Correcting the effect of temperature on image quality of thermal imaging objectives by wavefront coding technique

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ABSTRACT

The paper has proposed a method for correcting the effect of temperature on the imaging quality of thermal imaging systems by wavefront coding technology. A cubic phase mask was added to the aperture diaphragm of the thermal imaging objective to obtain a temperature-invariant point spread function (PSF). The received images will be of low quality but almost invariant with the change in temperature. An inverse filter was used to recover high-quality images over a variable temperature range. To demonstrate the effectiveness of the proposed method, a thermal imaging objective was used to experiment. The simulation results demonstrate that the proposed method can effectively eliminate the temperature influence on the image quality of the thermal imaging objective.

Keywords: Thermal objective; Defocus; Restored algorithm.

1. INTRODUCTION

Thermal imaging objectives are made from infrared materials such as Ge, ZnS, ZnSe, etc [1, 2]. The thermal refractive index coefficient, thermal expansion coefficient and photothermal constant of these materials working in the infrared spectral range are relatively large compared to these parameters of optical materials working in the daytime spectral region. Therefore, infrared materials used to fabricate thermal imaging objectives are often quite sensitive to temperature changes [3]. When the temperature changes, the parameters such as refractive index, thickness, and radius of curvature of the optical system will change significantly. The resulting change of these parameters leads to a significant change in the focal length of the thermal imager, the amount of which is called defocus [4]. This causes a position mismatch between the focal plane and the sensor plane of the receiver. This results in the image quality of the thermal imaging objective being degraded. In addition, when the parameters of the thermal imaging objective are changed, the aberration of the thermal imaging objective will also change and this also contributes to the change in the image quality of the thermal imager. However, the amount of defocus shift is a major contributing factor to the image quality deterioration of the thermal imaging objective. Therefore, a number of solutions have been proposed to compensate for the change of defocus shift such as the mechanical compensation method, optical compensation method, electromechanical compensation method [5]. The purpose of these methods is to place the image of the thermal imaging optical system in the correct position of the receiver matrix at any temperature value.

The wavefront coding method was first introduced in 1995 allowing to extend the depth of field [6-8]. In this method, a wavefront coding component is added to the conventional optical system in order to obtain an invariant point spread function over a wide range of depth of field. Figure 1 shows a schematic diagram of a wavefront coding optical system. The wavefront coding component has the function of changing the output wavefront of the optical system in order to provide a point spread function that is invariant over a wide range of depth of field compared to the function of traditional optical systems. Because the point spread function of the wavefront coding optics is nearly invariant over a wide range of depth of field, a point spread function can be used to restore sharp images close to the best quality images of conventional optical systems. Despite the fact that, the wavefront coding technique also has its limitation that the restored image is affected by noise and impurities.

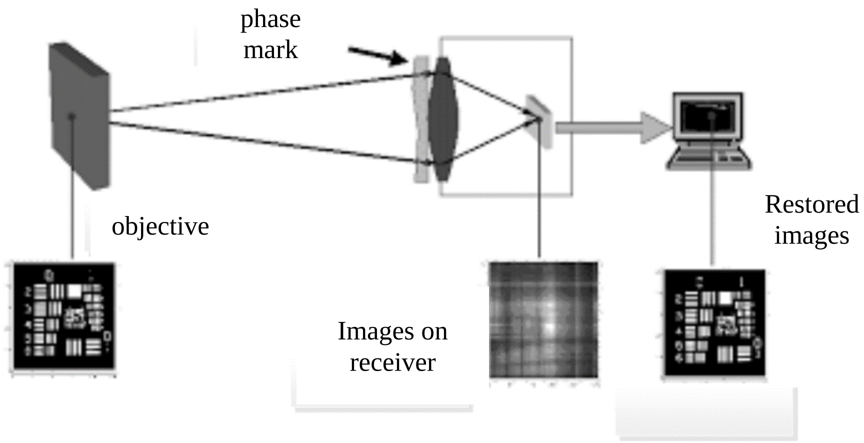


Figure 1. *Schematic diagram of wavefront coding method. A component that modifies the wavefront is incorporated into the conventional optical system.*

In this paper, we apply the wavefront coding technique to the thermal imaging objective to eliminate the influence of temperature on the image quality. In which, an inverse filter has been applied for image restoring.

2. THEORETICAL BASIS AND PROPOSED METHOD

2.1. Change of parameters of thermal imaging objective with temperature

As the temperature changes, the refractive index of the optical material changes and can be expressed by expression (1):

$$n = n_0 + \beta(T - T_0) \tag{1}$$

where, β is the coefficient of refractive index change with temperature, also known as the thermal refractive index coefficient of the material, n_0 is the refractive index at temperature T_0, T is the actual working temperature.

