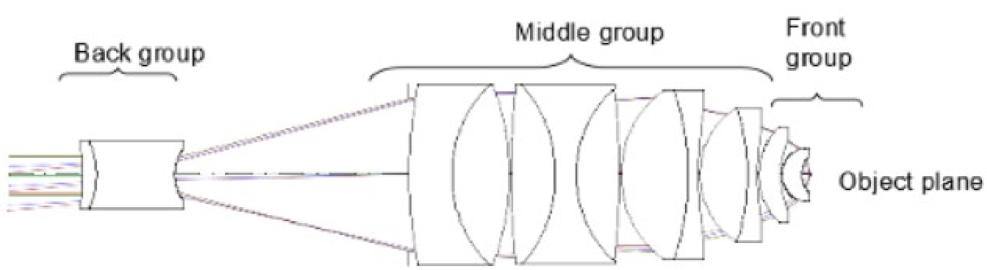

Fig. 3 High NA objectives lens

The middle group of this objective includes three pair of cemented doublet lens and cemented triplet. The triplet lens block use for apochromatic correction. Figure 4 illustrated apochromatic aberration correction in objectives shown on Fig 3.

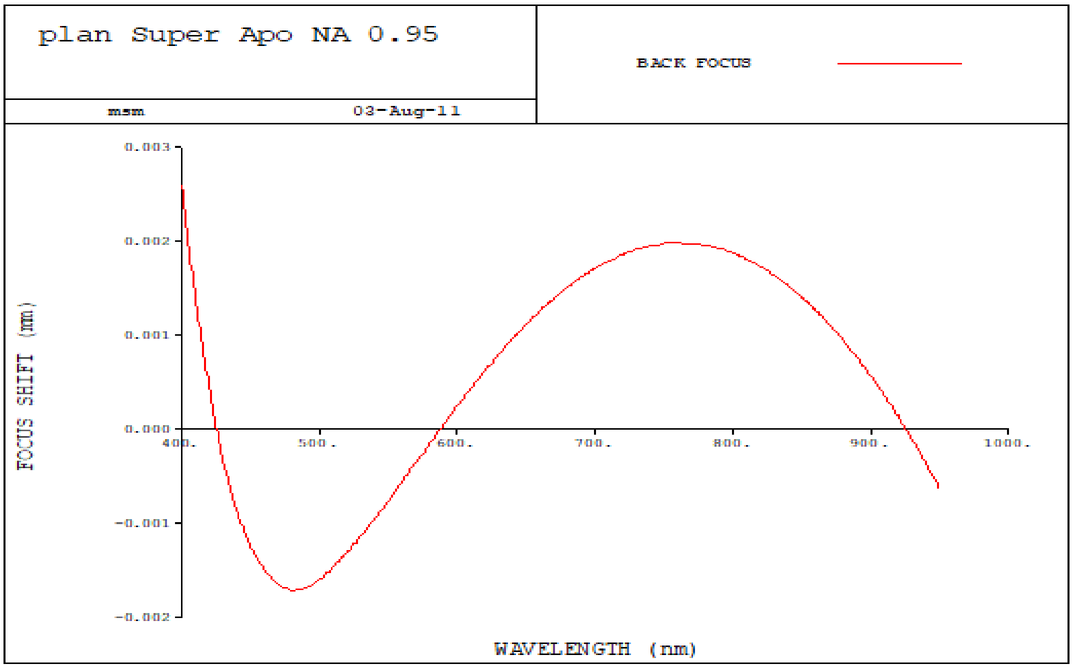

Fig.4 Chromatic aberration curve

To get apochromatic aberration correction for lens elements with positive optical power usually crown glasses are using. This glasses should have high Abbe number (>80) shown in formulae (4). The best candidate is CaF2 or fluorite, but CaF2 has one important disadvantage: large linear expansion coefficient. This fact limited using CaF2 in cemented lens components.

$$v = \frac{nd-1}{nF-nC}; \quad (4)$$

For the negative power lenses in the middle group heavy flint glass usually used. Refraction index for those lenses should be more than 1.7 and Abbe number less than 44. This condition provide better correction for high order spherical and coma aberrations. Also combination of high Abbe number crown glasses with high refractive index flint glasses provide better sphero-chromatic aberration correction. For dry type of high NA objectives middle lens group have more an optical components than any other part of objective. This group works with with smaller NA than front lens group. As it was mentioned before input NA for this group less than 0.1. The input and output rays have smallest incident and refraction angels. The optical components belongs to this group have smallest sensitivity comparable with other objective lenses and in view of this middle lens group optical components usually have weak optical power.

