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Optik 115, No. 1 (2004) 7–10
http://www.elsevier.de/ijleo

Optik Optics
International Journal for Light and Electron Optics

Design of refractive/diffractive objective for head-mounted night vision goggle

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Abstract: A refractive/diffractive objective for head-mounted night vision goggle was designed. This objective consists of six elements, including one binary surface and two hyperboloids. It has a 40° field of view, a 1.25 f-number, and a 18 mm image diameter, with a compact structure and a light weight. All optical specifications reach proposed designing targets. Besides, we considered fabrication issues about special surfaces of the system.

Key words: Head-mounted night vision – refractive/diffractive – binary surface – objective

1. Introduction

Low light night vision technologies bend themselves to obtaining, conversing, enhancing, recording, and displaying of targets' images in night or in other low-light-level conditions, which effectively extend the vision of the human eye in time domain, airspace, and frequency domain. They usually contain a high-speed objective that transfers a high-resolution image onto an image intensifier tube that amplifiers the image intensity that is observed by means of an eyepiece [1, 2]. Head-mounted night vision goggle has widespread applications in military field, such as night observation, patrol, vehicle-drive, reading-file, and field maintenance, etc. It has been also used in many civil fields, including police, ship-navigation and so on. Much of the performance of such a device depends on the throughput of the high aperture and high-speed objective on the front end. The goggles also should provide a light intensified view of the outside world over a wide enough field of view. Other than being compact and light weight, these objectives are also desired to provide minimum vignetting, in order to assure the relative illumination of the marginal field of view, and uniform performance throughout the image field [3]. Besides visible light, there are abundant near infrared bands in night sky radiation, so these objectives should be corrected in wide spectral band. Because of special exit pupil position, eyepieces generally have some inevitable distortion, which would require that a good objective should have some barrel distortion, to compensate for the eyepiece's pincushion distortion [4]. Often such complex design requirements restrict in achieving a compact and lightweight objective.

In modern optical design, many binary elements are used in the system, which have been proved that they can add designing freedoms, simplify the structure and reduce the weight [5, 6]. These elements play a large role in correcting the chromatic aberrations of a system because they have a large negative dispersion. For wavelengths of 650, 750, and 850 nm, the Abbe V-number equals to –3.75. Besides, they also can correct monochromatic aberrations by using aspheric terms of surface sag. For an objective meeting military requirements with a compact structure and a light weight, we introduced one binary surface in traditional double Gauss lens. The design results all attain the proposed targets.

2. Design of refractive/diffractive objective

2.1. Design

The required first-order properties on the new objective are shown in second column of table 1, and the modulation transfer function (MTF) should meet or exceed those shown in third column of table 2. The designing wavelengths are 560.8 nm, 665.3 nm, 721.3 nm, 777.4 nm, 831.9 nm, and 876.2 nm.

Received 25 November 2003; accepted 9 January 2004.

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0030-4026/04/115/01-007 $ 30.00/0

Table 1. The specifications of the refractive/diffractive objective in comparison with proposed designing targets.

	Target	Result
Field of View (°)	40	40
Focal Length (mm)	25	25.2
Relative Aperture	1/1.25	1/1.25
Image Size (mm)	18	18
Relative Illumination (%)	>45	>50
Distortion (%)	−5	−5

Table 2. The modulation transfer function (MTF) of the refractive/diffractive objective in comparison with proposed designing target.

	Frequency (lp/mm)	Target	Result
In Axial Field of View	10	0.90	0.95
	20	0.80	0.83
	30	0.65	0.68
	40	0.50	0.51
In Half Field of View	10	0.80	0.87
	20	0.60	0.60
	30	0.40	0.41
	40	0.30	0.35

The objective's image plane must be located on the back surface of the image intensifier tube's flat input faceplate. We considered that the faceplate is a 5.5 mm-thick piece of Schott FK5 glass [4].

In traditional refractive system, double Gauss lens is one kind of typical type with a large field of view and a large relative aperture, so we selected one double Gauss objective as original structure [7]. The selected lens consists of seven elements, shown in fig. 1, with a 40° field of view and a 1.2 f-number, but the MTF performances in above wide spectral band can't meet the requirements of night vision goggle. Besides, the relative illumination in marginal field of view of this structure is only 34%, due to too many vignetting.

