A quantitative analysis of most effective design configuration for complex optical system.

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Abstract

During design process of complex optical system such as high NA (numerical aperture) microscope objective lenses, camera lens objectives with F number < 2 or zoomable lenses usually several design configurations have been developed. Each complex objective lens consists of several lens components (groups). An optimal lens components configuration allows create most effective optical system design form with minimum number of optical lens elements. Optical design practice shown that most effective optical lens configuration can be found when several different designs form were developed. In this process one or several optical designers need to be involved in this process. The analysis method developed in this article allowed to quantified results for each optical system configuration and choose most optimal (efficient) optical system. This method based on assumption that for optimization of optical system commercially available optical design software has been used. In this case some lens parameters such as lens radiuses, glass thicknesses and lens shapes will be optimized at a high technical level. Advance lens design software also chooses fictious glasses for lens components. Usually, in complex optical system if designer used glasses with refractive index and Abbe number matching fictious glass "proposed" software next cases occurred: design has more lenses than necessary or design form does not achieve essential image quality requirements. Proposed method of optical systems analysis allows to compare different design forms with the same specification and thus find optical system which has least complex configuration or in other words, choose the most effective optical system configuration.

Introduction

One of the difficult tasks during optical design process complex optical system is to find an optimal lens components arrangement with minimum number of optical components, which satisfied an optical specification requirement. An objective lens design process required substantial time period for optical system optimization and usually lens designer can't investigate many alternative design options. In this case to find best possible lens design form is necessary that several designers simultaneously developed different optical system configurations and then best one has been developed for production. There are not clear evaluation criterium to define best solution for particular design form. Proposed method allowed numerically determine various design options. This method takes into account total number of lens components and evaluate effectiveness not only whole optical system but also effectivity of each lens components. Proposed lens components evaluation parameter includes glass refractive index and Abbe number. These glass parameters determine lens aberration corrective capabilities. In high numerical aperture (NA) optical system glasses with high refractive index bended aperture rays at most and as results decreased high order aberration. The optical glasses with high value of Abbe number (ν>65) usually used for chromatic aberration correction. Both glass parameters (n and ν) included in the formula for optical system (components, lens) and defined lens component effectivity i.e., aberration correction level which can be achieved by using this lens. For multiple-lens components and whole optical system formulas for determination effectiveness coefficients are proposed.

High NA objective lens structure

Most high-aperture optical systemsusing in microscopy include three lens groups specifically sets of front and middle lenses and output lenses groups. Each lens group works in different conditions. The front lenses decrease input NA, and correct (depends on design form structure) high order monochromatic or in some cases if aplanatic meniscus lenses include low order spherical and coma aberration and chromatism of position, the middle lens group works with

