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PAPER

Aberration correction of conformal dome based on rotated cylindrical lenses for ultra-wide field of regard

Aberration correction of conformal dome based on rotated cylindrical lenses for ultra-wide field of regard*

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A new compact conformal dome optical system was designed, and the aberration characteristics of the dome were investigated using Zernike aberration theory. The aberrations induced by the conformal dome at different fields of regard (FORs) from 0° to 90° were effectively balanced by a pair of rotating cylindrical lenses. A design method was introduced and the optimization results were analyzed in detail. The results showed that the Zernike aberrations produced by the conformal dome were decreased dramatically. Also, a complete conformal optical system was designed to further illustrate the aberration correction effect of the rotating cylindrical lenses. Using a pair of rotating cylindrical lenses not only provided an ultra-wide FOR, but also perduced a better image quality of the optical system.

Keywords: optical design, conformal dome

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1. Introduction

The missile domes today leave much to be desired in the realm of aerodynamic performance. The exterior spherical surface of a conventional missile dome creates up to 50% of the missile's drag.[1–3] Optimizing this exterior surface for aerodynamic performance can dramatically decrease the drag, resulting in increasing range, payload, or velocity. Besides, aerodynamic heating will produce a thermal barrier, impacting the target recognition.[4–9]

A conformal aircraft uses a streamline surface that can overcome the above drawbacks, but the curvature of the conformal dome varies with the field of regard (FOR) leading to dynamic aberration, which will increase the difficulty of designing an optical imaging system with wide FORs. A variety of aberration correction methods were proposed only for limited FORs, including a fixed aberration-correcting plate based on the Wassermann–Wolf equation, a pair of counter-rotating wedges, deformable mirrors, two axially movable cylindrical lenses, etc.[10–14] The configuration of two axially movable cylindrical lenses can bring in variable astigmatism, so it is well suited for conformal shapes that have astigmatism as the dominant aberration. But the FOR of this configuration is usually less than 45°. The limited FORs deeply affect the widely use of the conformal optical systems.

In this study, a new compact conformal optical system based on a pair of rotating cylindrical lenses is proposed. Since the astigmatism produced by rotating cylindrical lenses varies continuously, the wavefront error of the incident rays induced by the conformal dome could be minimized and the imaging quality of the conformal optical system is therefore improved. This optical system provides an ultra-wide FOR from 0° to 90°. We take an ellipsoidal dome for example. The objectives of this study are to (i) discuss the aberration of the ellipsoidal dome, (ii) analyze the astigmatism of a single rotating cylindrical lens and examine the aberration correction effect, (iii) present an improved method of using a pair of cylindrical lenses to compensate the aberration for ultra-wide FOR, and (iv) design a complete cooled conformal dome optical system and evaluate the imaging quality of the system.

2. Ellipsoidal dome aberration analysis

The aerodynamic performance of an ellipsoidal dome depends mainly on the length to diameter ratio. The face form of the inner surface is more or less arbitrary. To simplify the complexity of the analysis, the internal and external surfaces are set to be ellipsoidal and concentric, as shown in Fig. 1. L is the length of the dome, and D is its diameter.

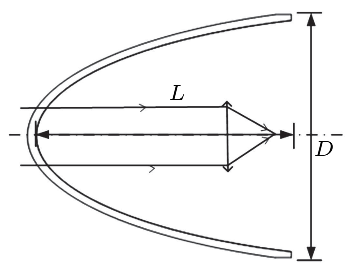

Fig. 1. Geometric model of the ellipsoid dome.

A conformal dome model is built to analyze the static and dynamic aberration properties for different FORs, as shown in Table 1. The outer surface of a conformal dome is continuous, so a conformal dome can provide an FOR much greater than

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a conventional spherical dome, without vignetting. A perfect lens is put 120 mm behind the dome as the imaging system. The circumrotation node is located at the center of the perfect lens; the rotation step of the gimbal is 10°, and the FOR is 100°.

Table 1. Parameters of an ellipsoidal dome.