When the temperature changes, the thickness and radius parameters of the thermal imaging objective will also change and can be expressed by the following expressions:

$$d = d_0[1 + \alpha(T - T_0)] \tag{2}$$

$$r = r_0[1 + \alpha(T - T_0)] \tag{3}$$

where d_0 and r_0 are the values of thickness and radius at temperature T_0; α is the thermal expansion of the optical material.

In the case of a single lens, the focal length of the lens is determined by the following expression:

$$\frac{1}{f^{'}}=(n-1)(\frac{1}{r_1}-\frac{1}{r_2}) \tag{4}$$

By differentiating expression (4), we get the following transformation:

$$\frac{df^{'}}{f^{'2}}=dn(\frac{1}{r_1}-\frac{1}{r_2})+(n-1)(\frac{dr_1}{r_1}-\frac{dr_2}{r_2}) \tag{5}$$

Replace d$n=\beta\Delta T$; d$r_1=\alpha\Delta T$; and d$r_2=\alpha\Delta T$ in the expression (5):

$$\frac{df^{'}}{f^{'}}=(\alpha-\frac{\beta}{n-1})\Delta T \tag{6}$$

$$\Delta f^{'}=f^{'}(\alpha-\frac{\beta}{n-1})\Delta T \tag{7}$$

in which, $\Delta T=T-T_0$ is the temperature difference.

As the focal length changes, the wavefront parameter of the defocus shift is as follows:

$$\mathrm{W}_{20}=\frac{\Delta f^{'}}{8(f^{'}/\#)^2}\text{ hay }\psi=\frac{2\pi}{\lambda}\mathrm{W}_{20} \tag{8}$$

Thus, when the temperature changes, the focal length of the thermal imaging objective changes, producing a defocus amount that changes the image quality of the thermal imager objective. If the thermal image objective is composed of many single lenses (multi-element objective), the change in temperature will lead to a change in the focal length (an amount of $\Delta f'$) of each lens in the system. That causes the focal length of the whole system to change. And the amount of defocus as the focal length changes are the sum of the defocus amounts of the single lens elements in the thermal imaging objective.

2.2. Method

In this paper, we apply wavefront coding technology to the thermal imaging objective. A cubic mask is introduced into the thermal imaging objective to obtain a point spread function that is invariant with temperature change. The cubic function has the following form:

$$f(x,y)=a(x^3+y^3) \tag{9}$$

where a is the mask parameter to control the phase profile.

When the cubic phase mask is applied to the thermal imaging objective, the restored image will be of much lower quality than that obtained by the conventional thermal imaging objective at 20 °C. Therefore, an image recovery process needs to be implemented.

The intensity image of the imaging system can be represented by the expression:

$$g=o\otimes h+n \tag{10}$$

where o is the observed object; h is the point spread function; n is noise; the symbol $\otimes$ is the convolution operator.

In the spatial frequency field, expression (10) is represented by [8, 9]:

$$G=O\times H+N \tag{11}$$

where G is the Fourier transform of the image, g; O is the Fourier transform of the image, o; H is the Fourier transform of the point spread function, h.

To perform the analysis of decoding capability of the digitization process, noise is ignored due to the PSF and h of a wavefront coding optical system with a cubic phase mask does not change much with focus deviation. In this paper, we propose a solution to eliminating the influence of temperature on the imaging quality of the optical system. An inverse filter is used for image restoration over a variable temperature range. The inverse filter is expressed as follows:

$$F = \frac{H_{L\_20}}{H_{C\_20}} \tag{12}$$

where H_{L_20} is the Fourier transform of the PSF corresponding to the traditional thermal imaging objective at 20 ^{o}C; H_{C_20} is the Fourier transform of the PSF for the thermal image objective with wavefront coding technology at 20 ^{o}C. At this temperature, the optical system is optimized and its value is usually around the middle of the temperature variation.

The Fourier transform of the restored image is shown:

$$O' = F \times G \tag{13}$$

Performing the inverse Fourier transform, we get the image o' after processing. This image is the system recovery image.

3. SIMULATION RESULTS

To test the effectiveness of the proposed method, a thermal imaging optical system is used with the system parameters at 20 °C as follows: input pupil diameter of 20 mm, the wavelength range of 8 μm -12 μm. Table 1 shows the structural parameters of a thermal imaging objective. Figure 2 shows the shape of the thermal imaging objective. The thermal objective is composed of three individual lenses. These three single objective lenses are all designed with Ge material.