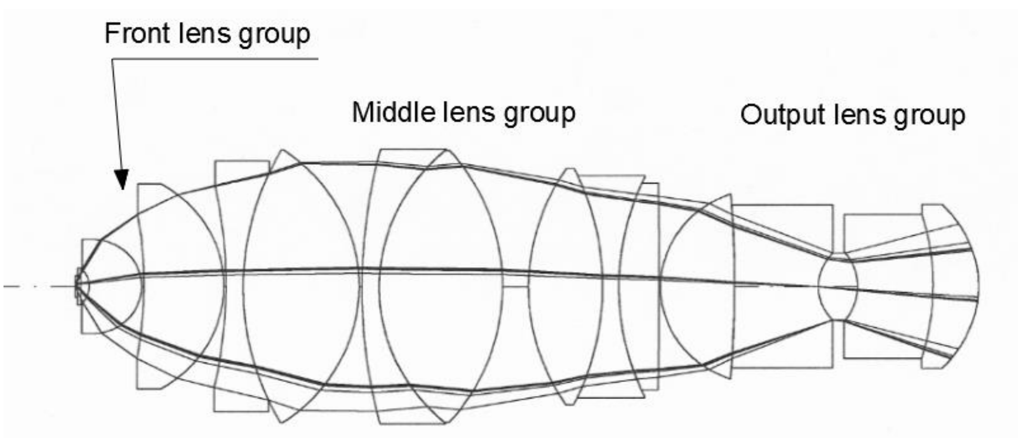

Fig. 1 High NA objective

low NA beams and correct chromatic aberration and output lens group represents relay type optical arrangements and very often correct Petzval sum (flat field optical system). The typical high NA microscope objective lenses (plan-apochromat objective lens) shown on Fig.1. Most common optical parameters for such objectives are: focal length (f'=2-5mm), numerical aperture (NA=1.2-1.4 for immersion system and NA=0.6-0.95 for dry type optical system), linear magnification M=20-100X and working distances WD>0.2mm. These parameters are given in the patent literature. The lens combinations in every lens group can have different number of lens components and can have varying complexity. Objective lens shown on Fig.1 represents most frequent types of lens components: singlets, cemented doublets and triplets. An objective complexity depends on specification requirements. The most complex objectives provide apochromatic aberration correction and create flat field image. To satisfy those complex conditions objectives consists of many lens components (8-17 lenses). It is important part of lens designer works to create an optical system with minimum number of lenses. Also objective with fewer lenses usually has better light transmission. The front lens group includes ball lens for immersion type of objective and 1-3 meniscus lenses, for objective working in air usually front meniscus lenses are using. The middle lens group mostly consists of cemented doublets or triplets it is depends correctable wavelength interval. The output lenses include Double Gauss lens arrangements if objective create plan image field or more simple components such as singlets and doublets.

An Objective lenses evaluation parameter

The glass refractive index **n** and Abbe number **ν** are the most common parameters characterizing optical glasses. That is why their composition is best suited for lens aberration correction abilities. During lens optimization an advance optical design software have availability to calculate optimal lens design parameters such as lens and air thicknesses and surface curvatures. The most important design process task is to choose proper glass for lens components. An optical design software can choose fictious glasses but for complex optical system that choice is not optimal. In this case using glasses with special characteristics is more justifiably and allows to use fewer lenses with high image quality. Proposed lens parameter comprised both glass constants. This parameter (K) defined by formula (1).

$$K=n\nu; \quad (1)$$

Here **n** is glass refractive index and **ν** is Abbe number. The cemented glass components (doublets) which consists of 2 lenses describes by two different K parameters. One parameter is for crown glass with positive optical power and other parameter used for flint glass with negative optical power. The cemented doublet parameter (Kdb) defined by next formula (2)

$$Kdb=\frac{Klp}{Knl}; \quad (2)$$

Where **Kpl** is K parameter for lens with positive power, **Knl** is K parameter for lens with negative power. It should be noted that for doublet lens component containing identical glasses **Kdb= 1**. In this case doublet equivalent a single lens. The cemented triplet lens component will be considered as two doublets optical system, where middle lens belongs to both doublets. For cemented triplet lens component K parameter will be defined by next formulae (3)

$$\text{Ktr}=\sqrt{Kdb_1{}^2 + Kdb_2{}^2} \quad (3)$$

Where Kdb_1 and Kdb_2 are K doublets parameters located inside cemented triplet lens and **Ktr** is triplet effectiveness parameter. For a complex optical system containing several optical components formula for to calculate effectiveness parameter is as follows.

$$\text{Kos}=(\sqrt{\Sigma(\text{Koc})^2/N}; \quad (4)$$

Where **Kos** is K parameter for whole optical system, **Koc** is K parameter for optical component and N is total number of optical lens elements. Special consideration should be given to single lenses in complex optical system structure. K-parameter such lenses must be given a similar view as cemented lens components. In this case Schott glass N-KF9 will take for comparison. The formula (5) describes single lens K parameter in complex optical system.

$$\text{Ks}=\frac{K1}{K2}; \quad (5)$$

Where K1 is K parameter for single lens components and K2 is K parameter for Schott glass N-KF9. Now we have set of parameters capable to determined effectiveness of whole optical system.