Parameters of system	Design value
Material of dome	MgF_2
Thickness of dome	5 mm
Entrance pupil diameter	40 mm
Field of regard (FOR)	100°
Field of view (FOV)	4.88°
Fineness	1
Length of dome	160 mm

In this paper, Zernike polynomials are used to analyze the aberrations generated by an ellipsoidal dome. The mathematical expression of a Zernike polynomial is

$$R_n^m(\rho) = \frac{1}{\left[\dfrac{n-m}{2}\right]!\rho^m}\left[\frac{d}{d(\rho^2)}\right]^{\frac{n-m}{2}} \times \left[(\rho^2)^{\frac{n+m}{2}}(\rho^2-1)^{\frac{n-m}{2}}\right], \quad (1)$$

where m and n are integers, $n-m \geq 0$ is an even number, and ρ is the normalized pupil radius. We use terms Z5–Z9 of the Zernike polynomial expansion; they are shown in Table 2.

Table 2. Terms Z5–Z9 of a Zernike polynomial expression.

Term	Name	Zernike polynomial
Z5	astigmatism	$r^2\cos(\theta)$
Z6	astigmatism	$r^2\sin(\theta)$
Z7	coma	$(3r^3-2r)\cos(\theta)$
Z8	coma	$(3r^3-2r)\sin(\theta)$
Z9	third-order spherical aberration	$6r^4-6r^2+1$

The astigmatism (Z5), coma (Z8), and spherical aberration (Z9) induced in the optical system by the dome are shown in Fig. 2. They vary with FOR. For a narrow FOR, the ellipsoidal dome is similar to a sphere, while for a wide FOR, it loses the spherical symmetry and gradually becomes similar to the structure of a cylinder, causing large coma and astigmatism. The spherical aberration stays at the level of -0.07 times the wavelength for any FOR, so can be ignored. The coma becomes most serious at 20°; when the FOR is greater than 30°, the coma is reduced to one wavelength and remains nearly constant. Compared with coma, the astigmatism is more serious, especially when the FOR is wider than 30° and the astigmatism is nearly 8λ, and varies with FOR. Thus astigmatism is the main dynamic aberration that needs to be corrected.

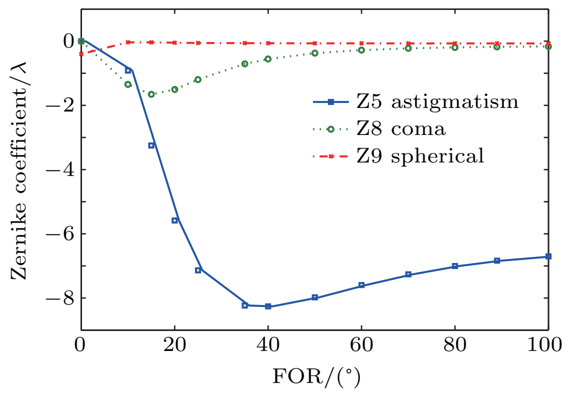

Fig. 2. (color online) The curve of astigmatism and coma vs. FOR.

3. Variable astigmatism correction via single rotated cylindrical lens

Astigmatism is generated by difference in optical powers in the tangential and sagittal planes, resulting in two separated line foci. It is well known that cylindrical elements can be introduced to an optical system to provide single-axis power compensation, to balance the relative mismatch in focal lengths, but a fixed cylindrical lens can only provide a certain astigmatism, and cannot correct the variable astigmatism at different FORs introduced by a conformal dome. This paper puts forward the use of a rotating cylindrical lens for variable astigmatism correction. When a cylindrical lens is rotated around the optical axis, the powers along the x and y axes projected from the cylindrical lens will change. This introduces a variable astigmatism to balance the astigmatism caused by the dome at different FORs.

The underlying rationale for this correction technique is derived from the paraxial power relation for a system of two separated, thick lenses, given by

$$\phi = \phi_1 + \phi_2 - \tau\phi_1\phi_2, \quad (2)$$

where ϕ is the total system power, τ is the distance between the elements, and ϕ_1 and ϕ_2 are the individual element powers.

