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The design of laser scanning galvanometer system

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Abstract: In this paper, we designed the laser scanning galvanometer system according to our requirements. Based on scanning range of our laser scanning galvanometer system, the design parameters of this system were optimized. During this work, we focused on the design of the *f-θ* field lens. An optical system of patent lens in the optical manual book, which had three glasses structure, was used in our designs. Combining the aberration theory, the aberration corrections and image quality evaluations were finished using Code V optical design software. An optimum *f-θ* field lens was designed, which had focal length of 434 mm, pupil diameter of 30 mm, scanning range of 160 mm × 160 mm, and half field angle of 18°×18°. At the last, we studied the influences of temperature changes on our system.

Key words: Laser, *f*-θ field lens, Aberration, Optical design, Image quality evaluation

1 Introduction

Scanning galvanometer system combing laser system was widely used in marked and rapid prototyping for its advantages of high scan speed, high precision, and low image distortion. Today, with the appearances of high power laser such as fiber laser and disk laser, the scanning galvanometer system has been used in kW system. So it is important to design and manufacture laser scanning galvanometer system with higher quality and higher precision [1].

As shown in Fig. 1, the laser scanning galvanometer system mainly include high quality laser, scanning galvanometer system and high precision control system. When the swing motor get a position signal from the computer, the swing motor will drive the optical galvanometers to rotate certain angle, which is proportional to the drive voltage. The whole system employ close loop feedback control system, including position sensors, error amplifiers, and power amplifiers, position differentiators, and current integrators. The optical galvanometer system, which is the main part in laser scanning galvanometer system, is used to scanning the work surface combining the laser system. The main functions of optical galvanometer system include focusing optic beam, scanning optical beam in 2-D plane, controlling the quality of light spots, and dynamically compensating the error of focus length. Due to the performances of whole system is determined by the optical galvanometer system, we need design high quality and high precision optical galvanometer system.

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2 Parameters

2.1 scan range of the optical galvanometer system

The input beam is reflected by two scanning galvanometers (6 and 7 in Fig.1) derived by swing motor（5in Fig.1） and focused on the work surface by *f-θ* lens (8 in Fig.1). Generally, the maximum rotate angle of scanning galvanometers is 12.5° and the input angle should be less than 45°. The scan ranges in X axis and Y axis should be $2f\cdot\tan q_{x,y}$, where q_x and q_x are the rotate angle in X axis and Y axis, respectively and f is the focus length of *f-θ* field lens. These two angles were set to be 10° and f was set to be 454 mm, according to print scale of 160×160mm^2 in our system[2].

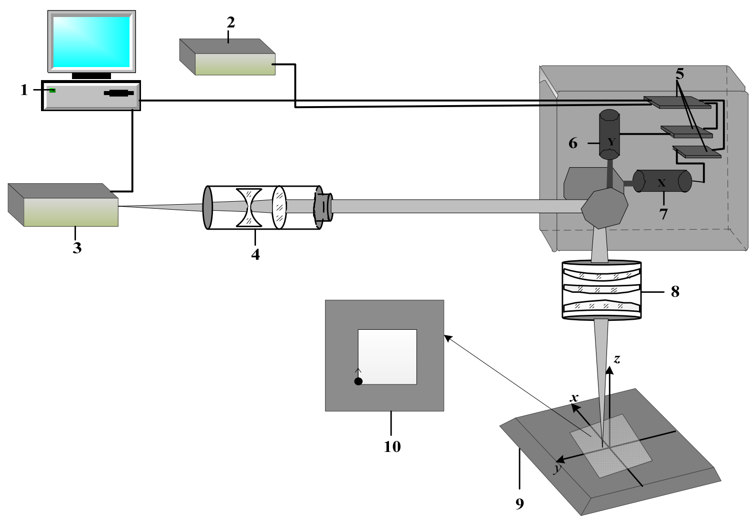

Fig.1 The schematic diagram of laser scanning galvanometer system.
1 is the computer;2 is the power supply;3 is laser;4 is the laser collimating beam amplifier;5 is the controller;6 is the Y axis galvanometer;7 is the X axis galvanometer; 8 is the *f-θ* field lens; 9 is the laser scanning plane; 10 is the ways for periodic scanning laser beam movement.

2.2 size of scanning galvanometers

The width of X galvanometer was determined by the diameter of input laser beam. The beam spot on X galvanometer is ellipse, and the size of spot will change as X galvanometer rotating. When input angle is 45°, X galvanometer should still reflect the whole beam spot. So the width of X galvanometer should be less large than diameter of input laser beam and the length of X galvanometer should be much larger than diameter of input laser beam.