ZEMAX provides a binary surface with a symmetrical phase polynomial [8], described as

$$\varphi(\varrho) = A_1\varrho^2 + A_2\varrho^4 + A_3\varrho^6 + \ldots . \quad (1)$$

Where ϱ is the normalized radial aperture coordinate related to a normalization radius setting in optimization. The first term indicates the power on the binary optical surface, which can be used to balance the color dispersion of other elements in the system, so it can correct chromatic aberrations. The other terms can provide additional aberrations correction.

In design, we replaced the cemented doublet with a single lens, keeping the power of the system unchanged. With putting the binary element in different surface of the different refractive element, we researched different configurations. A comparison of each system's performance revealed that the best system had a binary element on the second element after stop. Because of large field of view and large relative aperture, off-axis aberrations are hard to control. We introduced conic constants in some refractive surfaces. Besides, keep about 5% barrel distortion at a 9-mm semi-field height to compensate for the eyepiece's pincushion distortion.

With no vignetting, considering image qualities both in axial field of view and larger field of view, we optimized the system. The result shows that MTF of the system in axial field of view is slightly less than the target proposed in table 2, but that in half and in marginal field of view are largely under targets. If only considered the axial field of view in optimization, the MTF in axial can be improved, however, those in larger field of view fall down rapidly. For better performance in larger field of view, we set some vignetting in the system, and controlled the vignetting coefficient, in order to assure that illumination in marginal field of view is more than 45% of the on-axis illumination.

2.2. Results

The final system structure is shown in fig. 2. Except the faceplate, the system consists of six elements. The

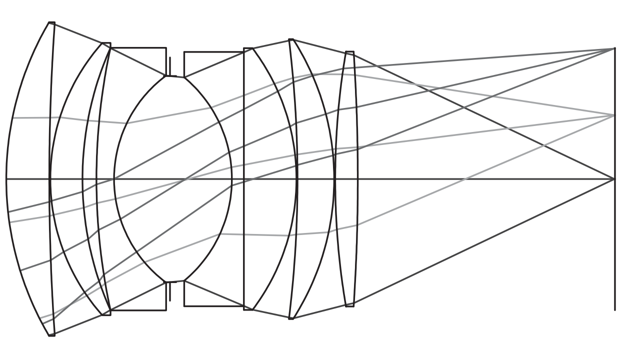

Fig. 1. The layout of the traditional double Gauss objective.

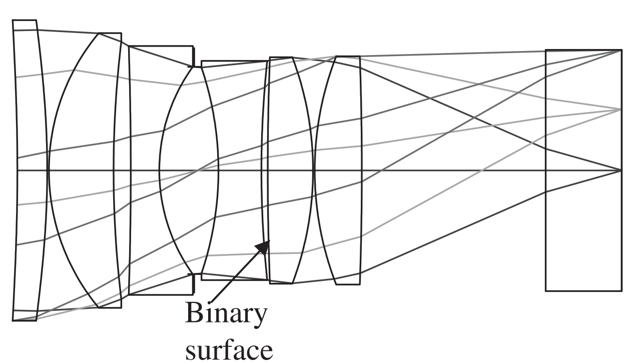

Fig. 2. The layout of the refractive/diffractive objective.

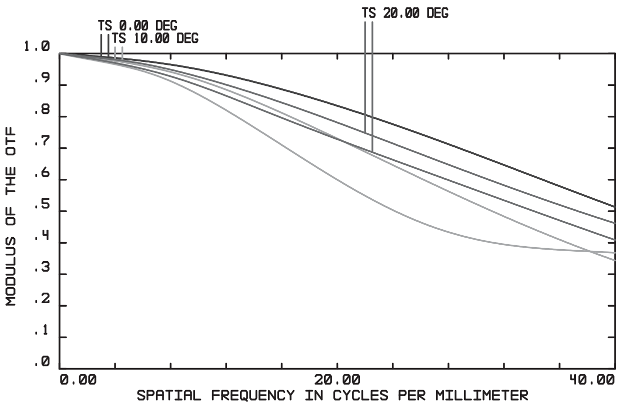

Fig. 3. The curves of modulation transfer function (MTF) of the refractive/diffractive objective.

