第 51 卷第 5 期
2022 年 5 月

光 子 学 报
ACTA PHOTONICA SINICA

Vol.51 No.5
May 2022

引用格式：YAN Junhua，HU Zijia，ZHU Deyan，et al. Design of Compact Off-axis Three-mirror Afocal System Based on Freeform Surface[J]. Acta Photonica Sinica，2022，51(5)：0511002
闫钧华，胡子佳，朱德燕，等. 基于自由曲面的紧凑型离轴三反无焦系统设计[J]. 光子学报，2022，51(5)：0511002

基于自由曲面的紧凑型离轴三反无焦系统设计

闫钧华，胡子佳，朱德燕，陈阳，张寅，俞立谦
（南京航空航天大学 空间光电探测与感知工业和信息化部重点实验室，南京 211106）

摘 要：为了满足空间光学系统结构紧凑、尺寸小型化和高分辨率的要求，提出了一种紧凑型离轴三反无焦系统初始结构的设计方法，应用Zernike多项式自由曲面对初始结构进行优化，分别完成了红外波段φ600 mm包络、入瞳口径为350 mm、压缩比为7倍的光阑离轴和视场离轴三反无焦光学系统的设计。设计结果表明两种光学系统各视场波像差均小于0.1 λ(λ=3.7 μm)。公差分析表明光阑离轴三反无焦系统波像差小于0.08 λ的概率达到90%以上，视场离轴三反无焦系统波像差小于0.07 λ的概率达到90%以上，说明了设计的有效性。同时将光阑离轴和视场离轴两种方式的光学系统进行对比，视场离轴三反无焦系统可以使结构更紧凑，波像差更小，分辨率更高。本文提出的无焦系统初始结构的设计方法满足结构紧凑、高分辨率的实际应用需求。

关键词：光学设计；无焦系统；离轴三反；自由曲面；公差分析
中图分类号：O435　　**文献标识码**：A　　**doi**：10.3788/gzxb20225105.0511002

0 引言

随着我国航天技术的不断进步，对空间光学系统的轻量化、小型化、分辨率等方面提出了更高的要求[1]。离轴三反光学系统具有无色差、工作波段宽[2]，无中心遮拦[3]，结构简单[4]等优点，结构紧凑的离轴三反光学系统可以减轻卫星平台承受重量，减小容纳空间[5]，提高空间利用率，越来越多地应用于资源普查、灾害预警、气象观测等领域。自由曲面具有多自由度[6]，强像差校正能力，打破了旋转对称的约束，适合校正离轴系统引起的非旋转对称像差[7]，同时可以减少系统中元件的数量，减小光学系统的体积及重量。将自由曲面应用到离轴三反射光学系统中，有利于压缩系统体积，提高系统分辨率[8]。

2014年，孟庆宇等设计了基于自由曲面的离轴三反光学系统，三镜为XY多项式表示的自由曲面，增加优化的自由度，设计结果显示最大波像差RMS为0.012 6 λ(λ=0.633 μm)，成像质量良好[9]。2019年，孟庆宇等设计出成像质量良好的自由曲面离轴三反系统[10]，系统焦距为1 000 mm，其主镜和三镜均为XY多项式表征的自由曲面，并给出了相应的优化设计策略，波像差为0.04 λ(λ=0.633 μm)。2019年，WU Weichen等设计了工作在长波红外波段，焦距为9.3 mm的基于自由曲面的离轴三反光学系统，图像质量接近衍射极限的[11]。虽然自由曲面已经广泛的应用于离轴反射式聚焦光学系统，但在离轴反射式无焦系统中的应用还较少。无焦系统以平行光入射和出射，焦距为无穷远，可以作为缩束系统，有较高灵活性和拓展性[12]。对大口径入射光束进行缩束，光以小口径出射，可以减小后接光学元件如分色片、透镜组及探测器的尺寸，从而降低成本、节省材料[13]，因此需要对结构紧凑的离轴反射式无焦系统进行深入研究。

离轴反射光学系统的初始结构是光学系统研究热点和难点。目前常用的几种方法如逐点构造迭代法(Construction-Iteration，CI)、多曲面同步法(Simultaneous Multiple Surface，SMS)等主要是针对离轴反射聚焦光学系统[14]，然而对于离轴反射无焦光学系统现有的设计方法基本都是由同轴结构逐步设计为离轴系统，加大了优化

基金项目：国家自然科学基金青年基金(No. 62105145)，南京航空航天大学空间光电探测与感知工业和信息化部重点实验室开放课题(No. NJ2020021-7)，中央高校基本科研业务费(Nos. NJ2020021，NT2020022)，五〇二所空间光电测量与感知实验室开放基金(No. LabSOMP-2020-04)

第一作者：闫钧华(1972—)，女，教授，博士，主要研究方向为空间光电探测、多源信息融合等。Email：yjh9758@126.com

收稿日期：2021-11-09；**录用日期**：2021-12-22

的难度。本文提出一种紧凑型离轴三反无焦系统初始结构的设计方法，构建了离轴三反光学系统模型并进行参数解耦与参数分析。离轴反射式光学系统采用较多的是Zernike多项式自由曲面和*XY*多项式自由曲面，相比于*XY*多项式自由曲面，Zernike多项式自由曲面能与波像差相对应，方便进行优化设计，易于加工、检测和装调[15]。因此，本文采用Zernike多项式自由曲面对两个系统进行优化，降低光学系统波像差同时缩小系统体积。分别完成了视场离轴和光阑离轴两种方式的三反光学系统设计，实现结构紧凑与高分辨率的设计目标，与光阑离轴三反光学系统相比，视场离轴三反光学系统体积更小，分辨率更高。该设计方法对紧凑型空间光学系统设计具有一定参考价值。

