Design of f-theta lens for laser beam scanning

M.R. Giliazov[1,2], A.Kh. Gilmutdinov[1], K.Yu. Nagulin[1]

[1] Department of laser technologies, Kazan National Research Technical University named after A. N. Tupolev – KAI, Kazan, Russia
[2]Laser-engraver LLC, Kazan, Russia

Abstract: The analysis of a two-dimensional scanner lens based on a triple lens system for a laser with a wavelength of 1.06 µm is performed. The first chapter indicates the scope and features of f-theta lenses. In the second chapter the initial conditions for the design of f-theta lens are given. In the third part, the simulation results, showing the parameters and efficiency of the system for 2 types of construction are given. The parameters and efficiency of the system are demonstrated. For each system, the optimal parameters are calculated, and the technical criteria for the possible application are outlined. The geometrical characteristics of the systems are shown, lens materials are described. A variant with a distortion of 0.0035% with a maximum focal spot of 24.9 µm was obtained.
Keywords: Scanning system, f-theta lens, optical design, laser engraving, galvo.

1. INTRODUCTION

Application of a scanner optical head based on two mutually perpendicular galvanometric scanners (galvo) has become common in the industry over the past two decades. This device is widely used in various applications from laser marking to additive SLM-machines [1,2]. Scanning speed is high enough for many applications, and by the ratio (accuracy x area of scanning) / price it remains the head of the list today.

Galvo-scanners allow organizing the positioning of the beam at any point on the working area [3]. Turning mirrors provide an optical path, and switching-on the laser at the right moment ensures ablation or sintering of the material on the surface of the object.

An optical system that sweeps the beam with rotating mirrors is the most popular one. A laser beam that is reflected from the first and then the second mirror may be localized in any spot of a certain rectangle with the sides depending on the corresponding rotation angles of mirror axes (Figure 1) [1-4]. Apart from changing the direction of the laser beam, it has to be focused on the treated surface to the same extent. When examining optical systems of the scanners, let's assume that the incoming laser beam is monochromatic and parallel.

A range of aberrations may occur when focusing the laser beam on a treated surface using a lens. First of all, it is distortion, as the one demonstrated in Figure 1.

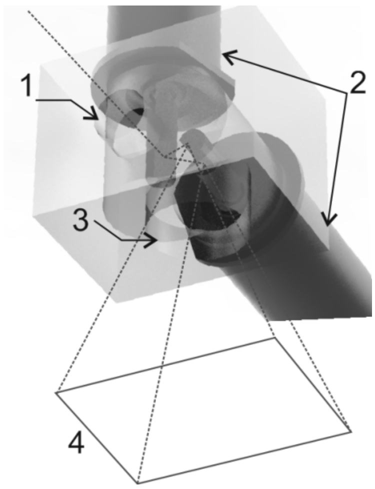


Fig. 1. – A scheme of a flat laser beam sweep on a plane surface. 1 – an inlet opening for the laser beam; 2 – a galvo with a rotating mirror; 3 – an outlet opening for the laser beam; 4 – a workspace of the beam sweep

Second, a standard biconvex lens (Figure 2a) focuses a laser beam on a sphere [4,8,12], and it is inappropriate for the treatment of flat objects.

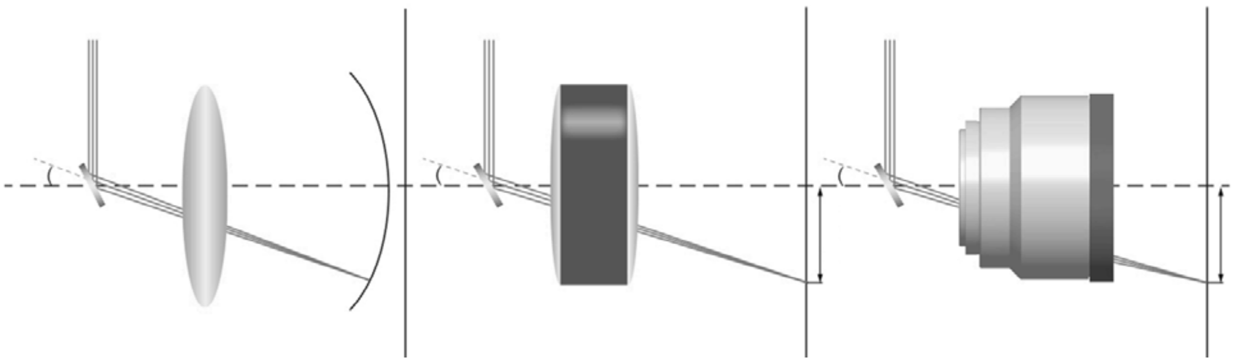


Fig. 2. – Types of lenses, used to focus a laser beam: a standard biconvex lens (a); a system of flat field lenses (b); the f-theta lens (c)

An optical system containing a number of lenses with flat focal surface has been developed to enhance the quality of laser beam focusing on the treated material [14]. The system is known as the flat field scanning lens (Figure 2b), and the object image height may be described using the following equation [5-8]:

$$y = f \times \tan\theta \qquad (1)$$

The optimum scanning system has a lens with a linear relationship between the object image height and the angle of incidence of a laser beam on the lens [5-9,14]:

$$y = f \times \theta \qquad (2)$$

A class of optical lenses, the f-theta lenses, was developed to implement this relationship (Figure 2c). There are two main types of the f-theta lenses: standard non-telecentric lenses [5-9] and telecentric lenses [7,13]. Standard f-theta lenses ensure the linear relationship (2) [10 12]; however, the angle of incidence of the laser beam on the treated surface may vary (Figure 3).