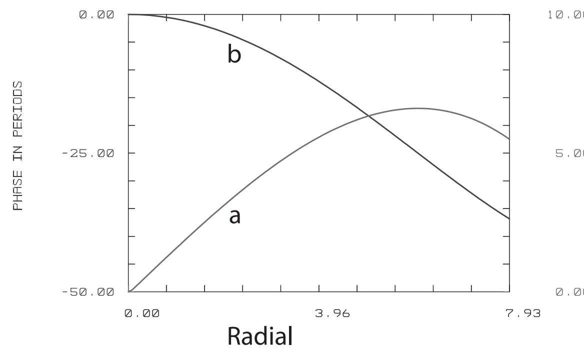

Fig. 4. Line frequency a) and phase b) vs. aperture of the binary surface.

front surface of the second element after stop is binary surface, and two surfaces of the first element are hyperboloids. The total track of the system is 43.7 mm and the weight is only 25 g. The designing results of specifications are shown in third column of the table 1. We can see that all parameters attain the targets. The curves of MTF are shown in fig. 3, and the specific values at four frequencies are shown in fourth column of table 2. We can see that MTFs in axial, half, and full field of view are all excellent. They indicate that the performances of the objective reach the proposed designing targets.

3. Fabrication issues

There are three special surfaces in this design, including two hyperboloids and one binary surface. The departure from the base sphere of the aspheric surface and the minimum line width of the binary surface determine the difficulty and cost of fabrication of the system.

The equation describing a conic asphere is given by

$$Pz^2 - 2zR + y^2 = 0\,, \tag{2}$$

where $P = 1 + K$, and K is conic constant; R is curvature radius of the base sphere. Using the quadratic equation to solve equation (2), and selecting z_- (which makes $z \to 0$, when $y \to 0$), then

$$z = \left(\frac{R}{P}\right)\left[1 - \sqrt{1 - P\left(\frac{y}{R}\right)^2}\,\right]. \tag{3}$$

Using the binomial expansion on the square root, we can achieve

$$z \sim \frac{y^2}{2R} + \left(\frac{P}{8}\right)\left(\frac{y^4}{R^3}\right) + \left(\frac{P^2}{16}\right)\left(\frac{y^6}{R^5}\right) + \left(\frac{5P^3}{128}\right)\left(\frac{y^8}{R^7}\right) + \ldots\,. \tag{4}$$

Setting $P = 1$ in equation (4), we can quickly obtain the mathematical description of a spherical surface

$$z_s \sim \frac{y^2}{2R} + \frac{1}{8}\left(\frac{y^4}{R^3}\right) + \frac{1}{16}\left(\frac{y^6}{R^5}\right) + \frac{5}{128}\left(\frac{y^8}{R^7}\right) + \ldots\,. \tag{5}$$

According $\Delta z = z - z_s$, the departure from sphere is

$$\Delta z \sim \frac{1}{8}\,(P-1)\left(\frac{y^4}{R^3}\right) + \frac{1}{16}\,(P^2-1)\left(\frac{y^6}{R^5}\right) + \frac{5}{128}\,(P^3-1)\left(\frac{y^8}{R^7}\right) + \ldots\,. \tag{6}$$

In our design, conic constants of two hyperboloids are −184.15 and −26.093, respectively. Applying eq. (6), the departure from sphere at full aperture of the first hyperboloid is 52.5 μm, and that of the second hyperboloid is 114.7 μm. It is possible to test such aspheric surface by current technology.

The binary surface is used with only first two terms of the eq. (1), so the number of periods of binary surface n is given by

$$-2\pi n = A_1\varrho^2 + A_2\varrho^4\,. \tag{7}$$

Fig. 4 shows the phase and line frequency vs. aperture of the binary surface. Curve a depicts the distribution of line frequency and curve b gives the phase in periods. From curve b, there are 37 periods in all on the binary surface, and from curve a, the maximum line frequency of this binary surface is 6.6 cycles/mm, correspond to the minimum line width is 151 μm. Higher diffraction efficiency can reduce the effect of the undesirable ghost images. When the number of etching levels is eight, a diffraction efficiency of 95% can theoretically be obtained [9]. In this way, the minimum characteristic size of diffractive surface is 19 μm, which is not a very high demand for technics.

4. Conclusion

Military optical performance and weight specifications for night vision objective are successfully met by one refractive/diffractive system. This objective consists of six elements, including one binary surface. The total track is 43.7 mm, and the weight is 25 g. With a 40° field of view and a 18 mm image size, the objective can match with small image intensify tube and can be used in head-mounted night vision goggle well.

This research is partially supported by National Nature Science Foundation of China (number 60277021) and United Academy of Nankai University and Tianjin University.

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