Table 1. *System parameters of the thermal imaging objective.*

Obj	Radius	Thickness	Glass	Semi-diameter
Stop	Infinity	2	Ge	11
1	Infinity	0.5		11
2	24.947	3.30	Ge	11
3	32.102	8.93		11
4	347.093	2.50	Ge	9.5
5	29.536	3.39		9.5
6	240.663	3.30	Ge	11
7	-56.374	24.326		11

We now consider the effect of temperature on the quality of the above thermal imaging objective using the PSF. The size of PSF is 128×128 pixels. The lower the PSF and the larger the size, the more degraded the image quality is. The temperature range considered is from 0 °C to 50 ^{o}C. The PSF for the thermal imaging objective at different temperature values is shown in figure 3. The thermal imaging objective is designed at a temperature of 20 °C so the PSF at this temperature is the best. As the temperature values are further away from the 20 °C temperature value, the lower the PSF becomes and the larger the size. With a temperature less than 20 °C, the PSF at 0 °C is much lower than the PSF at 20 °C. With a temperature greater than 20 °C, the higher the temperature, the lower the PSF and the larger the size. At 50 °C, the PSF is the lowest and the largest size.

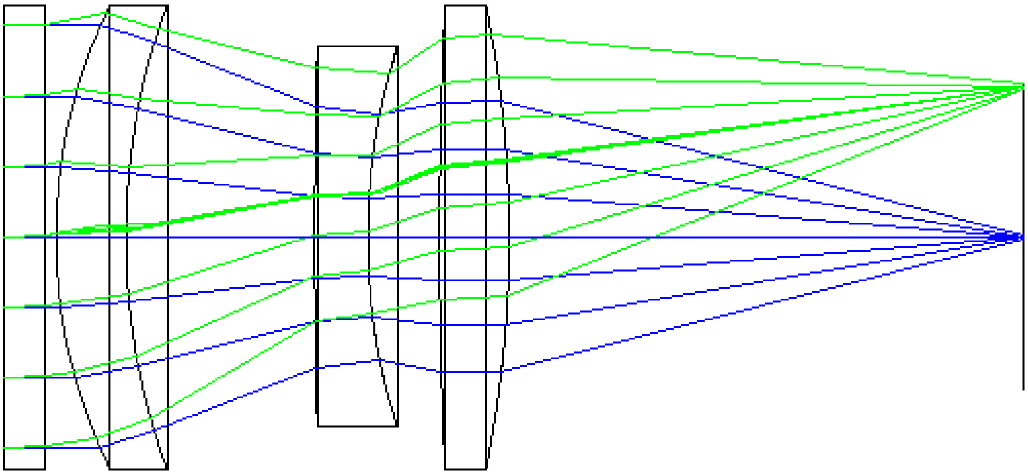
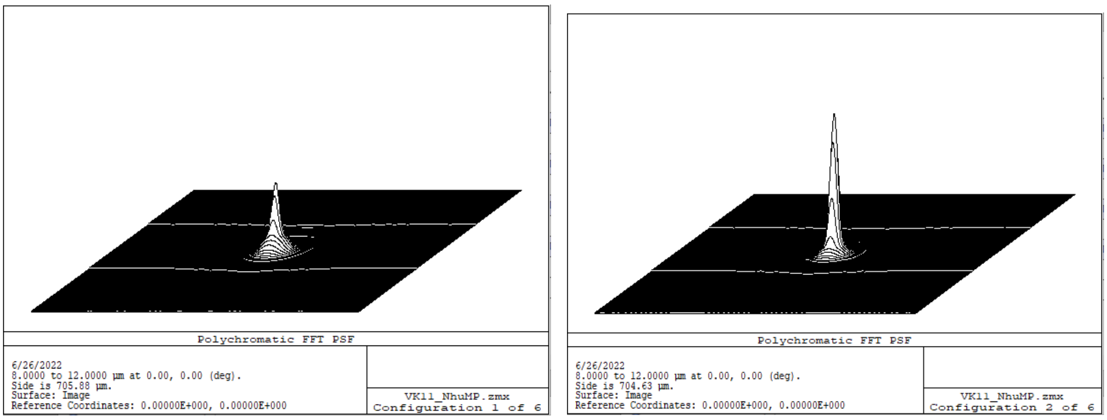
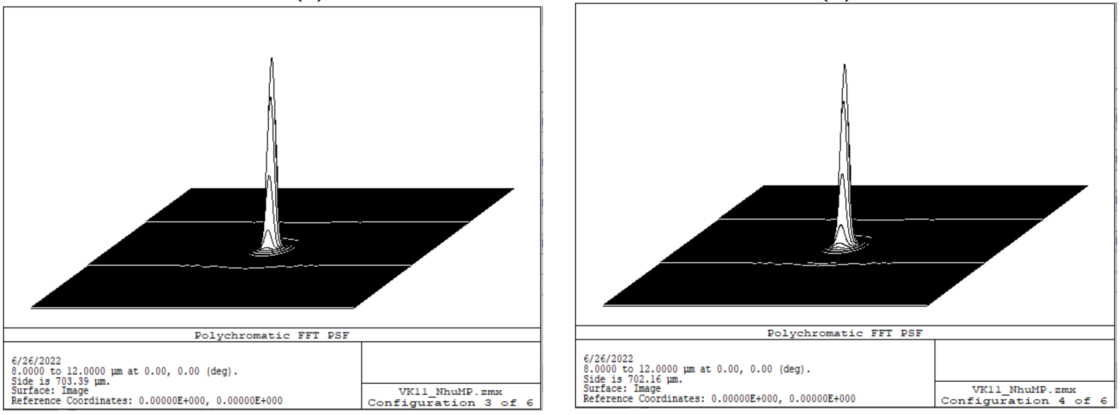