Y galvanometer should be large enough to hold the laser beam reflected by X galvanometer. Generally, Y galvanometer is much larger than X galvanometer, so the scan speed of whole system is limited by Y galvanometer. The laser beam spot on Y galvanometer will be stretched. Considering the error of mirror, the width of Y galvanometer should be equal to length of X galvanometer, which is less large than diameter of input laser beam.

According to geometry theory, the length and width of X, Y galvanometer can be calculated as followed:

for X galvanometer,

$$W_x = \frac{D}{\cos[90° - (a - q_x)]} \tag{1}$$

$$L_x = D \tag{2}$$

for Y galvanometer,

$$W_y = \frac{D}{\cos[90° - (b + q_y)]} \tag{3}$$

$$L_y = D + 2M\tan x \tag{4}$$

where W_x and W_y are width of X galvanometer and Y galvanometer, the L_x and L_y are length of X galvanometer and Y galvanometer, D is the diameter of input laser beam, a is the incident angle when the X galvanometer in initial position, b is the incident angle when the Y galvanometer in initial position，M is distance between X and Y galvanometers, q_x and $q_y$is the maximum scanning angle of X and Y galvanometers respectively[3].

2.3 Distortion

In f-θ field lens system, the height of image (y') can be expressed as f*θ, but in an ideal optical system, (y) is equal to f·tan(θ). With focus length (f) increasing, the difference between f-θ field lens system and ideal optical system become more and more. In order to compensate this difference, a positive distortion is introduced to get linear relationship, which can be express as:

$$\Delta y = y' - y = f \cdot (\theta - \tan(\theta)) \tag{5}$$

Parameter U is defined as:

$$U = \frac{f \cdot \theta - y}{f \cdot \theta} \times 100\% \tag{6}$$

With parameters in our system, U is calculated to be less than 0.9%, so we have to give $f-\theta$ field lens a positive distortion to achieve linear relationship. which is small enough for system[4-5].

2.4 Resolution

Resolution of f-θ field lens can be express as:

$$\sigma = 1.22\lambda / \frac{D}{f'} \tag{7}$$

From the above formula, the resolution σ of f-θ field lens is inverse proportion to D/f' The resolution of f-θ field lens will increase as the diameter of field lens increasing. During the f-θ field lens design process, due to the input laser is high brightness light source, we just need make sure the resolution of f-θ field lens is smaller than image spot. The parameters of f-θ field lens designed in our system are shown in Table 1.

Table1 The design parameters of f-θ field lens

parameters	symbol	Value	units
Focus length	f	454	mm
semiangular	ω	20×13	°
wavelength	λ	405	nm
distortion	/	<0.9%	/
Wave aberration	/	$<\lambda/4$	/
The number of lens	N	≤4	piece
Scan range	S	160×160	mm^2
MTF	/	reach the diffraction limit	lp/mm

3 The design of f-θ field lens

The f-θ field lens, which image height is $f \cdot \theta$, focus the input laser on the whole work surface. The f-θ field lens only change the position of image spot without changing the properties of the image beam. When the input laser beam rotate at fixed angular speed, the scan speed in the work surface is also fixed. The main properties of f-θ field lens include focal scanning range and focal length. In the f-θ field lens system, the more scanning range the better. With the scanning range increasing, the spot size will get bigger and the distortion will get more and more. The scanning range of f-θ field lens and diameter of image spot are proportion to focal length[6].

3.1 Aberration analysis

The f-θ field lens system is belong to big field of angle and relative small aperture optical system. During design process, the aberrations on-axis and off-axis need to be calibrated at same time. The aberrations affecting the size of spot,which is include spherical aberration, coma, astigmatism and field curvature. Because the relative aperture of this system is small, the spherical aberration is small. At the same time, the aberration, field curvature and coma are relative important to the system.

The criteria of calibrating field curvature is

$$\sum \frac{\phi_k}{n_k} = 0 \qquad (8)$$

where n_k is the reflective index of k lens, Φ_k is focal power of k lens. From this formula, the group of separate thin lens with negative and positive focal power can calibrate the field curvature. At the same time, the thick meniscus lens also can calibrate the field curvature. In order to calibrate the astigmatism and coma, we need to make the center of curvature get close to the aperture or turn to the aperture as more as possible. According to our experience, putting the aperture facing the lens at $0.3f$ in front of lens can compensate the astigmatism and coma at same time[7-8].