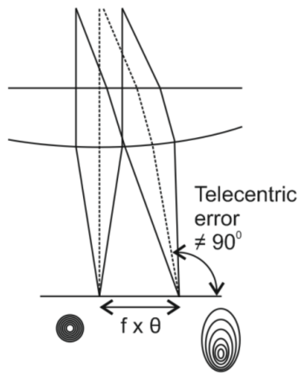


Fig. 3. – Telecentric error of f-theta lenses

As it is seen in Figure 3, when the angle of inclination of the laser beam changes, focusing conditions change in each spot of the treated surface, so the efficiency of surface and in-depth laser treatment may be reduced by tens of percent [13]. Thus, to improve the homogeneity and enhance the quality of focusing, it is necessary to ensure that the axis of the laser beam emerging from the lens is perpendicular to the optical axis of the system in all the focal points. Such an optical system is called telecentric. Telecentric lenses are most often used for micromachining, drilling, cutting and other operations that require the beam to be perpendicular or large power density in the focal point on the complete scanning area.

The aim of the research was to design telecentric systems based on three lenses. Also, the systems, developed in the course of the research, were compared to the similar standard non-telecentric systems.

2. DESIGN IDEA

Initially there was an aim to design a telecentric lens close to real and ready for production. That is why the lenses studied within the scope of the paper are axicentral and spherical.

Computation was performed in Zemax software with a specific target function for designing lenses. The following system parameters were used as optimization operands: distortion, curvature of the wave front, lens curvature radii, lens material, distance between the lenses. Each operand was assigned its weighting factor depending on the desired optimization result.

Thus, for the non-telecentric lenses the minimum diameter of a focal spot in the object plane was selected. To ensure telecentricity, it is the most important to achieve the minimum angle between the beams emerging from the last lens and the optical axis of the system. Simulation was performed for the existing brands of glass; input laser beam was 2 mm in diameter, the working distance was in the range of 160-300 mm, scanning area was around 160 mm, general scan region aperture was 52^0.

3. RESULTS AND DISCUSSION

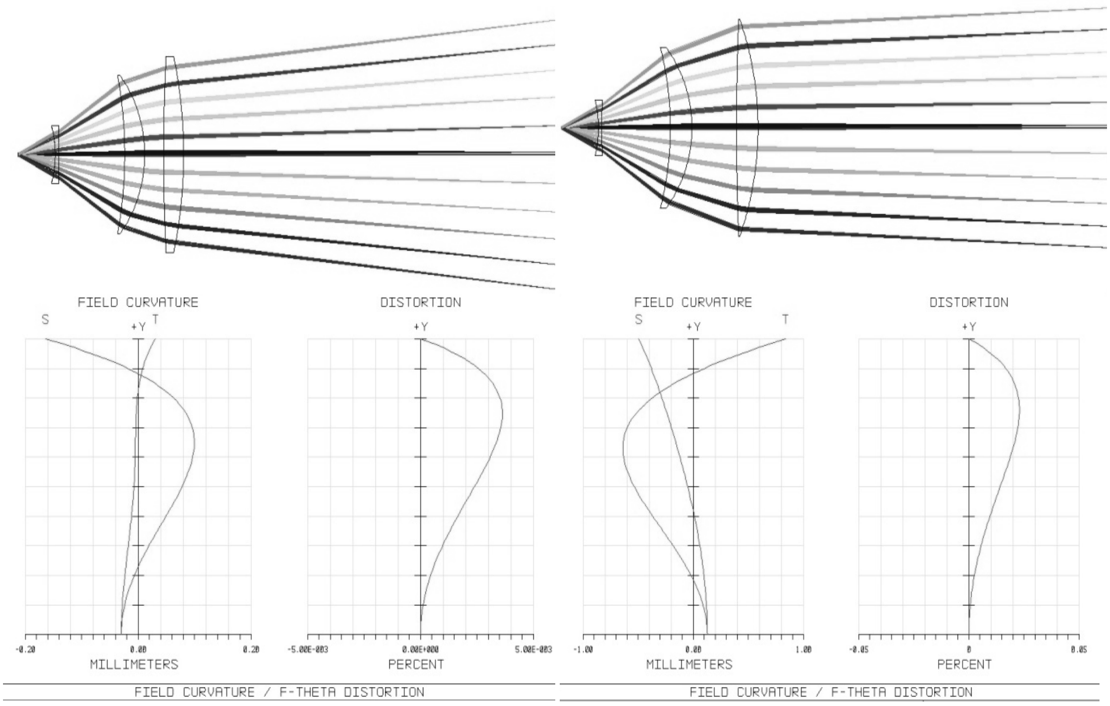
The key numerical characteristics of designed lenses are presented in Table 1.