1 设计原理

在光学系统设计中，根据系统入瞳口径D、系统尺寸等设计要求，构建了紧凑型离轴三反光学系统模型，对模型中的光学参数进行解耦，分析各光学参数对系统结构的影响，推导出光学系统的初始结构。

1.1 模型构建

考虑要适应空间载荷等应用领域结构紧凑、小型化的要求，同时要确保光学系统具有高分辨率。本文应用在次镜和三镜间有一次成像面的离轴三反光学系统结构[16]。对于红外波段探测，可以在中间像面加入光阑对杂散光进行抑制[17]，而且对于多自由度的自由曲面，可以通过一次成像面进行装调。

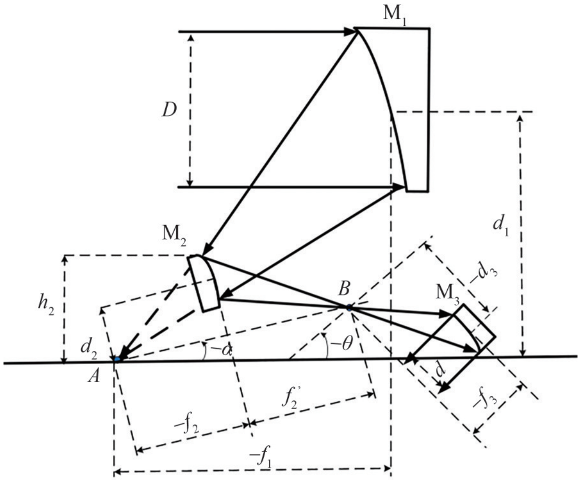


图1 离轴三反无焦光学系统示意图

Fig.1 Layout of off-axis three-mirror afocal optical system

如图1所示，M$_1$、M$_2$和M$_3$分别为主镜、次镜和三镜，次镜和三镜相对于主光轴都倾斜，倾斜角分别为α和θ。D为入瞳口径，d为出瞳口径。d_1，d_2和d_3分别为主镜、次镜和三镜的离轴量。经过初步分析与计算，主镜为抛物面，曲率半径为R_1，抛物面将平行入射的光线汇聚，在点A形成汇聚点。次镜为双曲面，曲率半径为R_2，双曲面在表面两侧形成共轭点，主镜抛物面的焦点和双曲面的虚焦点在点A处重合，光线经过双曲面后成像在实焦点B处。为了使光线平行光出射，同时满足与双曲面的实焦点重合，选择抛物面作为三镜的表面，曲率半径为R_3。离轴三反无焦系统满足

$$N=\frac{D}{d} \tag{1}$$

$$N\cos(\alpha+\theta)=-\frac{d_1}{d_3}=\frac{R_1}{R_3} \tag{2}$$

式中，N为光学系统的缩束比，为了防止次镜M$_2$与主镜M$_1$下边缘发生干涉，实现离轴光线无遮挡并且为装配留有机械结构余量，则有

$$\frac{d_1-\dfrac{D}{2}}{d_1+\dfrac{D}{2}}=0.3 \tag{3}$$

$$\frac{f_2}{f_1}\approx\frac{h_2}{d_1+\dfrac{D}{2}}=0.2 \tag{4}$$

式中，f_1、f_2分为主镜和次镜的焦距，根据图1所示的系统结构，结合抛物面和双曲面的面形特点，则有

$$l=f_1-f_2\cos\alpha \tag{5}$$

$$f_1=\frac{R_1}{2} \tag{6}$$

$$f_2=\frac{e_2R_2}{e_2{}^2-1}-\frac{R_2}{e_2{}^2-1} \tag{7}$$

式(5)中，l为主镜和次镜的间距，式(7)中$-e_2^2$为次镜的圆锥系数。以三镜的光轴作为参考并结合式(1)～(7)，可得出离轴三反系统包络圆的半径R与口径D的关系式为

$$R=\frac{\sqrt{\left[\left(d_1+\frac{D}{2}\right)\cos\theta-d_3+\frac{D}{2N}\right]^2+(f_1-f_2\cos\alpha)^2}}{2} \tag{8}$$