High NA optical system effectiveness calculation

High NA microscope objectives were chosen as the most illustrative examples for effectiveness parameter calculation. Design data for those objective lenses were taken from published US patents. [1,2,3,4,5]. Table 1 represents summary data for different objectives effectiveness parameters (Kos). Also, Tab. 1 contain basic optical specification.

Number	Lens data source	NA	Magnification	Focal length,mm	Number of lenses	Kos parameter
1	US 5978147	1.3	100X	2	13	0.3728
2	US 5805346	1	40X	3.93	11	0.4838
3	US 10042152	1.35	100X	1.8	17	0.377
4	US 5898524	1.25	100X	2	10	0.472
5	US 8199408	1.25	40X	5	16	0.2196

Table 1 Objective lenses effectiveness calculation results.

The objective lenses which are represented in Tab. 1 are high NA microscope objectives and includes many different types of lens components. The optical system effectiveness parameters were calculated using formulae (1)-(5). Highest value Kos parameter (optical system effectiveness parameter) as expected, belongs to objective lenses with smaller NA and minimal number of lens components. The other examples shown in the Table are two objective lenses with similar first order optical characteristics #1, #3 and #4. The objective #4 has zoomable working distance and this is why it contains more lenses. To compare the efficiency of different optical schematic the optical system specification must be identical. The most identical objective lenses from the table are #1 and #3. The objective #1 has 13 lens elements versus 10 elements in objective #4. This is one reason why #4 lens system has larger number Kos parameter than lens system #1, another reason related to lens glass characteristics (index of refraction and Abbe number). The main idea why this lens has more effective optical schematic consists in the following this objective has unusual design of objective front lens. This lens includes two cemented parts made from different optical glasses (plane parallel correction plate and ball lens) as it shown on Fig. 2. The correction plate made from glass with relatively high refractive index (n=1.64) which is more preferable for monochromatic aberration correction and ball lens has relatively high Abbe number (v=68), which allow to better correct chromatism. This glass combination in ball lens allows to decrease spherical, coma and chromatic aberration due to the glass for correction plate has refractive index larger than refractive indexes of immersion oil and cover glass [4]. Thus, the input lens unit allows to correct high order aberrations and at the same time corrects chromatic aberrations and as a consequence reduce the number of lenses in the subsequent objective part.

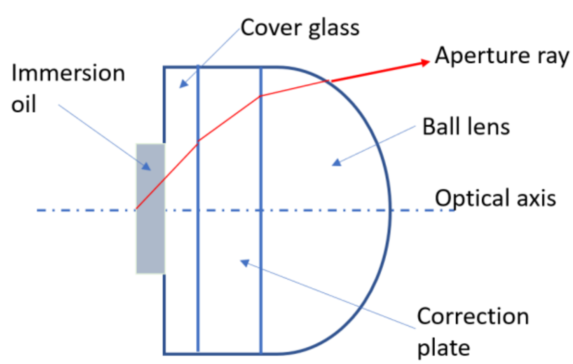

Fig. 2 Front part an objective lens with correction plate

Conclusion

Thus, it is shown that the proposed method of determining the efficiency of complex optical systems allows you to choose the most advantageous option. This method can be also used not only for complex optical system but also for any types of optical elements including singlet lenses, cemented doublets and triplets. An efficency any parts of optical system can be also defined. The proposed parameters for determining efficiency can be used for systems with any number of lens components. These examples of determining the effectivness of the various microobectives confirm this statement. The method will be especially useful for complex expensive systems with high image quality. This method has an additional advantage, which is that with a minimum number of lenses, light transmission increases. The method allows to obtain a numerical value of the efficiency indicator and thus objectively assess the advantages of a particular solution. 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. It should also be noted that this parameter is skewed level of mono and chromatic aberration in an objective lens.

References

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