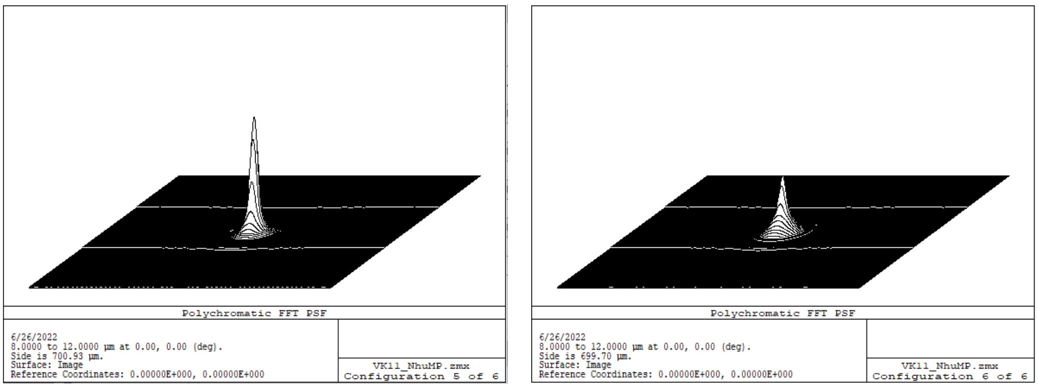
Figure 2. *Thermal imaging optical system.*



(a) 0 °C (b) 10 °C



(c) 20 °C (d) 30 °C



(e) 40 °C (f) 50 °C

Figure 3. *PSF at different temperatures.*

In the simulation, the sensor size is 256x256 pixels. The input image for the imaging simulation of the optical system is shown in figure 4.

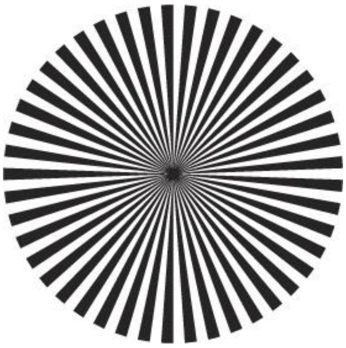


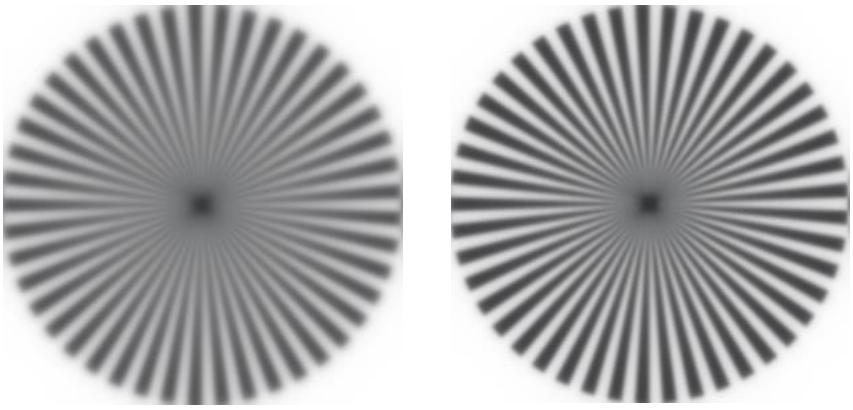
Figure 4. *Original image.*

Figures 5(a), 5(b), 5(c), 5(d), 5(e) and 5(f) show the obtained images of the optical system at different temperatures 0 ^{o}C, 10 ^{o}C, 20 ^{o}C, 30 ^{o}C, 40 ^{o}C and 50 ^{o}C, correspondingly. From figure 5, it can be seen that the image of the optical system at 20 ^{o}C has the best quality. As the temperature decreases or increases compared to the temperature value of 20 ^{o}C, the image quality of the optical system is deteriorated. As the temperature decreases, the image quality of the optical system at 0 ^{o}C is of the lowest. While the temperature increases, the image quality of that at 50 ^{o}C is the lowest, too. In particular, the image quality of the optical system at 50 ^{o}C is the worst in all temperature values. This is consistent with the evaluations of the PSF mentioned above.