1.2 参数分析

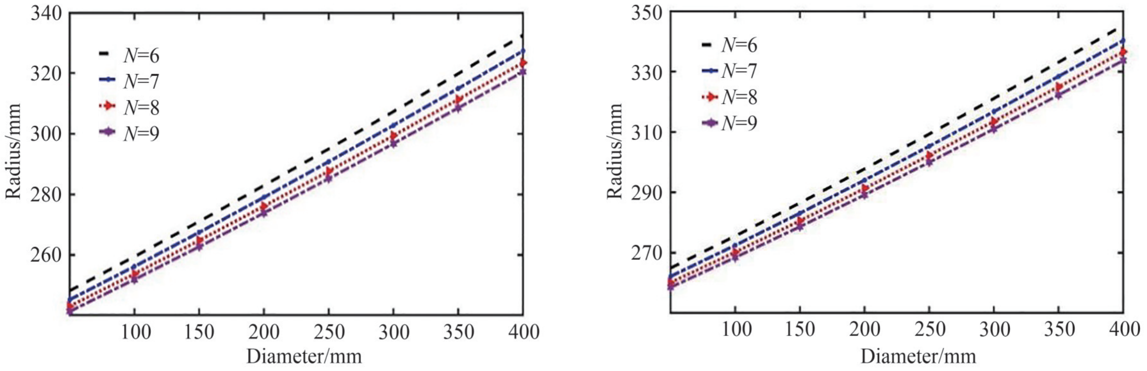
离轴三反光学系统设计指标如表1所示

表1 光学系统设计指标

Table 1 Design parameters of optical system

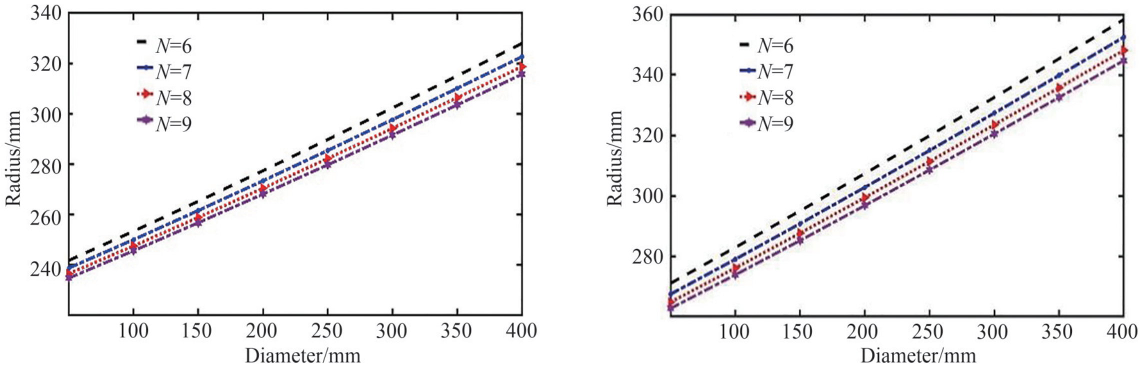
Parameter	Specification
Entrance pupil diameter /mm	350
Wavelength/μm	3.7～4.8 7.7～10.5
Compression ratio	7

根据表1的光学系统设计指标,结合式(1)～(7)参数之间的关系式,可以求得每个参数的变化范围。利用控制变量的方法,得出包络圆半径R与口径D的关系,如图2所示。



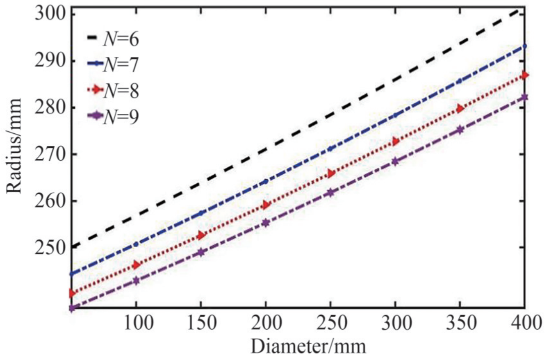
(a) R_1=–900, R_2=–300, d_1=260, α=0°, θ=0°

(b) R_1=–1000, R_2=–300, d_1=260, α=0°, θ=0°



(c) R_1=–900, R_2=–300, d_1=300, α=0°, θ=0°

(d) R_1=–900, R_2=–320, d_1=260, α=0°, θ=0°



(e) R_1=–1000, R_2=–300, d_1=260, α=–15°, θ=50°

图2 入瞳口径D与包络R之间的关系

Fig.2 Diagram of the relationship between entrance pupil diameter D and envelope R

根据其应用特点，该系统的空间物理尺寸约束在φ600 mm范围内，以保证其结构紧凑与小型化。根据图2中光学参数对于光学系统结构尺寸的影响，如主镜和次镜的曲率半径会导致包络圆半径的增长。综合考虑参数的取值，建立离轴三反光学系统的初始结构。

2 基于自由曲面的离轴三反光学系统设计

离轴三反光学系统具有偏心量和倾斜量，引入了非旋转对称的高阶差，若仅用球面或二次曲面，可优化自由度较少，很难平衡离轴反射系统产生的高阶像差。为了很好地校正像差，三个反射镜均采用Zernike多项式表征的自由曲面，即在初始结构中抛物面和双曲面面形的基础上加上高次项系数，完成满足结构紧凑和高分辨率要求的光阑离轴和视场离轴两种方式的三反光学系统的设计。

2.1 光阑离轴三反光学系统设计

光阑离轴三反光学系统主镜、次镜和三镜均无倾斜，α和θ均为0。主镜、次镜和三镜均采用Zernike多项式自由曲面，通过不断优化主镜、次镜和三镜之间的距离和曲率半径来缩小主镜和三镜Y方向上的距离。优化后光学系统的参数如表2所示，Zernike多项式系数如表3所示。

表2 光阑离轴三反光学系统参数

Table 2 Parameters of the aperture off-axis three-mirror optical system

Mirror	Radius/mm	Thickness/mm	Conic	Rotation angle/（°）
Primary Mirror（PM）	−1260	−484.655	−1	0
Secondary Mirror（SM）	−300.145	490.237	−4.501	0
Tertiary Mirror（TM）	−180	−300	−1	0

表3 光阑离轴三反光学系统Zernike多项式系数

Table 3 Zernike polynomial coefficients of the aperture off-axis three-mirror optical system

