ZnSe-material phase mask applied to athermalization of infrared imaging systems

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This paper reports a ZnSe-material phase mask that is applied to athermalization of a conventional infrared imaging system. Its principle, design, manufacture, measurement, and performance validation are successively discussed. This paper concludes that a ZnSe-material phase mask has a permissible manufacturing error 2.14 times as large as a Ge-material phase mask. By constructing and solving an optimization problem, the ZnSe-material phase mask is optimally designed. The optimal phase mask is manufactured and measured with a form manufacturing error of 1.370 μm and a surface roughness value of 9.926 nm. Experiments prove that the wavefront coding athermalized longwave infrared (LWIR) imaging system works well over the temperature range from −40°C to +60°C.

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1. INTRODUCTION

Infrared imaging systems outperform visible cameras in night vision capability and find a wide range of applications in the areas of military, space exploration, and security surveillance. However, the thermal defocus aberration caused by the environmental temperature seriously affects the performance of an infrared imaging system [1,2].

In order to maintain the in-focus imaging quality over a wide range of environmental temperatures, many approaches have been developed to achieve the athermalization of infrared imaging systems such as the mechanically active method [3], the mechanically passive method [4], and the optically passive method [5]. Compared with those previous methods, the athermalization by wavefront coding technique has many advantages, such as avoiding the use of less desirable and exotic materials relaxing manufacturing tolerances for some optical and mechanical elements and shortening time for adjusting focus [6,7]. At the same time, both the rapid development of ultraprecision diamond machining techniques [8] and the continuously reduced cost of an infrared detector [6] help with its wide application.

Our previous research proposed a calculating model for equivalent thermal defocus amount in infrared imaging systems [2] and proposed an analytical model for the effect of temperature variation in wavefront coding infrared imaging systems [9]. For further developing a wavefront infrared imaging system, the material of an optical phase mask should be considered first. Commonly, optical phase masks have an axisymmetric surface or a free-form surface and are made of brittle-crystal infrared material such as Ge and ZnSe. Therefore, an optical cubic phase mask is difficult to be manufactured accurately. Our previous manufacturing test proves that a common ultraprecision machining technology tends to cause the detachment of crystal particles.

This paper discusses the permissible manufacturing errors of a ZnSe-material cubic phase mask; then its principle, design, manufacture, measurement, and performance validation are successively discussed.

2. OUR ATERMALIZED INFRARED IMAGING SYSTEM

A raytrace diagram of a wavefront coding infrared imaging system is shown in Fig. 1. An optical phase mask mounted in the pupil is responsible for optical coding. Optical coding makes the near-focal plane array (FPA) rays curved. Accordingly, the coded image captured by infrared detector is blurred.

The wavefront coding technique mainly includes two stages of optical coding and digital decoding [10]. The wavefront coding imaging system performs the wavefront modulation
of incident rays by mounting a purposely designed phase mask in its pupil to produce an intermediate coded image, which is given by

$$g(x_s, y_s) = f(x_s, y_s) \otimes h(x_s, y_s),$$  \hspace{1cm} (1)

where $f$ represents the observed scene, $h$ is the point spread function (PSF) of the wavefront coding infrared optical system, $g$ is the intermediate coded image, symbol $\otimes$ denotes the convolution operation, and $(x_s, y_s)$ are spatial coordinates.

Then, the intermediate coded image is digitally decoded to output a sharp decoded image, which is given by

$$\hat{f}(x_s, y_s) = g(x_s, y_s) \otimes m(x_s, y_s),$$  \hspace{1cm} (2)

where $m$ denotes the digital decoding function, and $\hat{f}$ is the decoded image.

Usually, a purposely designed cubic phase mask is mounted in a pupil of a wavefront coding infrared imaging system [6]. The surface form of a cubic phase mask is expressed as

$$z = \alpha (x^3 + y^3),$$  \hspace{1cm} (3)

where $(x, y)$ are the normalized coordinates and $\alpha$ denotes the form parameter of the cubic phase mask. The optical path difference (OPD) caused by the cubic phase mask is expressed as

$$\text{OPD} = (n - 1)\alpha (x^3 + y^3),$$  \hspace{1cm} (4)

where $n$ is the refractive index.

The maximum value of OPD caused by a cubic phase mask with a circular aperture is given by

$$\text{OPD}_{\text{max}} = 2(n - 1)\alpha.$$  \hspace{1cm} (5)

Obviously, if the purposely introduced maximized value of OPD is fixed, the smaller refractive index will correspond to a greater form parameter.