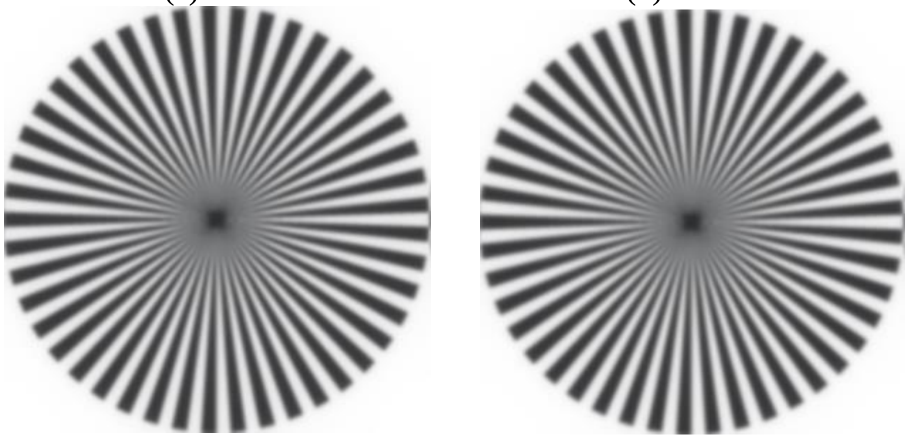
Table 2. *Parameters of the thermal imaging objective.*

Obj	Radius	Thickness	Glass	Semi-diameter
Stop	Cubic phase mask	2	Ge	11
1	Infinity	0.5		11
2	24.947	3.30	Ge	11
3	32.102	8.93		11
4	347.093	2.50	Ge	9.5
5	29.536	3.39		9.5
6	240.663	3.30	Ge	11
7	-56.374	24.326		11

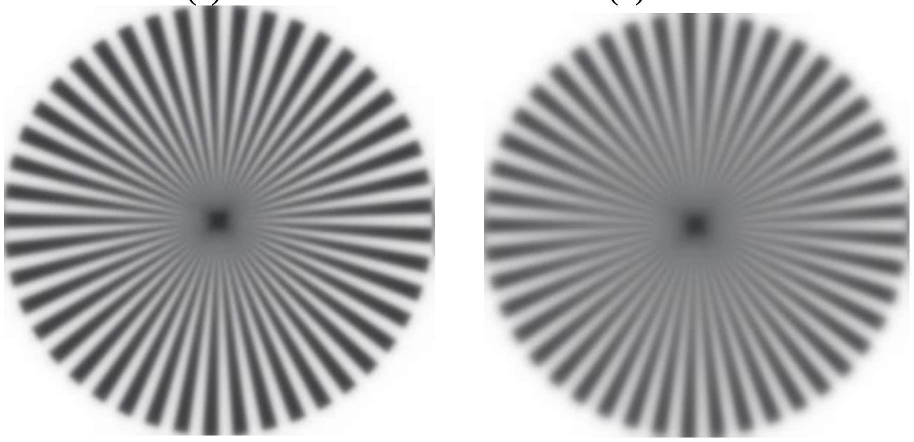
Next, we apply the wavefront coding technique to the thermal imaging objective. A cubic phase mask is added to the pupil of the thermal imaging objective with the parameters shown in table 2.