Item	Coefficient（PM）	Coefficient（SM）	Coefficient（TM）
Z_4	-2.154	0.093	4.036
Z_5	2.241×10^{3}	2.745×10^{-3}	1.829×10^{-4}
Z_8	-3.984×10^{-3}	-3.613×10^{-3}	-1.181×10^{-3}
Z_9	-4.471×10^{-4}	-3.322×10^{-4}	-2.722×10^{-5}
Z_{11}	-1.615×10^{-5}	2.106×10^{-4}	5.745×10^{-5}
Z_{12}	-4.593×10^{-4}	-4.248×10^{-4}	1.876×10^{-4}
Z_{15}	1.033×10^{-4}	3.919×10^{-4}	-1.054×10^{-4}
Z_{16}	-1.876×10^{-5}	1.344×10^{-4}	-1.414×10^{-5}
Z_{17}	5.123×10^{-5}	-1.400×10^{-4}	2.566×10^{-5}
Z_{20}	-8.191×10^{-5}	1.116×10^{-4}	2.684×10^{-5}

基于自由曲面光阑离轴三反光学系统如图3所示，主镜和三镜在Y方向上的尺寸约为550 mm，次镜和三镜在Z方向上约为490 mm，整个系统在φ600 mm的包络圆内。

无焦系统的像质评价与聚焦系统不同，主要采用波像差和斯特列尔比进行分析。(0°，0°)、(−0.318°，−0.318°)、(0.45°，−0.45°)和(0.45°，0.45°)四个视场的波像差如图4所示，最大波像差RMS为0.012 9 λ。四个视场的斯特列尔比如图5所示，在红外波段，光学系统各视场波前差RMS值均优于0.1 λ(λ=3.7 μm)，斯特列尔比均大于0.8，表明光学系统像差得到了良好校正，满足高分辨率的要求。

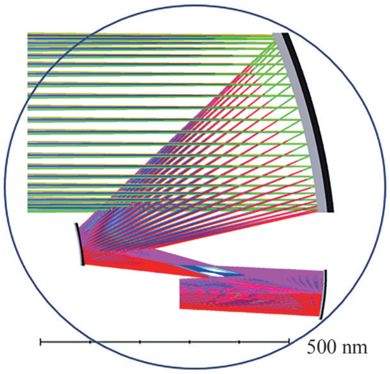
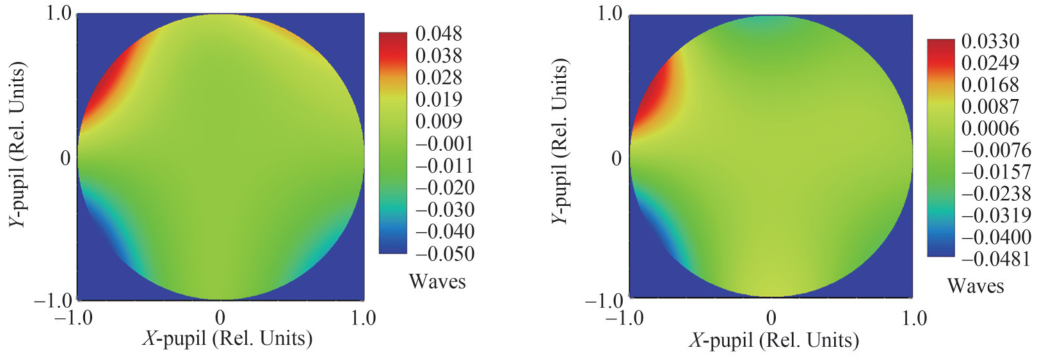


图3 基于自由曲面的光阑离轴三反无焦系统

Fig.3 Aperture off-axis three-mirror afocal system based on freeform surface

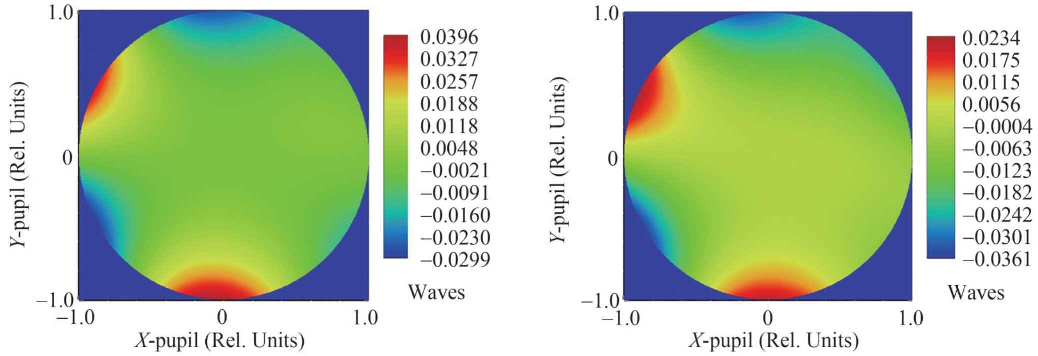


3.7000 μm at 0.0000, 0.0000 (deg)
Peak to valley=0.0977 waves, RMS=0.0129 waves

(a) Field of view (0°, 0°)

3.7000 μm at −0.3180, −0.3180 (deg)
Peak to valley=0.0812 waves, RMS=0.0097 waves

(b) Field of view (−0.318°, −0.318°)