4. Output lens group

Complexity of Output lens group is different for dry and immersion type of high NA objective lenses. The reason for this is different shape of objective front lens. For immersion objective front lens is Plano-convex with flat first surface. This lens introduce large Petzval sum- S_{IV} (curve). This curve need to be corrected in output part of objective lens. For dry type of objective front lens usually is meniscus with positive power and this lens does not put large Petzval sum value, so output objective lens group has to be simple than in immersion type of objective lens. Figure 3 represents dry type objective. The output lens group there is just cemented doublet. The oil immersion type of plan-apochromatic microscope objectives lens shown on Figure 4. NA of this objective < 1.4.

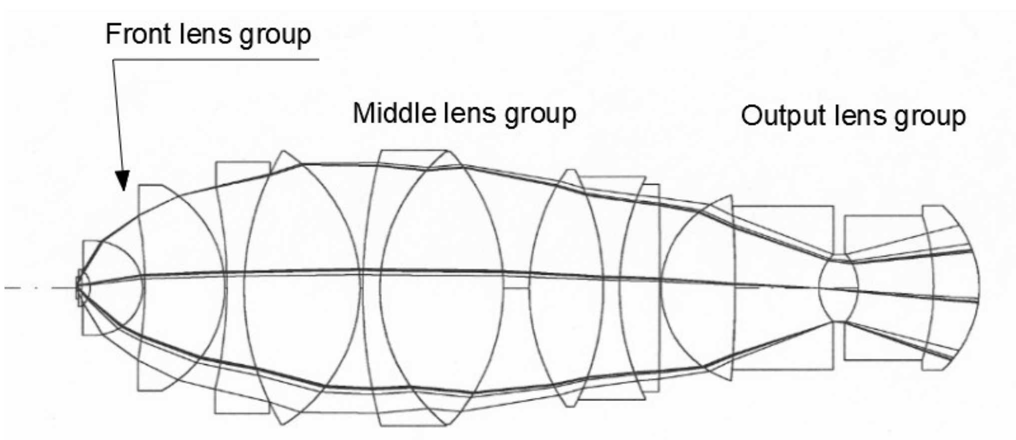

Fig. 4. Microscope objective lens

The output lens group of this objective represents Double Gauss type of optical system. Front parts of Double Gauss lens group decrease height of aperture rays and making size of beam diameter small. The reason for this is decrease residual aberrations from front part of output lens. The final part of Double Gauss lens group usually have weaker optical power than front part and have meniscus shape. That shape is similar to shape of the dry type objective lens front lens group. Both lens group includes thick positive meniscus with positive optical power. Main function of final part of output lens group is provide telecentric (or very weak convergent rays bundle). The main compensator of the Petzval sum (curve) is negative lens in front part of output lens group. Objective lens with Double Gauss lens group call objective lens with plan image field. As it was mentioned before for dry type objective high NA objectives Petzval sum corrected without Double Gauss lens group. On Figure 5 examples flat field astigmatism curves presented. The average line between sagital and meridional astigmatic curves have no tilt with respect of coordinate axis.

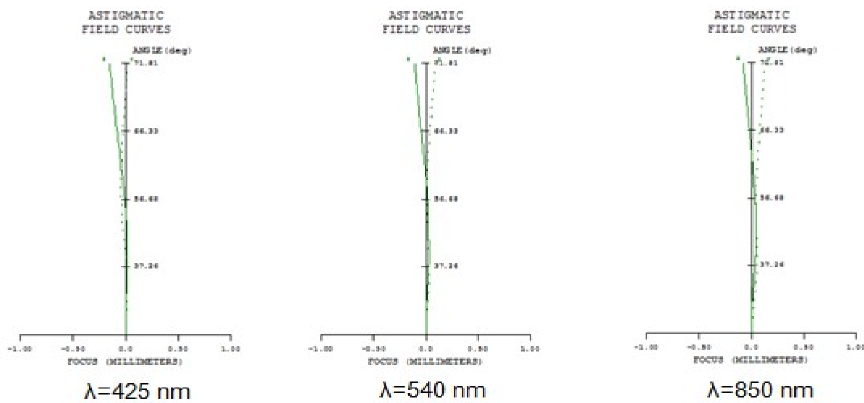

Fig. 5 Flat field objective astigmatism aberration

5. Lens components arrangement evaluation methodology

During design process most important task is to find optimal lens configuration. It is mean find objective arrangement, with minimal number of lenses, low sensitivity, wide manufacturing tolerances and with essential image quality. For lens arrangement evaluation in high NA objectives glass parameters will be used. Most common glass parameters are index of refraction (n) and Abbe number (v). During lens design process when designer works on design form glass choices usually carry out without simultaneously evaluation of refraction index and Abbe number. There is no quantitative evaluation of glass with when both parameters are included. In proposed methodology new glass parameter which includes index of refraction and Abbe number will be introduces. This parameter **K** will call “Glass integrated parameter”. This parameter includes refractive index and Abbe number. Parameter **K** **i**n general describe by formula (5)