(a) 0 °C (b) 10 °C



(c) 20 °C (d) 30 °C

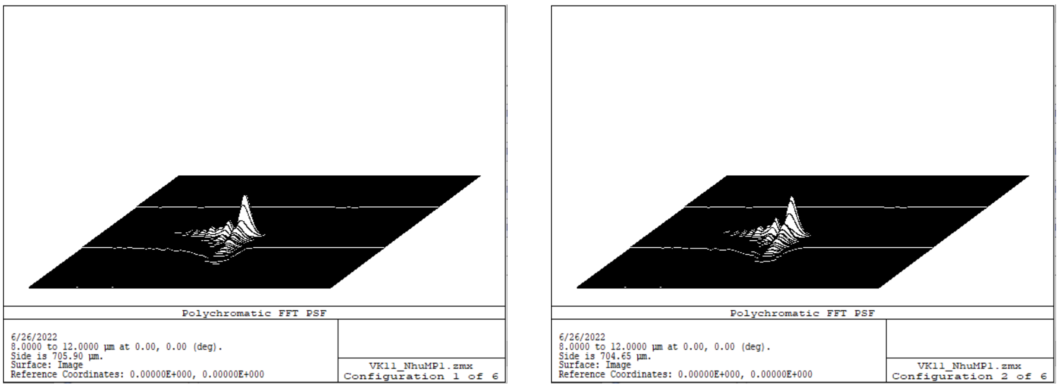


(e) 40 °C (f) 50 °C

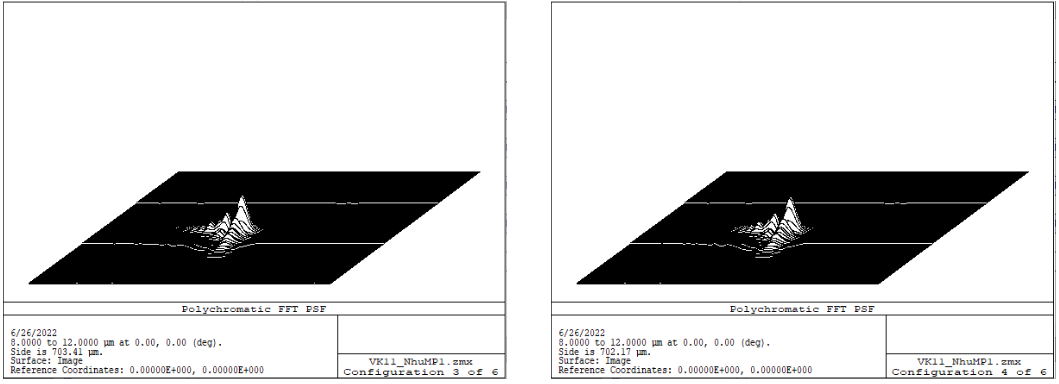
Figure 5. *Obtained images of the optical system at different temperature values.*

In order to obtain good image quality, the phase mask parameters need to be optimized so that the MTF function is invariant to the change of temperature in the range from 0 °C to 50 °C. The optimized cubic phase mask equation leads to the invariant point spread function over the temperature range determined in Zemax software as follows:

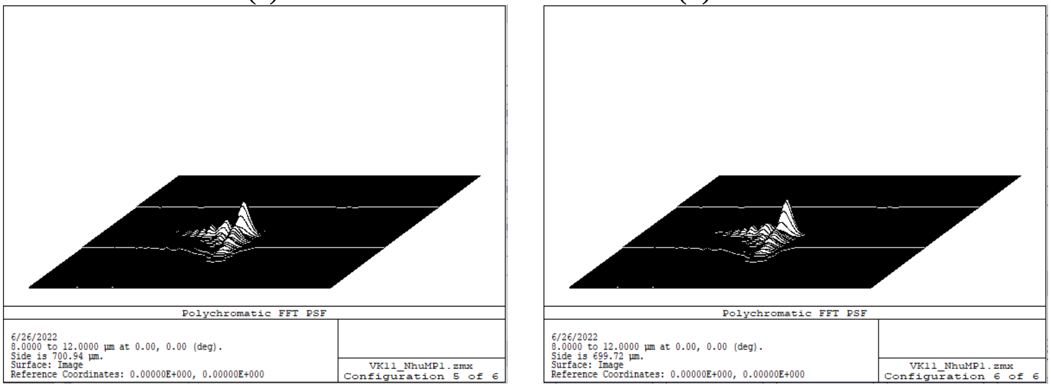
$$f(x,y)=4*10^{-6}(x^3+y^3) \qquad (14)$$