3.7000 μm at 0.4500, −0.4500 (deg)
Peak to valley=0.0695 waves, RMS=0.0101 waves

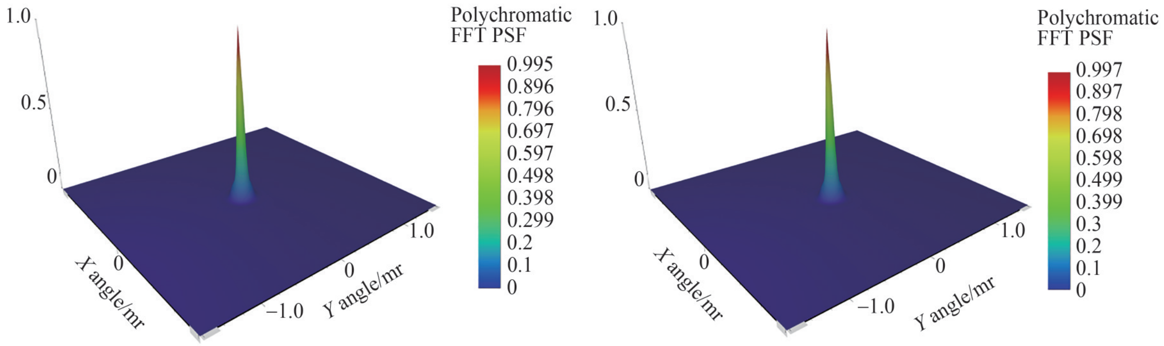
(c) Field of view (0.45°, −0.45°)

3.7000 μm at 0.4500, 0.4500 (deg)
Peak to valley=0.0595, waves, RMS=0.0094 waves

(d) Field of view (0.45°, 0.45°)

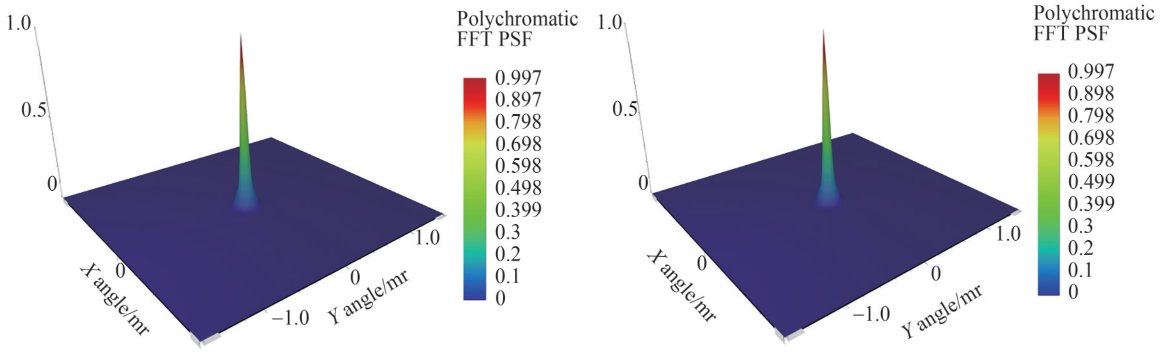
图 4　光阑离轴三反光学系统波像差

Fig.4　Wave aberration of the aperture off-axis three-mirror optical system



(a) Field of view (0°, 0°)

(b) Field of view (−0.318°, −0.318°)



(c) Field of view (0.45°, −0.45°)

(d) Field of view (0.45°, 0.45°)

图 5　光阑离轴三反光学系统斯特列尔比

Fig.5　Strehl Ratio of the aperture off-axis three-mirror optical system

2.2 视场离轴三反光学系统设计

视场离轴三反光学系统与光阑离轴三反光学系统相比，次镜和三镜有了倾斜角度，增加了可优化的自由度，减小了系统的波像差。另外加入倾斜角可以使系统整体尺寸更紧凑。主镜、次镜和三镜均采用Zernike多项式自由曲面，优化后光学系统的参数如表4所示，Zernike多项式系数如表5所示。

表4 视场离轴三反光学系统参数

Table 4 Parameters of the field of view off-axis three-mirror optical system

Mirror	Radius/mm	Thickness/mm	Conic	Rotation angle/(°)
Primary Mirror (PM)	-986.159	-410.063	-1	0
Secondary Mirror (SM)	-268.288	342.656	-4.529	-14.4
Tertiary Mirror (TM)	-374.606	-300	-1	-52.8

表5 视场离轴三反光学系统Zernike多项式系数

Table 5 Zernike polynomial coefficients of the field of view off-axis three-mirror optical system

Item	Coefficient (PM)	Coefficient (SM)	Coefficient (TM)
Z_4	0.391	-0.313	-0.033
Z_5	-0.527	0.280	0.366
Z_8	-0.015	0.015	-0.029
Z_9	-0.269	0.208	-0.189
Z_{11}	0.05	-0.014	6.074×10^{-3}
Z_{12}	0.126	-0.098	-0.036
Z_{15}	-0.152	-0.070	0.052
Z_{16}	5.401×10^{-3}	0.018	7.341×10^{-3}
Z_{17}	0.028	-0.033	0.026
Z_{20}	-0.062	-0.089	-0.016

基于自由曲面视场离轴三反光学系统如图6所示，主镜和三镜在Y方向上的尺寸约为500 mm，次镜和三镜在Z方向上约为350 mm，整个系统在φ600 mm的包络圆内。