The performance of an athermalized infrared imaging system directly depends on the volume of a purposely introduced OPD rather than the material of an optical phase mask. Let $\alpha_{\text{ZnSe}}$ and $n_{\text{ZnSe}}$, respectively, represent the form parameter and refractive index of a ZnSe-material phase mask. Similarly, let $\alpha_{\text{Ge}}$ and $n_{\text{Ge}}$, respectively, denote the form parameter and refractive index of a Ge-material phase mask. Assuming their introduced maximized OPDs are equal, the following expression holds:

$$\frac{\alpha_{\text{ZnSe}}}{\alpha_{\text{Ge}}} = \frac{(n_{\text{Ge}} - 1)}{(n_{\text{ZnSe}} - 1)},$$  \hspace{1cm} (6)

The refractive index of Ge material is 4.003 and the refractive index of ZnSe material is 2.403 [11]. Thus, one can conclude that the permissible manufacturing error of a ZnSe-material cubic phase mask is approximately 2.14 times as large as that of a Ge-material cubic phase mask.

This paper aims to design, manufacture, and validate an optical phase mask that is expected to make the conventional infrared imaging system work well over a wide temperature range, from $-40^\circ C$ to $+60^\circ C$. With a larger permissible manufacturing error than a Ge-material optical phase mask, a ZnSe material phase mask is preferred.

As shown in Fig. 2, a conventional infrared imaging system to be athermalized is first developed with a focal length of $f = 65$ mm, F/1.0 and a field of view (FoV) of $6 \times 8$ deg, integrating with an uncooled, long-wave infrared FPA of 320 pixels $\times$ 240 pixels on a 38 $\mu$m pitch. Its operating wavelength covers 8–12 $\mu$m.

Because all the elements are made of Ge material, the performance of the conventional infrared imaging system is strongly sensitive to temperature variation. This can be evaluated by its modulation transfer function (MTF) at different temperatures. As shown in Fig. 3, MTF is numerically simulated according to its designed optical layout. The conventional
infrared imaging system achieves a higher MTF at +20°C. However, there is a serious degradation of the MTF for useful frequency range at the environmental temperatures of -40°C and +60°C. There are several nulls in MTF at some frequencies, which may result in irrecoverable loss of imaging information. This also proves that the conventional infrared imaging system has not been athermalized and cannot work well over the temperature from -40°C to +60°C.

For athermalization of the conventional infrared imaging system, a cubic phase mask will be mounted in its pupil. The form parameter \( \alpha \) of a cubic phase mask has a direct effect on the performance of an athermalized infrared imaging system. Usually, a large value improves the OTF consistency at different temperatures but degrades the MTF at room temperature. Therefore, the design of \( \alpha \) is related to the temperature range of athermalization. In this paper, the expected athermalization temperature range is from -40°C to +60°C.

Before optimizing the form parameter \( \alpha \), some work needs to be done in advance.

(i) A conventional infrared imaging system to be athermalized is optimized by ZEMAX Optical Design Software [12].

(ii) A ZnSe-material lens with 5 mm thickness and with two plane surfaces is inserted in its pupil in the design layout.

(iii) The infrared imaging system is refocused by only adjusting displacement of an infrared detector.

(iv) Based on the refocused infrared imaging system, the form parameter \( \alpha \) of a cubic phase mask is the only parameter to be optimized.

The form parameter \( \alpha \) is optimally designed by constructing and solving an optimization problem as follows.

This paper defines three variables \( C_{\text{PSF}}, \hat{C}_{\text{PSF}}, \) and \( \text{MTF}_{\text{min}} \):

\[
C_{\text{PSF}}(T_i, \alpha) = \frac{\langle V_{\text{psf}}(T_i, \alpha), V_{\text{psf}}(T_0, \alpha) \rangle}{\|V_{\text{psf}}(T_i, \alpha)\| \cdot \|V_{\text{psf}}(T_0, \alpha)\|}.
\] (7)

Here, \( V_{\text{psf}} \) represents the vectorization of the PSF matrix, \( V_{\text{psf}}(T_i, \alpha) \) denotes the PSF vector for \( i \)-th temperature sampled point, \( V_{\text{psf}}(T_0, \alpha) \) is the PSF vector at room temperature, \( \langle \rangle \) denotes an inner product operator, and \( \| \| \) represents the norm of a vector. The more the \( V_{\text{psf}}(T_i, \alpha) \) approaches \( V_{\text{psf}}(T_0, \alpha) \), the larger the \( C_{\text{PSF}}(T_i, \alpha) \) is. The maximum value of \( C_{\text{PSF}}(T_i, \alpha) \) is 1.0.

Based on \( C_{\text{PSF}} \), the mean \( \hat{C}_{\text{PSF}}(\alpha) \) is defined as follows:

\[
\hat{C}_{\text{PSF}}(\alpha) = \frac{1}{N} \sum_{i=0}^{N-1} C_{\text{PSF}}(T_i, \alpha),
\] (8)

where \( N \) denotes the number of temperature sampled points.