Each of these power relations is separable in x and y,

$$\phi_y = \phi_{ys1} + \phi_{ys2} - \tau\phi_{ys1}\phi_{ys2}, \quad (3)$$

$$\phi_x = \phi_{xs1} + \phi_{xs2} - \tau\phi_{xs1}\phi_{xs2}, \quad (4)$$

where ϕ_y is the total system power along the y axis, and likewise ϕ_x is the total system power along the x axis. ϕ_{ys1} and ϕ_{ys2} are the individual element powers along the y axis. ϕ_{xs1} and ϕ_{xs2} are the individual element powers along the x axis.

The powers of the dome along the x and y axes can be suggested as ϕ_{xs1} and ϕ_{ys1}, varying with FOR. The cylindrical lens can provide a single axis power, defined as ϕ_{s2}; the power along the vertical axis is zero. As shown in Fig. 3, the powers of the cylindrical lens along the x and y axes can be expressed as

$$\phi_{xs2} = \phi_{s2} \cos\beta, \tag{5}$$

$$\phi_{ys2} = \phi_{s2} \sin\beta. \tag{6}$$

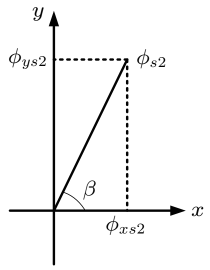

Fig. 3. The power of the cylindrical lens along x and y axes.

When the FOR changes, the cylindrical lens will be rotated around the z axis. The ϕ_{ys2} in Eq. (3) is the same as the ϕ_{ys2} in Eq. (6). ϕ_{xs2} and ϕ_{ys2} will consequently change to compensate the variable power of the dome. For an optical system without astigmatism, the total system power including the dome and cylindrical lens along the x axis should equal to that along the y axis, then we have

$$\phi_x = \phi_y. \tag{7}$$

To achieve this, a correction structure is put forward, as shown in Fig. 4. L1 is an ellipsoidal dome, L2 is a cylindrical lens, and L3 is a perfect lens for imaging. The circumrotation node is located at 120 mm behind the dome. At different FOR α, the cylindrical lens rotates β degrees about the optical axis z, and it can be derived from Eqs. (2)–(7). Figure 5 gives the rotated angle of the cylindrical lens vs. the FOR.

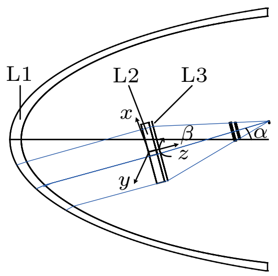

Fig. 4. (color online) Conformal optical system with rotated cylindrical lens.

When correcting aberrations using a rotating cylindrical lens, the error function based on Zernike aberrations is found to converge rapidly and the value of the error function is substantially reduced. The aberrations are obviously corrected. Since the error function has a few minima, the rotation angle must be appropriately adjusted according to the values and types of residual aberrations in an optimization process. The weights of different FOR should also be appropriately distributed according to the residual aberrations of each FOR. Sequentially, optimizing the optical system again achieves the minimal error function.

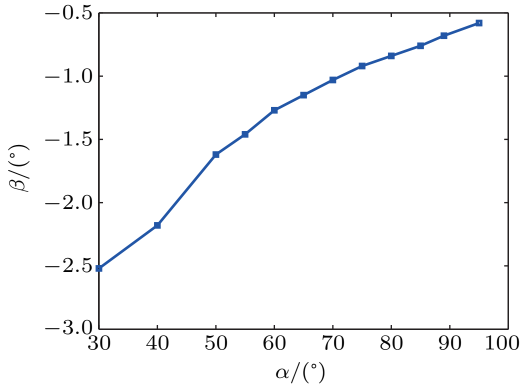

Fig. 5. (color online) The rotated angle of the cylindrical lens vs. the FOR.