3.2 System design

The pupil aperture D of our system is 30 mm and actually image range is 160×160 mm^2. The parameters we choose are shown in table 2 and the structure of lens is shown in Fig. 2.

Table2 The initial structure parameters of *f-θ* field lens

Surface #	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Apeture
Object	Sphere	Infinity	Infinity		Refract	
Stop	Sphere	Infinity	207.8070		Refract	15
2	Sphere	795.8977^{V}	121.1745	BSM24_O	Refract	100.5936
3	Sphere	2610.8884^{V}	4.1309^{V}		Refract	121.3168
4	Sphere	483.3214^{V}	172.1228	SK1_SCH	Refract	127.4240
5	Sphere	Infinity	69.2690		Refract	139.8972
6	Sphere	Infinity	52.3253	F15_SCHO	Refract	149.0024
7	Sphere	-874.3875	257.7493^{S}		Refract	152.1483
Image	Sphere	Infinity	0.0000^{V}		Refract	181.4256
			End Of Data			

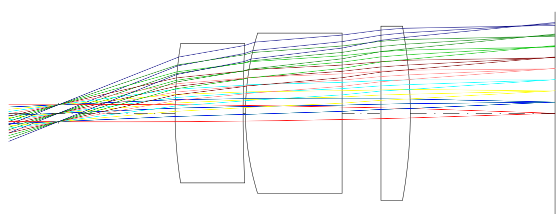

Fig.2 The initial structure of *f-θ* filed lens

The criteria of optimization of *f-θ* filed lens include that focal length is 454 mm, distortion is less than 1.0% and the system length is less than 400 mm. Generally, the system barometric pressure is standard atmospheric pressure and the temperature is 20°. The parameters of *f-θ* filed lens optimized is shown in Table 3 and the structure is shown in Fig. 3.

Table3 The optimized system structure parameters of *f-θ* field lens

Surface #	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-apeture
Object	Sphere	Infinity	Infinity		Refract	
Stop	Sphere	Infinity	48.2323^{V}		Refract	15.0000
2	Sphere	-53.7285^{V}	7.0000^{V}	K9_CHINA	Refract	28.8609
3	Sphere	-59.7949^{V}	24.9789^{V}		Refract	31.6631
4	Sphere	-430.9357^{V}	7.0000^{V}	K9_CHINA	Refract	42.9495
5	Sphere	-129.4242^{V}	375.3091^{V}		Refract	43.3834
6	Sphere	-250.1989^{V}	7.0000^{V}	K9_CHINA	Refract	118.6886
7	Sphere	2150.1829^{V}	60.0000^{S}		Refract	129.2787
Image	Sphere	Infinity	0.0000^{V}		Refract	158.1118
			End Of Data			

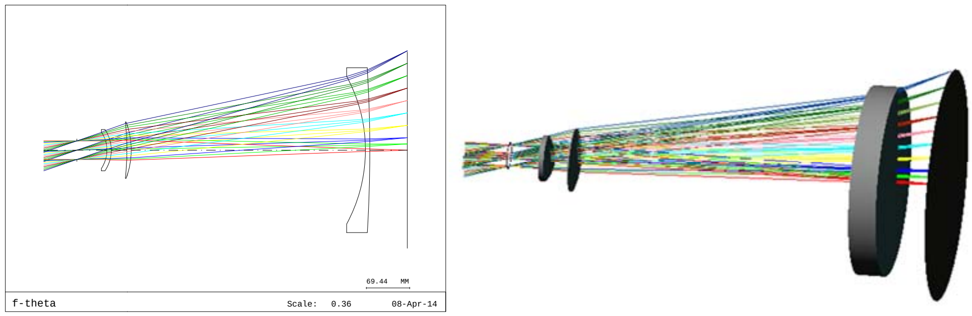

Fig.3 Optimized system structure of *f-θ* filed lens

3.3 The evaluation of image quality

Through optimization, imaging quality of the system was improved obviously. Fig.4 show MTF curve at different fields of optimized *f-θ* filed lens and Fig. 5 show the distortion curve of system. From Fig. 4, we can see the MTF curves at different fields are close to diffraction limit. And from Fig. 5, the distortion of optimized system is less than 1%, which can satisfy our system requirements.