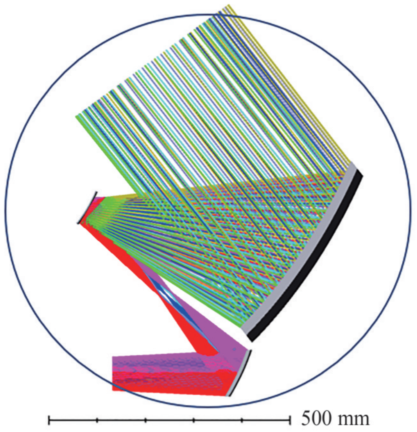
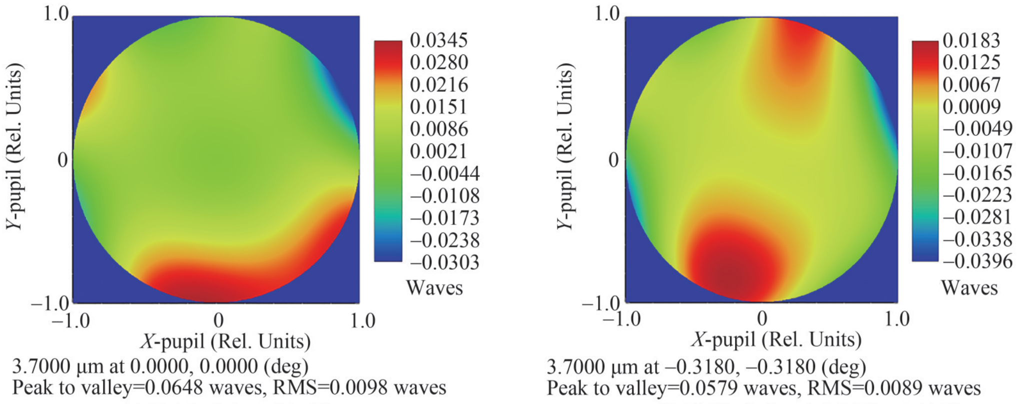


图6 基于自由曲面的视场离轴三反无焦系统

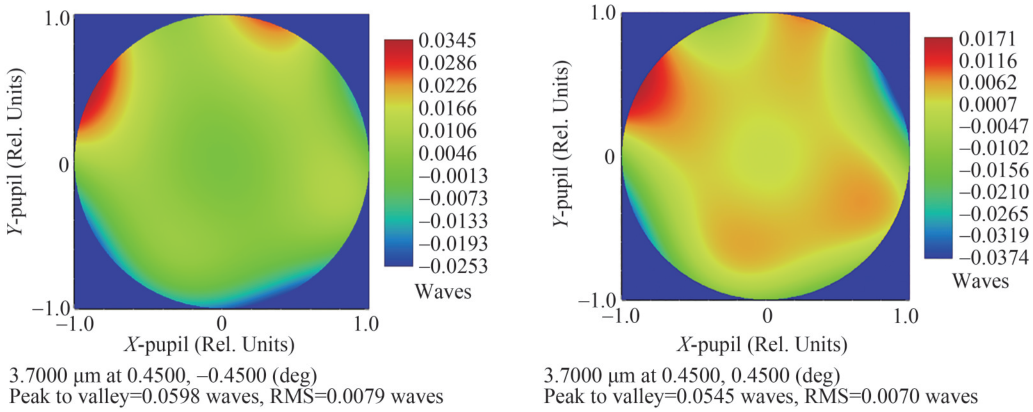
Fig.6 Field of view off-axis three-mirror afocal system based on freeform surface

图7分别为(0°,0°)、(0.318°,0.318°)、(0.45°,−0.45°)和(0.45°,0.45°)四个视场的波像差，在红外波段各视场的波像差均小于0.1λ(λ=3.7 μm)，图8为视场离轴光学系统的斯特列尔比，四个视场的斯特列尔比均大于0.8，能量集中度较高，满足光学系统高分辨率的要求。

由图3、6光阑离轴和视场离轴的两种光学系统结构对比可知，利用视场离轴的方式可以得到更加紧凑的系统结构。由图4、7两种光学系统在(0°,0°)、(−0.318°,−0.318°)、(0.45°,−0.45°)、(0.45°,0.45°)四个视场的波像差对比可知，视场离轴三反光学系统波像差RMS小于光阑离轴三反光学系统得到的波像差。因



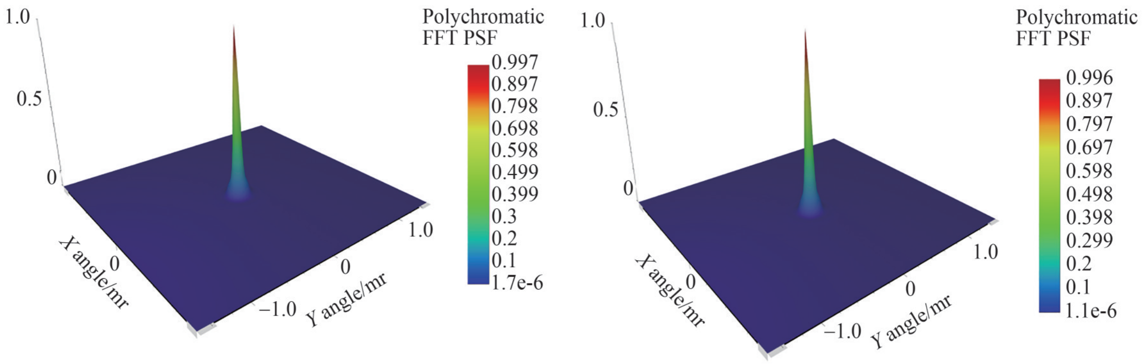
(a) Field of view (0°, 0°) (b) Field of view (−0.318°, −0.318°)