Figure 6 shows the astigmatism and coma of the conformal optical system after correction by a single rotated cylindrical lens. For FOR over 30°, the residual aberration is less than 0.5λ, and the fluctuation range is very small, less than 0.75λ. Therefore, the astigmatism induced by the conformal dome is well compensated by the rotating cylindrical lens from 30° to 100°. For FOR below 30°, the residual astigmatism is still more than 3λ. Although the astigmatism of the conformal dome is nearly zero at 0°, the cylindrical lens itself will induce lots of astigmatism, which cannot be balanced. So the single rotated cylindrical lens can only realize the aberration compensation of the conformal optical system from 30° to 100°.

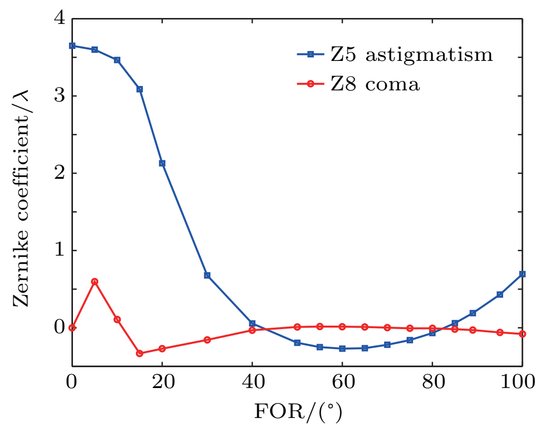

Fig. 6. (color online) Aberration characteristics of conformal optical system after optimization.

4. Aberration correction using a pair of rotated cylindrical lenses

In order to correct the aberration of the single rotated cylindrical lens structure from 0° to 30°, and improve the performance of the conformal optical system from 0° to 100°, two methods are presented in this section.

Firstly, as shown in Fig. 7, another cylindrical lens is added in the optical path near the former cylindrical lens. For FOR below 30°, the two cylindrical lenses are placed orthogonally. t_1 is the distance between the two cylindrical lenses. t_2

is the distance between cylindrical lens I and the focal plane. The astigmatism of the two lenses on the focal plane can be zero by choosing the appropriate focal power and t_1, which is given by

$$t_1 = \frac{1}{\phi_2} - \frac{1}{\phi_1}, \tag{8}$$

where ϕ_1 is the power of cylindrical lens I, and ϕ_2 is the power of cylindrical lens II. So the astigmatism caused by the single rotated cylindrical lens during narrow FOR could be eliminated.

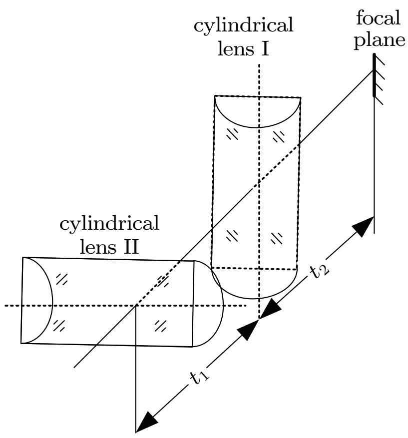

Fig. 7. Two cylindrical lenses placed orthogonally.

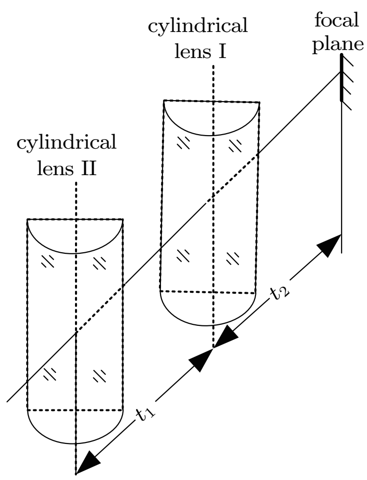

Fig. 8. Two cylindrical lenses placed in parallel.

While the FOR is over 30°, the two cylindrical lenses are placed in parallel as shown in Fig. 8. The pair of cylindrical lenses can be equivalent to a single cylindrical lens and correct the astigmatism caused by the conformal dome during wide FOR. The power of equivalent cylindrical lens ϕ_3 can be expressed as

$$\phi_3 = \phi_1 + \phi_2 - t_1\phi_2\phi_1. \tag{9}$$

Figure 9 is the configuration of the conformal optical system using two rotated cylindrical lenses.