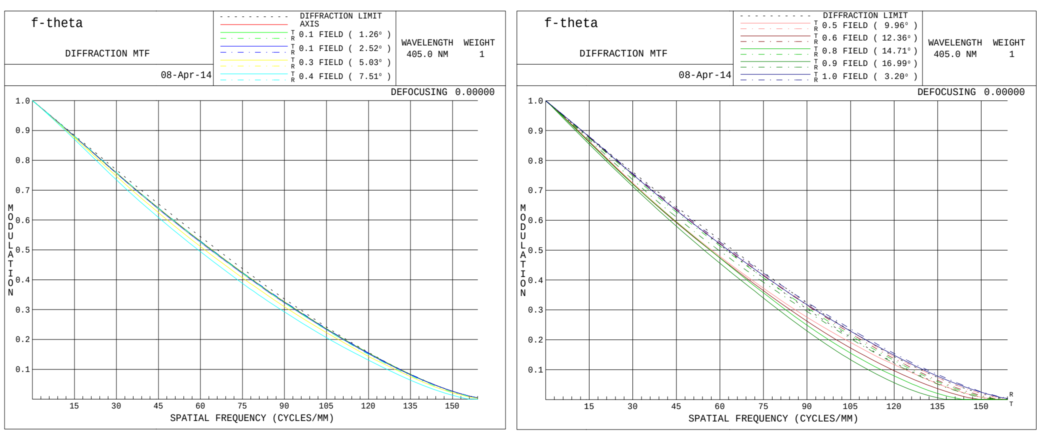

Fig.4 MTF curves of the system

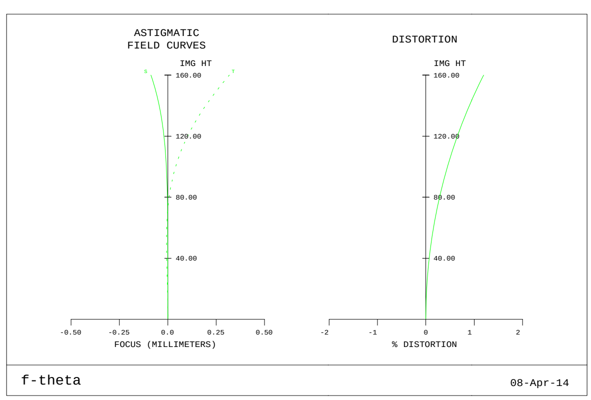

Fig.5 The distortion curve of the system

3.4 Temperature effect analysis

Because the *f-θ* field lens system is used combining high power laser, the lens will accept a lot of heat during work process. The temperature change can cause the changes of lens curvature, lens reflective index, lens thickness and lens mechanical structure. These changes will make focal points move, so it is important to select optical material with high thermal stability.

For most optical materials, their reflective index will increasing with their temperature increasing. The relationship between reflective index and temperature is shown in formula (9).

$$\frac{\mathrm{d}n}{\mathrm{d}t}=\frac{n^2-1}{2n}[D_0\Delta t+D_1\Delta t^2+D_2\Delta t^3+\frac{E_0\Delta t+E_1\Delta t^2}{\lambda^2-\lambda_{rk}^2}] \tag{9}$$

where n is the reflective index, Δt is the temperature change, and Δt is equal to t-20; D_0、D_1、D_2、E_0、E_1 and λ_{rk} are the parametersof the optical glasses. We chose K9 glass as optical materials, which parameters are shown in Table 4 [9].

Table4 Thermal characteristics of the K9 glass

parameters	D_0	D_1	D_2	E_0	E_1	λ_{rk}（μm）
K9	1.86×10^{-6}	1.31×10^{-8}	-1.37×10^{-11}	4.34×10^{-7}	6.27×10^{-10}	0.17

The change of temperature will cause the deformation of mechanical structure, which can change the optical structure, and then make the image quality changed finally. The thermal effect of mechanical materials is related to their linear expansion coefficient (D_0 in formula 9). Generally, the material of being acquiescent using design software is aluminum whose linear expansion coefficient is 236.0×10^{-7} mm/°C. In optical system, the radius of curvature and thickness of the optical material change with temperature changing, due to the optical material will deform when the temperature changed. The linear expansion coefficient of K9 glass is $\alpha_{(-30\text{-}+70℃)}=7.1\times10^{-6}$ mm/°C[10].

n order to evaluate the image qualities in different temperature, we compile the macros under different temperature in the CodeV software. Fig. 6 and Fig.7 show the MTF curves at temperature of 50 °C and -20°C, respectively.