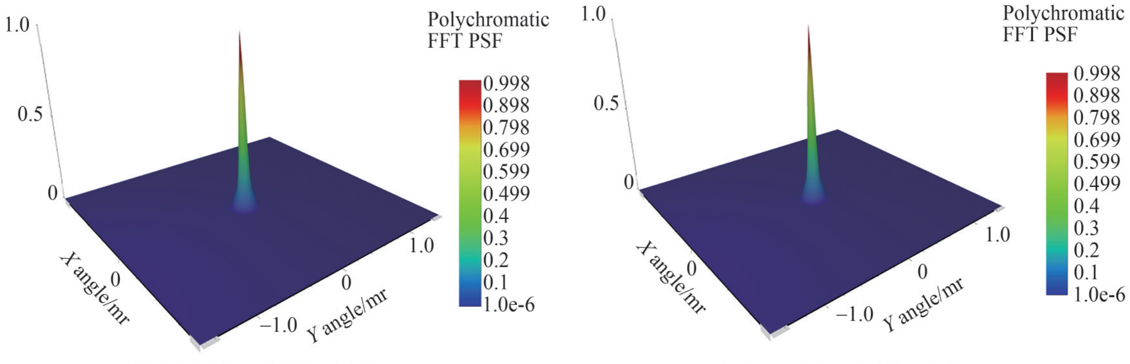
(c) Field of view (0.45°, −0.45°) (d) Field of view (0.45°, 0.45°)

图 7 视场离轴三反光学系统波像差

Fig.7 Wave aberration of the field of view off-axis three-mirror optical system



(a) Field of view (0°, 0°) (b) Field of view (−0.318°, −0.318°)



(c) Field of view (0.45°, −0.45°) (d) Field of view (0.45°, 0.45°)

图 8 视场离轴三反光学系统斯特列尔比

Fig.8 Strehl Ratio of the field of view off-axis three-mirror optical system

此带有倾斜角度的视场离轴三反光学系统像质更好，分辨率更高。

3 公差分析

对于完成设计的光学系统，公差分析是评价系统可行性的重要因素，合理的分配公差既可以保证光学系统的性能，又可以提高光学系统的加工、装调性能，因此公差分析对于一个光学系统很重要[18]。当前，我国自由曲面加工水平取得了很大的发展与进步，自由曲面加工精度通常可达到$\lambda/30$（$\lambda=632.8$ nm），如有特定要求，精度可进一步提高。

结合目前加工水平，对自由曲面面型、曲率半径、间隔、Y偏心和绕X轴倾斜五个参数分配公差值，公差分配如表6所示。

表6 光学系统的公差分配

Table 6 Tolerance distribution of optical system

	Surface type/λ ($\lambda=632.8$ nm)	Radius/mm	Distance/mm	Decenter/mm	Tilt/(°)
Primary Mirror (PM)	1/50	±0.1	±0.1	±0.01	——
Secondary Mirror (SM)	1/50	±0.1	±0.1	±0.01	±0.01
Tertiary Mirror (TM)	1/50	±0.1	——	±0.02	±0.01

3.1 光阑离轴三反光学系统公差分析

对所设计的基于自由曲面的离轴三反光学系统公差分配完成后，为了最大程度模拟实际装调可能遇到的情况，依然采用系统波像差RMS作为最终评价准则，对系统进行100次蒙特卡罗分析，每个样本就是实际加工、装调的光学系统的模拟，仿真具体结果如表7所示。

表7 光阑离轴三反光学系统蒙特卡罗分析结果

Table 7 Monte Carlo analysis results of the aperture off-axis three-mirror optical system

	Value/λ
Monte Carlo	90% :0.085 037 11
	80% :0.074 126 10
	50% :0.040 324 53
	20% :0.018 510 26
	10% :0.012 537 94

根据蒙特卡罗分析得知，90%以上样本波像差小于0.08 λ，满足波像差小于0.1 λ（$\lambda=3.7$ μm）的标准，符合设计要求。

3.2 视场离轴三反光学系统公差分析

结合表6的光学系统公差分配，对系统进行100次蒙特卡罗分析，仿真具体结果如表8所示。

表8 视场离轴三反光学系统蒙特卡罗分析结果

Table 8 Monte Carlo analysis results of the field of view off-axis three-mirror optical system

	Value/λ
Monte Carlo	90%:0.077 603 30
	80%:0.066 189 41
	50%:0.037 371 87
	20%:0.016 235 19
	10%:0.012 912 49

根据蒙特卡罗分析得知，90%以上样本波像差小于0.07 λ，满足波像差小于0.1 λ（$\lambda=3.7$ μm）的标准，符合设计要求。仿真结果表明视场离轴三反光学系统样本的波像差比光阑离轴三反光学系统样本的波像差小。

4 结论

针对空间光学系统领域的实际需求，提出了一种基于自由曲面的离轴三反无焦光学系统初始结构的设计方法，构建了紧凑型离轴三反无焦光学系统模型并结合包络圆半径R和入瞳口径D之间的关系完成了初始结构的建立。应用Zernike表征的自由曲面对初始结构进行优化，分别完成了红外波段φ600 mm的包络圆内、入瞳口径为350 mm、压缩比为7倍的光阑离轴和视场离轴的三反光学系统设计。设计结果表明，两种离轴方式的光学系统各视场波像差均小于0.1 λ(λ=3.7 μm)，满足结构紧凑和高分辨率的要求。公差分析表明光阑离轴三反系统波像差小于0.08 λ的概率达到90%以上，视场离轴三反系统波像差小于0.07 λ的概率达到90%以上，表明了光学系统设计的有效性和合理性。与光阑离轴三反光学系统相比，视场离轴三反光学系统可以使结构更紧凑，波像差更小，验证了设计方法的可行性。本文研究对高分辨率、轻量化的光学系统设计具有参考意义。

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Design of Compact Off-axis Three-mirror Afocal System Based on Freeform Surface

YAN Junhua，HU Zijia，ZHU Deyan，CHEN Yang，ZHANG Yin，YU Liqian
(*Key Laboratory of Space Photoelectric Detection and Perception*，*Ministry of Industry and Information Technology*，
Nanjing University of Aeronautics and Astronautics，*Nanjing* 211106，*China*)