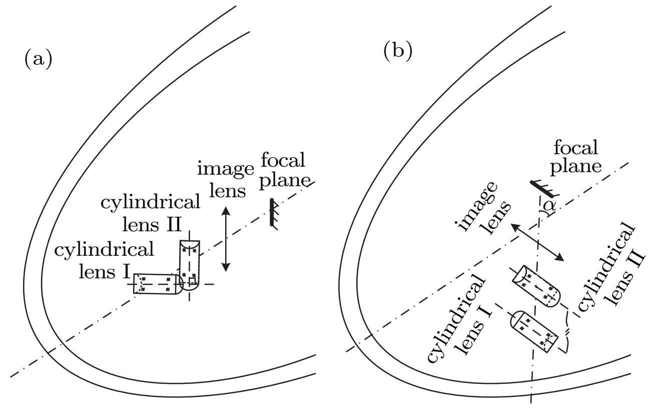

Fig. 9. Optical configuration of two rotated cylindrical lenses: (a) 0° FOR, (b) 45° FOR.

Secondly, binary surfaces etched in the inner surface of the conformal dome can compensate the residual astigmatism and coma at narrow FOR from 0° to 30°, as shown in Fig. 10. The astigmatism and coma in Fig. 11 become less by using a binary optical surface compared with the result shown in Fig. 6. When the FOR varies from 0° to 100°, the astigmatism of the system approximately increases steadily from 0 to 5λ. At 30° FOR, there is only 2.5λ of residual astigmatism compared with 8λ of astigmatism before compensation. Thus the binary optical surface performs well on the conformal dome aberration and is correct at small FOR.

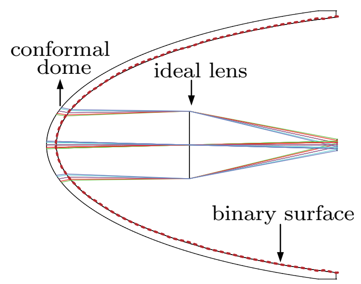

Fig. 10. (color online) Ideal conformal optical system with etched binary surface.

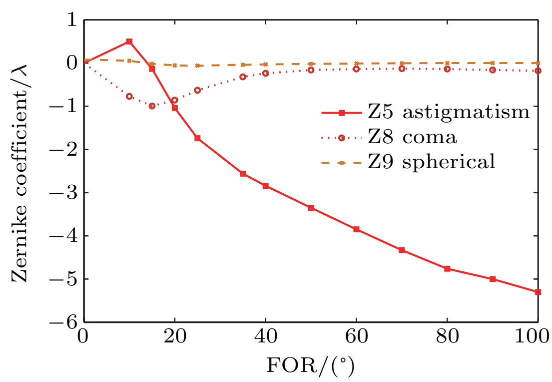

Fig. 11. (color online) Conformal hood inner surface after carving a binary diffractive surface aberration curve.

5. Optical design results

To further illustrate that the two rotating cylindrical lenses structure has a better aberration correction effect, finally, a conformal optical imaging system with ultra FOR has been designed using optical design solftware Zemax, as shown in Fig. 12.[15] Cylindrical lenses I and II are laid inside the conformal dome. When the FOR varies from 0 ° to 30°, the cylindrical lenses are placed vertically to avoid the astigmatism produced by themselves. The binary surface will play a key role in balancing the aberration of the conformal dome. When the FOR varies from 30° to 100°, the two cylindrical lenses will first rotate 90° and become parallel. Then they will rotate together and are equivalent to one single cylindrical lens to compensate the astigmatism induced by the conformal dome.

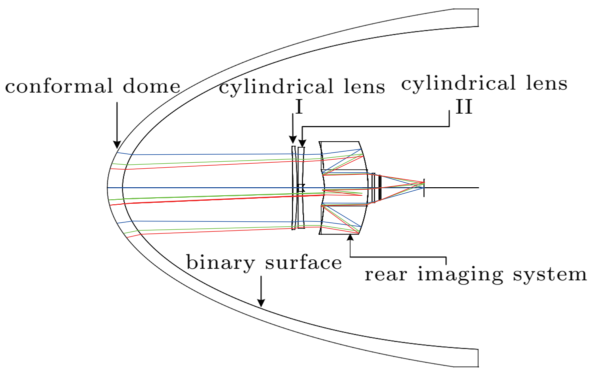

Fig. 12. (color online) Schematic of a cooled conformal optical system.