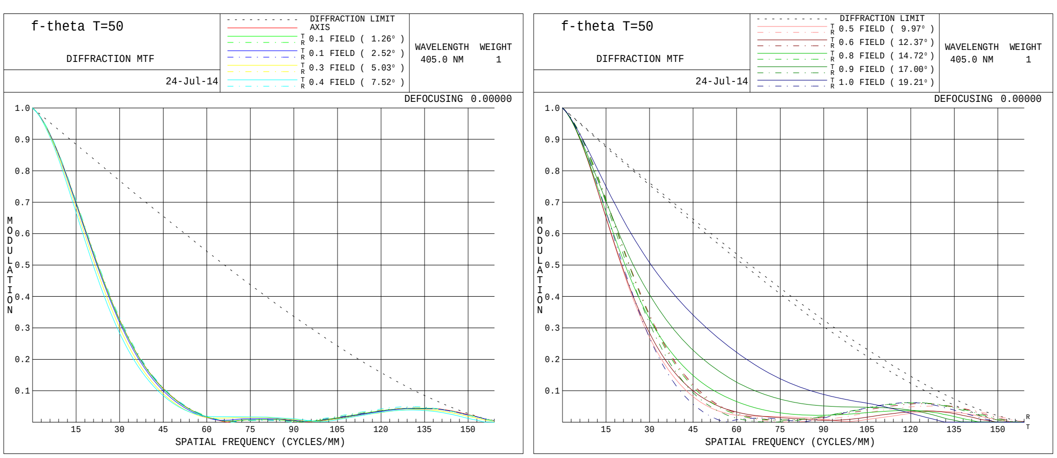

Fig. 6 T=50℃The MTF curve of the system

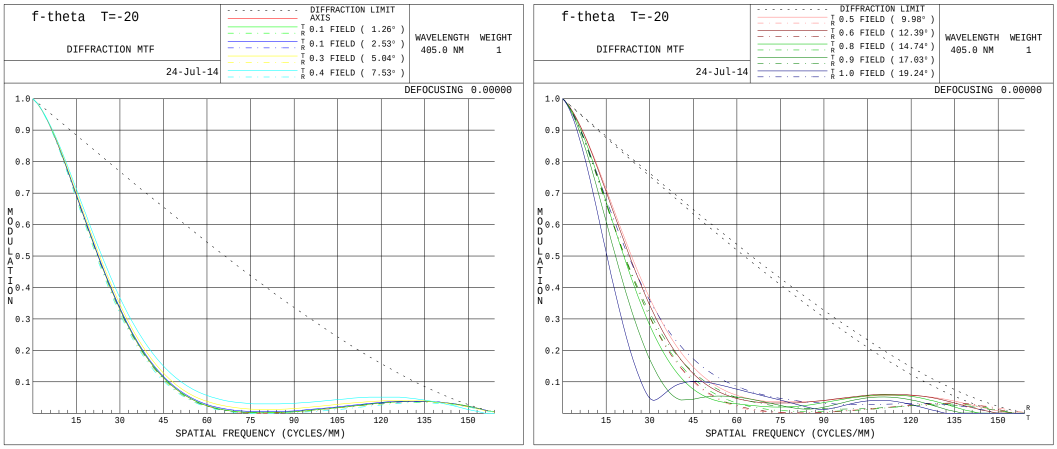

Fig. 7 T=-20℃, The MTF curve of the system

From these two figures, we can see the image quality of optical system changed greatly when the temperature changed. Regardless of high temperature and low temperature environment, the MTF had dropped below 0.1, which seriously affect the scanning precision of the system.

Heat in laser scanning galvanometer system mainly come from motors and drive electronics devices.On one hand, the thermal drift can cause deviation of laser orientation with characteristic numbers of thermal drift of < 30 rad/K and of gain drift of < 50 ppm/K (axis). On the other hand, thermal effect can seriously affect image quality, and then decrease the precision of whole system. A way to eliminate the thermal effect is using laser scanning galvanometer system with water cooling system.

4. Conclusions and Remarks

In this paper, we studied the principle of the laser scanning galvanometer system and calculated the related parameters of the system. Then, based on the design parameters, we using CodeV optical design software to design f-theta field lens which worked at the wavelength around 405 nm. Analysis of aberration showed that the system had excellent chromatic aberration, field curvature and f-θ error characteristics. Especially the emergent light spot reached the diffraction limit and uniform beam, the f-θ system has excellent scanning features.

In order to improve the efficiency of the laser scanning, laser scanning galvanometer system can adopt the way of multiple beam scanning. In this system, one single laser beam will be divided into multiple beam through a beam splitter, and then get through the scanning galvanometer system. These laser beam arranged in array (1 * N) or matrix (M * N). In this way, there will be multiple clear patterns on the work surface. With the scanning galvanometers rotating, every laser beam can produce the same pattern on the work surface, which means the efficiency is N times than one laser beam, without losing the geometry freedom of the whole system.

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