(a) 0 °C (b) 10 °C



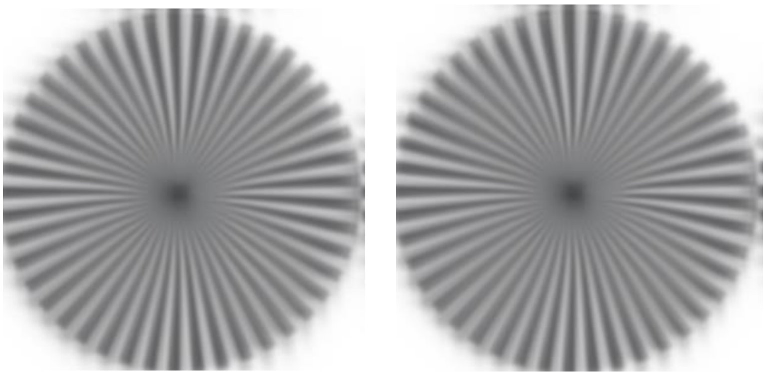
(c) 20 °C (d) 30 °C



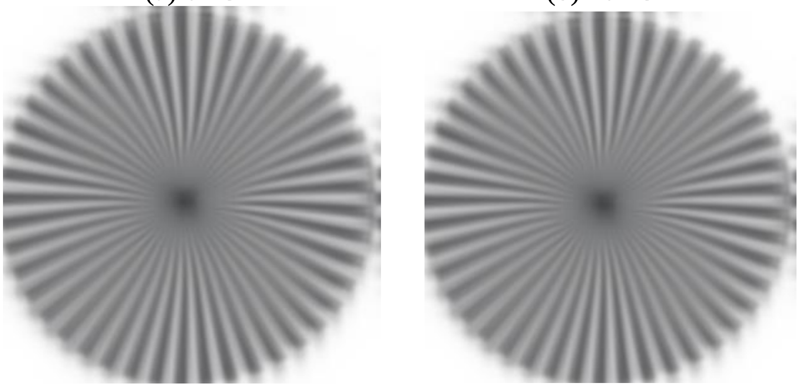
(e) 40 °C (f) 50 °C

Figure 6. *PSF at different temperatures of the proposed m.*

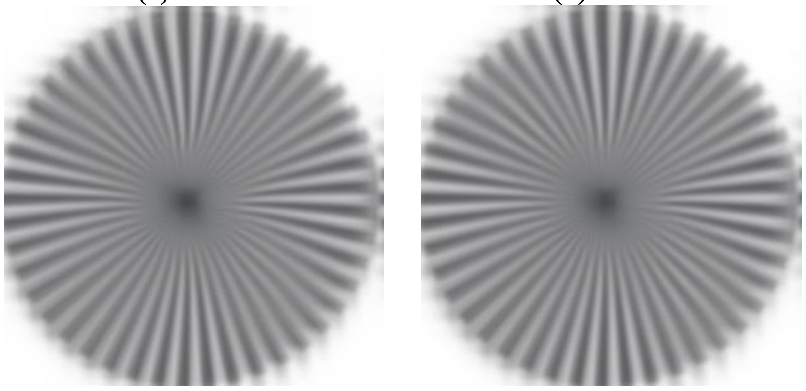
Figure 6 shows the PSF of a thermal imaging objective with a cubic phase mask at different temperatures, respectively. The PSF at 0 ^{o}C, 10 ^{o}C, 20 ^{o}C, 30 ^{o}C, 40 ^{o}C and 50 ^{o}C are shown in figure 6(a), figure 6(b), figure 6(c), figure 6(d), figure 6(e) and figure 6(f), respectively. Figure 6 shows that the PSF of the thermal imaging objective is nearly invariant with the change of temperature. However, the PSF value is relatively low and the size is enlarged. This means that the resulting image of the thermal imaging objective with the cubic phase mask will be blurred but almost invariant to the temperature change. These PSFs are nearly identical, so it is possible to use a single PSF function at one location to recover over the entire temperature range.



(a) 0 °C (b) 10 °C



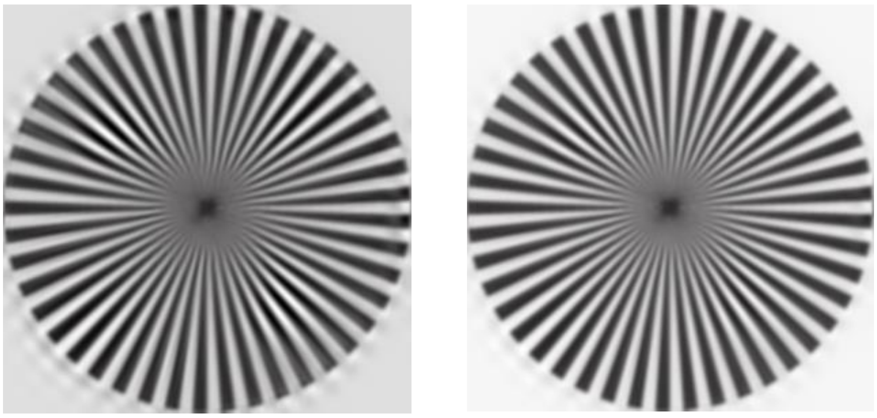
(c) 20 °C (d) 30 °C



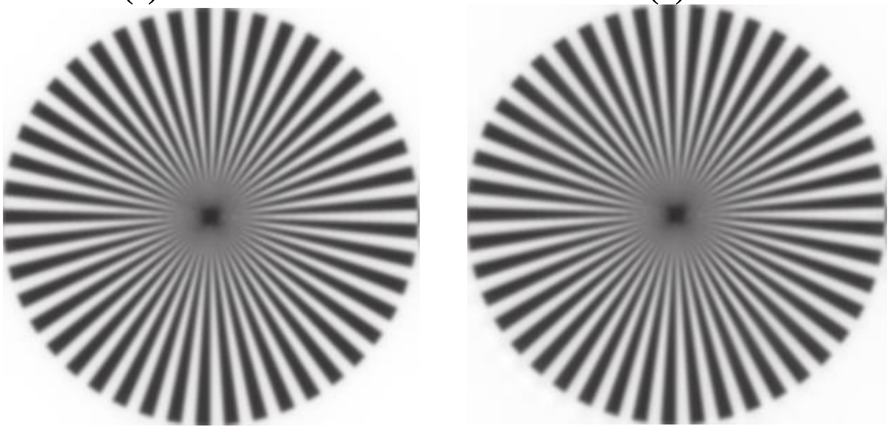
(e) 40 °C (f) 50 °C

Figure 7. *Obtained images of the optical system at different temperature values.*