Based on the above focused conventional infrared imaging system, MTFs at different frequencies decline with the increasing spatial frequencies, under conditions of different values of form parameters. Therefore, our optimization method only needs to set a constraint for MTF at Nyquist frequency. The another index at Nyquist frequency is \( \text{MTF}_{\text{min}}(\alpha) \) defined as

\[
\text{MTF}_{\text{min}}(\alpha) = \min_i \{\text{MTF}(T_i, \alpha)\},
\] (9)

where \( \text{MTF}(T_i, \alpha) \) denotes the MTF value at Nyquist frequency and the \( i \)-th temperature sampled point.

Based on the definition of \( C_{\text{PSF}} \) and \( \hat{C}_{\text{PSF}} \), this paper constructs an optimization problem to maximize the value of \( \hat{C}_{\text{PSF}} \):

\[
\max_{\alpha} \hat{C}_{\text{PSF}}(\alpha),
\] (10)

whose constraint is \( \text{MTF}_{\text{min}}(\alpha) > K \).

Therefore, our optimization method need only set a constraint for MTF at Nyquist frequency (about 13.16 cycles per mm). The parameter \( K \) is related to the detector noise. Practically, parameter \( K \) greater than 0.1 helps to reduce the effect of detector noise. Considering that the optical system assembly will reduce the MTF, and in order to guarantee the assembled MTF (at Nyquist frequency) greater than 0.1, the parameter \( K \) is set to 0.2 in the process of optimization design.

By solving the optimization problem, the optimal form parameter \( \alpha_{\text{opt}} \) is 59.2 \( \mu \)m. It has a sag peak-to-valley (PV) of 118.4 \( \mu \)m. Figure 4 shows MTF at different temperatures. MTF is numerically simulated according to its designed optical layout. Compared with the MTF of the conventional infrared imaging system, the optimal phase mask ensures the MTF consistency at different environmental temperatures and removes the nulls of MTF. The MTF is measured at +20°C. With lens assembly error, measured MTF (at Nyquist frequency) is about 0.1.

Based on the optimal cubic phase mask, this paper further manufactures a ZnSe-material phase mask by our ultraprecision diamond machining technique, as shown in Fig. 2.

In order to improve the quality of the optical phase mask, an efficient and key technique was previously proposed by us to machine ZnSe material with a negative cutting angle under the extrusion state [8]. The proposed technique is reported as nanometric machining of ion implanted materials (NiIM) [13], which is based on the extrusion deformation theory. An ion implantation process is used to modify the surface mechanical properties of single crystal material before cutting.

![Fig. 4. Numerically simulated MTFs of the athermalized infrared optical system at different temperatures as well as measured MTF at +20°C.](image-url)
Measurement of a form manufacturing error of the cubic surface is shown in Fig. 5. Its form manufacturing error is measured by a Taylor profiler of PGI 1250, with a PV form manufacturing error of approximately 1.37 μm, and its central region has a smaller manufacturing error.

In order to accurately obtain a decoding PSF, we compensate the manufacturing error by fitting Zernike polynomials. The cubic phase mask affected by the form manufacturing error is fitted by means of Zernike polynomials [14].

The basic principle of Zernike polynomial fitting is that an arbitrary surface is regarded as a synthesis of a sequence of linear base surfaces. Since Zernike polynomials are orthogonal, an arbitrary surface is regarded as a synthesis of a sequence of linear combinations of Zernike polynomials:

\[ F(\rho, \theta) = \sum_{j=0}^{231} q_j Z_j(\rho, \theta), \tag{11} \]

where \( F(\rho, \theta) \) is the surface form to be fitted, subscript \( j \) denotes the ordinal number of Zernike polynomials, \( (\rho, \theta) \) denotes the polar coordinates, \( Z_j \) and \( q_j \), respectively, stand for the \( j \)-th Zernike polynomial and its coefficient.

The fitted Zernike coefficients can be obtained by the least squares method, which is expressed as follows:

\[
\begin{bmatrix}
\hat{q}_1 \\
\hat{q}_2 \\
\vdots \\
\hat{q}_{28}
\end{bmatrix} = \begin{bmatrix}
Z_1(\rho_1, \theta_1) & Z_2(\rho_1, \theta_1) & \cdots & Z_{28}(\rho_1, \theta_1) \\
Z_1(\rho_2, \theta_2) & Z_2(\rho_2, \theta_2) & \cdots & Z_{28}(\rho_2, \theta_2) \\
\vdots & \vdots & \ddots & \vdots \\
Z_1(\rho_{28}, \theta_{28}) & Z_2(\rho_{28}, \theta_{28}) & \cdots & Z_{28}(\rho_{28}, \theta_{28})
\end{bmatrix}^{-1}
\begin{bmatrix}
\hat{g}_1 \\
\hat{g}_2 \\
\vdots \\
\hat{g}_{28}
\end{bmatrix},
\tag{12}\]

where symbol \( \dagger \) represents the pseudoinverse operator. \( (\rho_i, \theta_i) \) and \( g_i (i = 1...M) \) are, respectively, the polar coordinates of the \( i \)-th measured point and its sag. \( M \) is the number of measured points.