$$K=f(n;v); \quad (5)$$

As a first approximation it will be defined as K= **nv.** Parameter K defined lens ability for aberration correction. For example for CaF_2 (fluorite) K=1.434x95.2=136.5. This K number has maximum value for all optical glasses. This particular crystal provide best chromatic aberration correction. Flint glass with high refractive index SF6 (Schott) has K=1.80x25.4=45.8. This K number has small value because Abbe number is small. This glass usually decrease NA due to high value of refractive index and can be used in front lens of objective, also due to small Abbe number it can be use in the middle lens group together with crown glasses having low refraction indexes but high Abbe number. Such type of lens components usually use in apochromatic objectives. Sometimes due to specific requirements (high transmittance in UV region), instead using high refractive index glasses with low Abbe number, high refractive index glasses with medium Abbe number should be used. The main advantage those glasses is better light transmission in UV. For example it is glass N-LASF31A (SCHOTT) . For this glass K=1.883x40.8=76.9. For most optical glasses K parameter is located in interval 37-137. As shown above glass integrated parameter (K) have different values for various lens components. For example in positive optical power lenses using for achromatization K should have large value, but for optical components with negative power K need to be much smaller. Also K value depends of optical system NA. High NA optical system required maximum for positive and minimum for negative power lenses permissible K values. K parameter evaluation for high NA microscope objectives shown in Table 1. The lens data for were taken from published patents. [3,4,5,6,7,8,9,10,11,12}

Objective lens group	Optical component	Glass refractive index	Abbe number	K-parameter
Front group	Front lens	1.6-2.0	25-60	50-96
	Meniscus lenses	1.43-1.5	80-95.6	120-137
	Cemented doublets positive lens	1.43-1.7	70-95.6	119-137
Middle group	Cemented doublets negative lens	1.6-1.8	25-50	40-90
	Cemented triplet positive lens	1.43-1.7	60-95.6	102-137
	Cemented triplet negative lens	1.6-1.8	25-50	40-90
Output group	Cemented doublets positive lens	1.5-1.7	55-82	82-140
	Cemented doublets negative lens	1.6-1.8	23-60	37-108

Table 1 High NA microscope objective lens data

The glass refractive indexes and Abbe numbers were taken from microscope objective lenses embodiment design examples . For each case K-parameter were calculated. The objective lens were divides on three functional groups. For each lens components Min. and Max. values of glass parameters from different design were defined, then K-parameters values were calculated. The last column data with K-parameters give approximate range for each objective lens group. This information can be use for finding optimal objective lens arrangements. Most beneficial K parameter value depends on specification requirements such as NA, objective optical power, magnification, working wavelength range, transmission etc. If objective lens has strong optical power and have volume limitation this mean most objective components should also have short focal length (strong optical power) if they have small air gaps between each other and in this case an optical components should have steep radiuses and high refractive index glasses. Objective lens optical power can be calculated by using formula (6). [13].

$$\varphi = \frac{1}{h1} \sum_{i=1}^{m} hi\varphi i ; \quad (6)$$

Where **φ** is objective lens optical power; **hi** is an aperture ray height on the lens surface; **φi** is lens components optical power. The optical power is reciprocal value of the focal length. In high NA microscope objective air distances between optical components usually small due to volume restriction. In this case formula (6) can be simplified to **φ=Σφ**i.

6. Conclusion

Important issues of high NA objective lens for choosing an optimal objective design configuration are discussed. For high NA objectives an optimal lens components arrangement approach based on more sufficient glass choices proposed. New integrated glass parameter specify new glass characteristic was introduced. Novelty of this K- parameter conclude in that its value simultaneously includes two important glass constants: refraction index and Abbe number. K-parameter allow at the same time incorporate monochromatic and chromatic aberration, which is never done before. Using this parameter in objective deign process will help to find an optimal objective lens arrangement. K-parameter values were calculated for real high NA microscope objective lenses. New design methodology of high NA objectives design process based on choosing glasses for an optical component by calculating most efficient K parameter value was proposed.

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