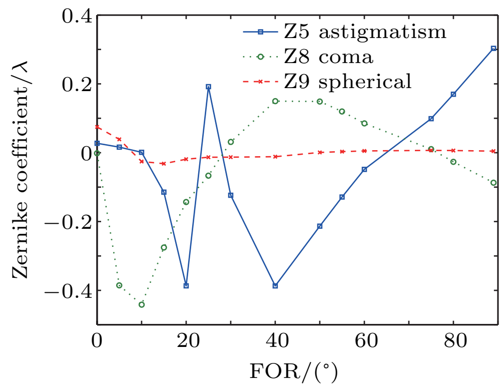

Fig. 13. (color online) Aberration characteristics of a conformal optical system after optimization.

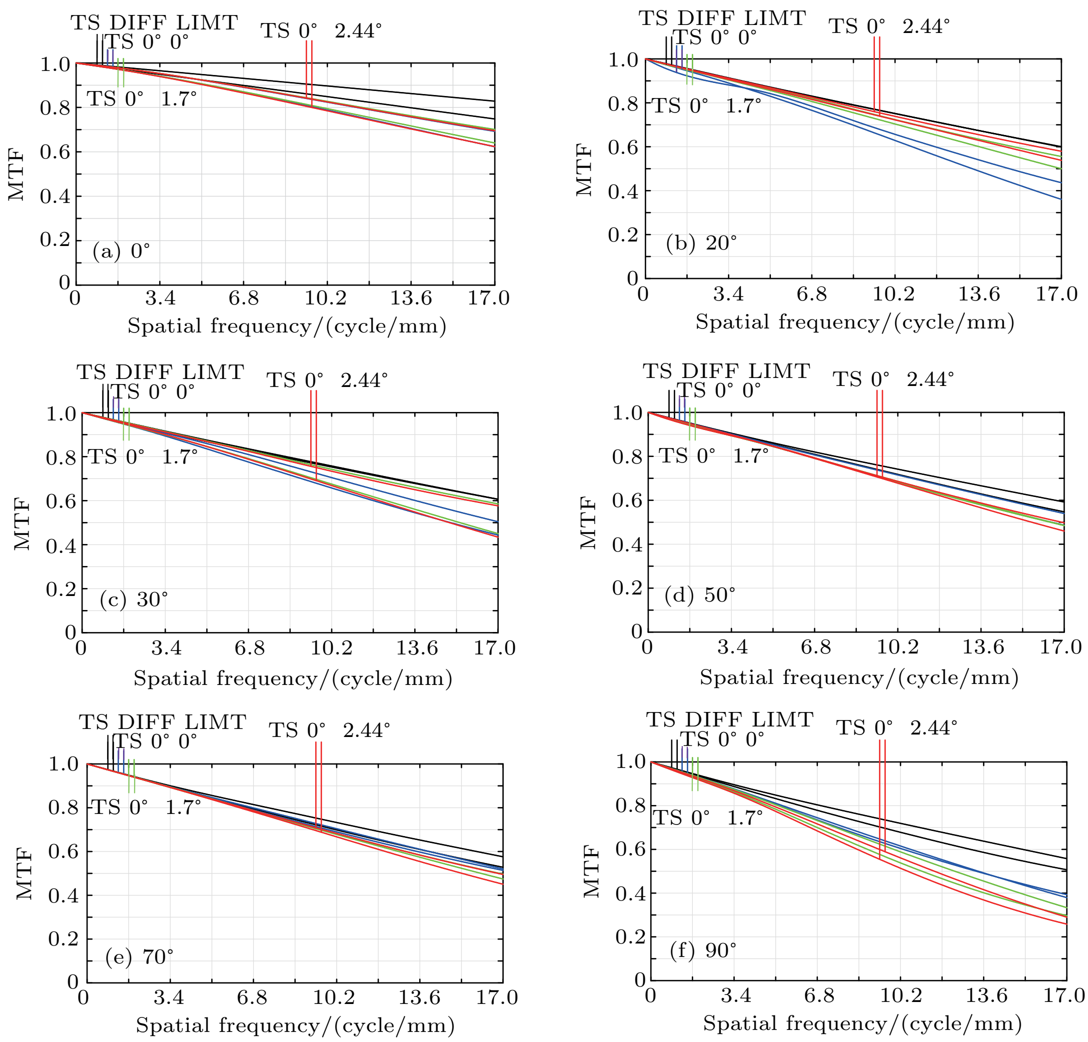

Fig. 14. (color online) Modulation transfer function of conformal optical system at different FOR: (a) 0°, (b) 20°, (c) 30°, (d) 50°, (e) 70°, (f) 90°.

The whole conformal optical system consists of only five optical elements. The optical system FOV is circular and of value $2\omega = 4.88°$. The total length of the system from the apex of the dome to the image plane is 140 mm, less than the dome length. The aperture stop is placed at 19.8 mm from the image plane, and the diameter of the exit pupil is set to 10.6 mm, to bring the cold aperture efficiency to 100%.

The imaging part of the system behind the dome is a solid catadioptric structure. This optical system can effectively shorten the light path and make the system more compact. To correct other aberrations, all of the surfaces are chosen to be aspherical, with a profile

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \sum_{i=1}^{6} \alpha_i r^{2i}, \tag{10}$$

where c is the curvature (the reciprocal of the radius), r is the radial coordinate in lens units, k is the conic constant, and α_i is the coefficient.

Figure 13 shows the aberration characteristics of a conformal optical system after optimization. Figure 14 shows the modulation transfer function (MTF) of the optical system for different FOR, wherein most MTF values are close to the diffraction limit, and a few are nearly 0.41 at the Nyquist frequency of 17l p/mm. The optical system offers excellent image quality.

6. Conclusion