ZEMAX Optical Design Software [12] supports a surface type of “Zernike Standard Sag.” Importing the fitted Zernike coefficients into the “Extra Data Editor” module of ZEMAX, we can obtain a simulated PSF with a form manufacturing error.

Additionally, surface roughness of the manufactured cubic phase mask is measured by a white light interferometer of Bruker Contour GT-K0. The cubic surface has a surface roughness Ra of 9.926 nm, as shown in Fig. 6. This figure was obtained by taking photos for a screen of a measuring instrument, so it looks like an aliased picture.

This paper further develops a real-time athermalized infrared imaging system that outputs decoded images at 30 frames per second. The manufactured and measured phase mask is mounted in the pupil of the conventional infrared imaging system, and the classical Wiener filtering method is utilized to decode an intermediate coded image. At digital decoding stage, the simulated PSF at +20°C with a form manufacturing error is used as a decoding kernel.

3. EXPERIMENTAL RESULTS

Figure 7 shows an intermediate coded image (left) and its corresponding decoded image (right) of our wavefront coding athermalized infrared imaging system at a temperature of +20°C. Our decoded image clearly shows the building structures such as square roof panels, triangle holes and circle holes in a wall, as well as a walking worker.

This paper further makes a comparison between the wavefront coding athermalized infrared imaging system with a ZnSe-material phase mask and its corresponding conventional infrared imaging system.
An experimental setup shown in Fig. 8 is constructed to verify the athermalization. This experimental setup is constructed from a modification of a high-low temperature test chamber (Model D/GDW-150L, manufactured by Shanghai Dianhe Laboratory Instrument Factory) by mounting an infrared germanium window on its one side. An infrared imaging system is placed in the high-low temperature test chamber for more than one hour at the preset temperature. Outdoor scenes are observed through the infrared germanium window of the high-low temperature test chamber. The environmental temperatures of the infrared imaging system are indirectly changed by adjusting the high-low temperature test chamber. Infrared imaging systems are separately set at temperatures of $+20^\circ$C, $+60^\circ$C, and $-40^\circ$C by adjusting the chamber temperature and keeping it at about an hour per temperature point.

As shown in Fig. 9(a), the images being captured by a conventional infrared imaging system is sharp, with good image quality at the temperature of $+20^\circ$C. However, with thermal defocus, the conventional infrared imaging system outputs degraded images with slight blurriness at $+60^\circ$C and with serious blurriness at $-40^\circ$C. Figures 9(b) and 9(c), respectively, show the intermediate coded images and the decoded images captured by our wavefront coding athermalized infrared imaging system. Our wavefront coding athermalized infrared imaging system with a ZnSe-material phase mask still outputs decoded images with sharpness at $+20^\circ$C, $+60^\circ$C, and $-40^\circ$C.

Additionally, in order to compare the signal-to-noise ratio (SNR) indices between the conventional infrared imaging system and the wavefront coding infrared imaging system, a square target pattern plate (as shown in Fig. 10) is mounted in focus of a portable infrared target projector (Model 66504 produced by Electro Optical Industries, Inc.) to create target and background regions. This setup is set to 10 K differential with respect to an ambient temperature background plate. Under these conditions, 100 frame conventional infrared images are captured and their signal and noise are calculated. The signal and noise calculation is the same as that of noise equivalent temperature difference (NETD) [15]. Similarly, 100 frame-decoded images captured by our wavefront coding athermalized infrared imaging system and their signal and noise (containing spatial and temporal noise) are calculated. Under these conditions, the SNR of the conventional infrared imaging system is 133.4 and the SNR of the wavefront coding infrared imaging system is 69.1. With the noise amplification of the Wiener filtering decoding method, the SNR of decoded images is 0.518 times as large as the conventional infrared imaging system.

### 4. CONCLUSIONS

This paper reports a ZnSe-material phase mask applied to athermalization of a conventional infrared imaging system. This paper concludes that a ZnSe-material phase mask has a permissible manufacturing error 2.14 times as large as a Ge-material phase mask. By constructing and solving an optimization problem, the ZnSe-material phase mask is optimally designed. A manufactured phase mask is measured with a form manufacturing error PV of 1.37 $\mu$m and a surface roughness value of 9.266 nm. By Zernike polynomials fitting, the effect of a form manufacturing error is numerically simulated. This paper develops a real-time athermalized infrared imaging system that can output decoded image at 30 frames per second. Experiments prove that the wavefront coding athermalized infrared imaging system works well over a temperature range from $-40^\circ$C to $+60^\circ$C.
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