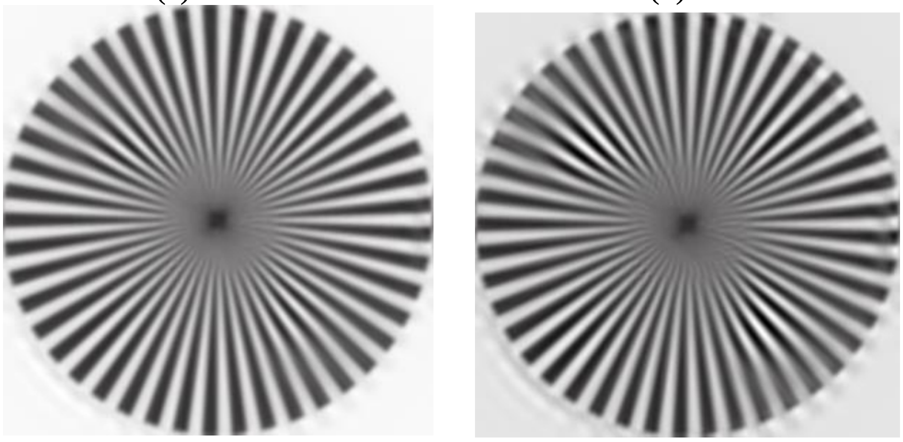
The images of the thermal imaging objective with the cubic phase mask at 0 ^{o}C, 10 ^{o}C, 20 ^{o}C, 30 ^{o}C, 40 ^{o}C, and 50 ^{o}C are shown in figures 7(a), 7(b), 7(c), 7(d), 7(e) and 7(f), respectively. From figure 7, it can be seen that the image quality of the thermal imaging objective with the cubic phase mask is almost invariant with the change of temperature. However, the received image is relatively blurry. Therefore, an image processing method needs to be deployed to obtain sharp image quality.



(a) 0 °C (b) 10 °C



(c) 20 °C (d) 30 °C



(e) 40 °C (f) 50 °C

Figure 8. *Obtained images of the optical system at different temperature values.*

Figure 8 shows the restored image obtained from a thermal imaging objective with a cubic phase mask at temperature values of 0 ^{o}C, 10 ^{o}C, 20 ^{o}C, 30 ^{o}C, 40 ^{o}C, 50 ^{o}C using the inverse filter in formula (12). From figure 8, it is clear that the restored image quality of the thermal imaging objective with the cubic phase mask is sharp and almost invariant to temperature changes. However, the restored image at values further away from the 20 ^{o}C temperature showed some impurities. Due to this, PSFs at these values are different from the PSF at 20 °C. This proves that the proposed method can eliminate the influence of temperature changes on the image quality of the thermal imaging objective.

4. CONCLUSIONS

In this paper, we successfully propose a solution to apply wavefront coding technology to thermal image objectives in order to eliminate the effect of temperature change on image quality. A thermal imaging objective was chosen as an example. A cubic phase mask was added to the thermal imaging objective to obtain a point spread function that is invariant to temperature variation. The inverse filter has been designed for image restoration. The image simulation results have demonstrated that the proposed method can eliminate the influence of temperature changes on the image quality of the thermal imaging objective.

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TÓM TẮT

Hiệu chỉnh ảnh hưởng nhiệt độ đến chất lượng ảnh vật kính ảnh nhiệt bằng công nghệ mã hoá mặt sóng

Bài báo đã đề xuất một giải pháp cho hiệu chỉnh ảnh hưởng của nhiệt độ đến chất lượng tạo ảnh của hệ thống ảnh nhiệt bằng công nghệ mã hoá mặt sóng. Một mặt nạ pha bậc ba đã được thêm vào diafram khẩu độ của vật kính ảnh nhiệt để thu được hàm nhoè điểm bất biến với nhiệt độ. Ảnh nhận được sẽ có chất lượng thấp nhưng gần như bất biến với sự thay đổi của nhiệt độ. Một phin lọc nghịch đảo đã được sử dụng cho khôi phục ảnh chất lượng cao trên một khoảng nhiệt đột thay đổi. Để chứng minh hiệu quả của phương pháp đề xuất, một vật kính ảnh nhiệt đã được sử dụng làm ví dụ. Kết quả mô phỏng chứng minh rằng, phương pháp đề xuất có thể loại bỏ hiệu quả ảnh hưởng nhiệt độ đến chất lượng vật kính ảnh nhiệt.

Từ khoá: Vật kính ảnh nhiệt; Lệch tiêu; Thuật toán khôi phục ảnh.