Abstract：With the rapid development of space remote sensing technology，higher requirements are put forward for the compact structure and high resolution of the optical system. Among various optical system structures，compared with refraction and catadioptric optical systems，off-axis three-mirror optical systems have the advantages of high temperature stability，no chromatic aberration and central obstruction，wide wavelength range and compact structure. Off-axis three-mirror optical systems are widely used in space detection，astronomical observation，and other fields. Traditional spherical and aspherical surfaces have some limitations in correcting the non-rotationally symmetric aberrations produced by off-axis reflective systems，which reduces the resolution of the optical system. The freeform surface has multiple degrees of freedom，which can effectively improve the aberration correction capability and reduce the size of the optical system. With the advancement of digital control optical element processing technology，optical elements containing freeform surfaces are gradually applied to various optical systems. Applying freeform surfaces to off-axis reflective optical systems can greatly simplify the structure of the optical system，reduce wave aberration，and improve the resolution of the optical system.

The design of freeform surfaces has become an important direction for the development of high-performance optical systems. In 2018，ZHAO Yuchen et al. designed an off-axis three-mirror optical system with the tertiary mirror as XY polynomial freeform surfaces. The average wave aberration RMS value of the optical system is 0.034 λ，and the image quality of the system is good. In the same year，LI Xuyang et al. designed an off-axis three-mirror optical system in which the primary and the tertiary mirrors are XY polynomial freeform surfaces，the optical system has an average wavefront aberration of 0.07 λ. In 2019，MENG Qingyu et al. designed a freeform off-axis three-mirror system with good imaging quality，the focal length of the system is 1 000 mm. The primary mirror and the tertiary mirror are both XY polynomials freeform surfaces，the wave aberration RMS value of the optical system is 0.04 λ (λ=0.633 μm). In 2019，WU Weichen et al. designed an off-axis three-mirror optical system based on freeform surfaces. The optical system works in the long-wave infrared band with a focal length of 9.3 mm，and the image quality is close to the diffraction limit. In 2020，CAO Chao et al. designed an off-axis three-mirror optical system based on XY polynomial freeform surface，the transfer function is close to the diffraction limit. At present，freeform surfaces have been widely used in focusing optical systems，but their applications in the field of afocal optical systems are relatively few. The afocal system uses parallel light to enter and exit，and the focal length is infinite. It can be used as a beam-reducing system to reduce the size of subsequent optical elements, reduce costs, and save materials. Further exploration and research on off-axis three-mirror afocal optical systems based on freeform surfaces are needed. The initial structure of off-axis reflective optical systems has become a hot and difficult point in optical system research. At present, methods to solve the initial structure such as Simultaneous Multiple Surface (SMS) method, Partial Differential Equation (PDE), and Construction-Iteration (CI) method are all used in off-axis reflective imaging systems. However, the existing design methods for off-axis reflective afocal optical systems are based on the coaxial structure, this design method cannot directly design the initial structure of the off-axis reflective afocal system.

In this paper, a design method of the compact off-axis three-mirror afocal optical system is proposed. Based on parameter requirements the compact off-axis three-mirror afocal optical system model is constructed. The secondary mirror and the tertiary mirror have tilt angles relative to the optical axis, the relationship between the parameters in the model is established and the value ranges of the parameters are got. The influence of optical parameters on the structure of the optical system is analyzed, the initial structure of the off-axis three-mirror optical system is established. At present, Zernike polynomial freeform surfaces and XY polynomial freeform surfaces are widely used in off-axis reflective optical systems. Compared with XY polynomial freeform surface, Zernike polynomial freeform surface can correspond to wave aberration, which is convenient for the optimization design and easy to process, detect, and assemble. In this paper, Zernike polynomial surface is selected as the mirror freeform type to optimize the initial structure. The design of aperture off-axis and field of view off-axis three mirror optical system with the infrared band φ600 mm envelope, entrance pupil diameter of 350mm, and a compression ratio of 7 times are completed. The secondary mirror and the tertiary mirror of the field of view off-axis three-mirror optical system have an inclination angle, while the aperture off-axis three-mirror system has no inclination angle. The design results show that the wave aberrations of the two optical systems are less than 0.1 λ (λ=3.7 μm) in each field of view. For the designed optical system, tolerance analysis is an important step in evaluating the feasibility of the optical system. Tolerance values of the optical system are reasonably allocated and Monte Carlo analysis is performed to simulate the actual processing conditions. Tolerance analysis shows that the probability of wave aberration less than 0.08 λ for the aperture off-axis three-mirror system reaches more than 90%, and the probability of wave aberrations less than 0.07 λ for the field of view off-axis three-mirror system reaches more than 90%, indicating the effectiveness and rationality of the optical system design. The comparison of the two systems shows that the field of view off-axis three-mirror optical system can make the structure more compact and the wave aberration smaller, which verifies the feasibility of the initial structure design method of the optical system proposed in this paper, and meet the practical application requirements of compact structure and high resolution.

Key words: Optical design; Afocal system; Off-axis three-mirror; Freeform surface; Tolerance analysis

OCIS Codes: 110.4850; 220.0220; 220.4830; 080.4035

Foundation item: National Natural Science Foundation of China Youth Fund (No. 62105145), Open Project of Key Laboratory of Space Photoelectric Detection and Perception, Ministry of Industry and Information Technology, Nanjing University of Aeronautics and Astronautics (No. NJ2020021-7), Fundamental Research Funds for the Central Universities (Nos. NJ2020021, NT2020022), Open Fund of 502 Space Photoelectric Measurement and Perception Laboratory (No.LabSOMP-2020-04)