In conclusion, a compact conformal optical system based on a pair of rotating cylindrical lenses was presented, with ultra-wide FOR and excellent imaging quality. The aberration characteristics of the ellipsoidal dome were well investigated. Using the structure of rotating cylindrical lenses, the aberrations introduced by the dome from 0° to 90° were decreased dramatically. Finally, a complete cooled conformal optical system with only five optical elements was presented. Compared with the traditional aberration correction method, the method presented in this paper not only improved the imaging quality, but also simplified the structure of the conformal optical system.

References

[1] Shannon R R 1999 *Proc. SPIE* **3705** 180

[2] Mills J P 2001 *Proc. SPIE* **4442** 101

[3] Wang C, Zhang X and Qu H M 2013 *Chin. Phys. B* **22** 074212

[4] Leroux C E, Tzschachmann A and Dainty J C 2010 *Opt. Express* **18** 21567

[5] Chang J, Liu L P, Cheng D W and Zhao N 2009 *J. Infrared Millim. Waves* **28** 204

[6] Trotta P A 2001 *Proc. SPIE* **4375** 152

[7] Jacob R, Aaron B, Kevin P T and Jannick P R 2016 *Light: Science & Applications* **6** e17026

[8] Christopher J R, Demian P and Oliver T B 2017 *Light: Science & Applications* **6** e16255

[9] Lei Z M, Sun X Y and LV F N 2016 *Chin. Phys. B* **25** 114201

[10] Zhang W, Zuo B J and Chen S Q 2013 *Applied Optics* **52** 461

[11] Li Y, Li L, Huang Y F and Liu J G 2009 *Chin. Phys. B* **18** 2769

[12] Sun J X, Sun Q, Li D X and Lu Z W 2007 *Acta Phys. Sin.* **56** 3900 (in Chinese)

[13] Sparrold S W 1999 *Proc. SPIE* **3705** 189

[14] Whalen M R 1999 *Proc. SPIE* **3482** 201

[15] Lambda Research Corporation 2014 *Zemax Reference Manual*