Table 1. Configuration parameters of designed f-theta lens

Item	1	2
Effective focal length, mm	200	185
Working distance, mm	300	290
Working area diameter, mm	185	170
Maximum curvature of the field, mm	0.16	0.84
Maximum distortion, %	0.0035	0.024
Distance from the center of the swing, mm	30	30.5
Center spot, µm	0.23	0.92
Maximum spot (on the edge of working area), µm	24.9	28.1
1st lens diameter, mm	41	40
2nd lens diameter, mm	112	115
3rd lens diameter, mm	135	155
Lens material	N-BK7	N-BK7
	ZF10	ZF10
	ZF10	ZF10
Max entrance beam, mm	2.0	

Let's discuss a triplet system. Figure 4 shows calculated parameters of standard (a) and telecentric (b) modifications of the system.

Apparently, working distance increases as the number of f-theta lens elements grows. Technical characteristics of standard and telecentric triplet lenses are presented in Table 1, in columns 1 and 2 respectively. The curvature of the field of a standard triplet lens was 0.16 mm, while the curvature of the field of a telecentric lens was 0.84 mm. The standard lens had a better distortion compared to the telecentric one – 0.0035 % against 0.024 %. The maximum sizes of focal spots at the edge of the field were comparable, although in the central part they were 3 times different in favor of the standard lens. It should be noted that a 155 mm lens will be required at the output for the telecentric lens.



a b

Fig. 4. – Layout of a standard (left) and a telecentric triplet f-theta lens

As for the shapes of the focal spots, Figure 5 shows calculated sizes of focal spots at the off-axis angles of 0^0, 11^0 and 26^0. Based on the results of calculation, a focal spot in the standard triplet lens was bell-shaped. In a telecentric lens, it is possible to achieve a relatively uniform shape of the focal spot in the working area; however, its focusing power is less compared to a standard triplet lens.

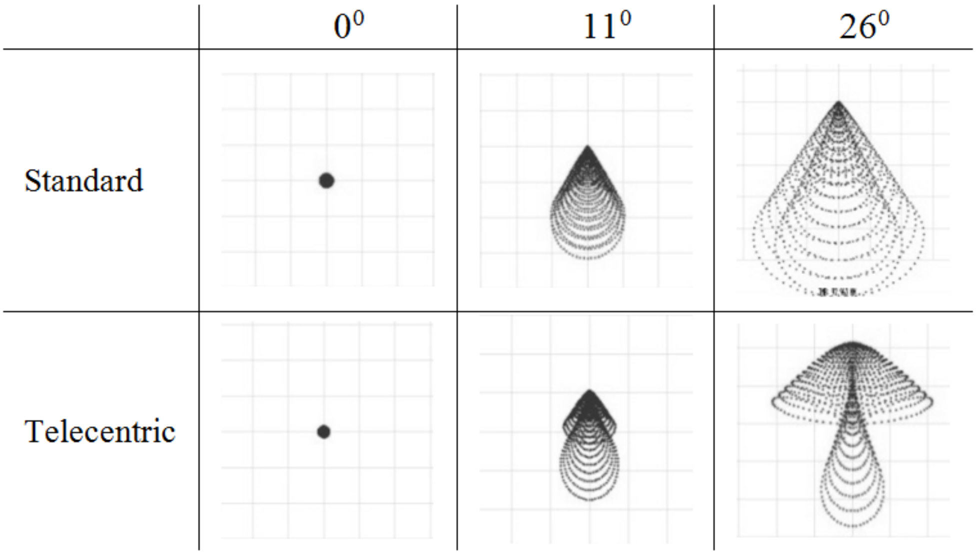


Fig. 5. – Triplet f-theta lens focal spots

Standard lens data are in good agreement with the data obtained by other authors [7,15,16]. It is expected that the focal spot in telecentric lenses tends to keep its shape and size in every point. At the same time, the focal spot of the telecentric lens takes shape of a mushroom at the edge of the working area.

Such a specific shape of the focal spot is the price paid for achieving telecentricity at the edge of the working area. As the optical axis is approached, laser focal spot tends to a point in all modifications.

4. CONCLUSION

The paper presents a development of standard and telecentric f-theta lenses design. Two different variants of focusing lenses were obtained. Properties and practical applicability of each lens were discussed.

There is two positive lenses in the triplet systems with. It has a double function: it focuses the beams in a focal point and partially controls orientation of the focal point to comply with f-theta law. That’s why this lens has a great optical power, and it is usually produced from heavy glass with a high refractive index. It would be challenging to ensure telecentricity of the lens with these characteristics.

This work is supported by the Ministry of Education and Science of the Russian Federation (research grants №14.Z50.31.0023 and 9.3236.2017/4.6), Federal Target Program 1.3 (agreement № 14.578.21.0245) and grant of Foundation for Assistance to Small Innovative Enterprises, contract №2438GS2/22662.

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