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A wide-FoV athermalized infrared imaging system with a two-element lens

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HIGHLIGHTS

- Design and develop a wide-FoV athermalized infrared imaging system(AIIS) with a two-element lens.
- Manufacture a phase mask containing an aspheric surface and a cubic surface.
- Validate our wide-FoV wavefront coding AIIS has full FoV of 26.10° and operating temperature over −20 °C to +70 °C.

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ABSTRACT

For infrared imaging systems to achieve wide field of view (FoV), wide operating temperature and low weight, this work designs a wide-FoV athermalized infrared imaging system (AIIS) with a two-element lens. Its principle, design, manufacture, measurement and performance validation are successively discussed. The two-element lens contains four surfaces, where three aspheric surfaces are introduced to reduce optical off-axis aberrations and a cubic surface is introduced to achieve athermalization. The key coding mask containing an aspheric surface and a cubic surface is manufactured by nano-metric machining of ion implanted material (NiIM). Experimental results validate that our wide-FoV wavefront coding AIIS has a full FoV of 26.10° and an operating temperature over −20 °C to +70 °C.

1. Introduction

For the reader's convenience, this paper replaces some phrases with their acronyms. The phrase "athermalized infrared imaging system" is replaced with "AIIS". The phrase "wide-FoV athermalized infrared imaging system" is replaced with "WF-AIIS". The phrase "wavefront coding athermalized infrared imaging system" is replaced with "WC-AIIS". The phrase "wide-FoV wavefront coding athermalized infrared imaging system" is replaced with "WFWC-AIIS".

With a large field of view (FoV) and night-vision ability, a wide-FoV infrared imaging system is widely used in security monitoring. For a wide-FoV infrared imaging system to work over a wide temperature range, the variation of environmental temperature causes thermal defocus aberration resulting from varied curve and refractive index of infrared lens [1]. This defocus aberration strongly affects the performance of an infrared optical system. Therefore, athermalization should be taken into account.

Available approaches of infrared athermalization include the active mechanical [2], passive mechanical [3] and passive optical [4] measures. As a computational imaging technique, wavefront coding is a powerful hybrid optical-digital technique for extending an operating temperature range of an infrared imaging system [5–8]. Wavefront coding technique applied to the athermalization has many advantages such as avoiding less desirable and exotic infrared materials, relaxing manufacturing tolerances for some optical and mechanical elements, shortening time consumption of adjusting focus [6,9].

Among wavefront coding techniques, this approach using a binary phase mask [10,11] as a coding mask was validated by simulation over a temperature range of 40 °C. Decoded images by this approach [12] are serious in noise. This approach [6] focuses on correcting off-axis aberrations at a room temperature. Our previous approach [13] works well over a temperature range of 110 °C. However, both our previous approach [13–15] and other researchers' approaches [6,16] have a relatively narrow FoV.

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For a WFWC-AIIS, the off-axis aberrations cause optical transfer function (OTF) differences between FoV areas. As a result, utilization of a single decoding kernel to all the wide-FoV areas of an intermediate coded image will cause serious artefacts [6]. In order to correct off-axis aberration and meanwhile extend operating temperature range, utilization of many infrared spherical lenses will reduce the transmission efficiency and increase the weight and cost.

Actually, for application of infrared imaging systems on aerial vehicles for the protection or detection of high value targets [17,18], all the three aspects of athermaliztion, wide FoV and low weight are significant. To meet requirements for those three aspects of infrared imaging systems, this paper proposes a joint design. In this design, wavefront coding technique is utilized to achieve a wide operating temperature range; aspheric surfaces are utilized to achieve a wide FoV; and a phase mask containing an aspheric surface and a cubic surface is designed to further reduce the weight and cost.

This paper reports a WFWC-AIIS with a two-element lens. This work reports the largest FoV AIIS by wavefront coding imaging technique. Its principle, design, manufacture, measurement and performance validation are successively discussed. This paper constructs an optimization problem which maximizes the weighted mean of point spread function (PSF) consistency for both the FoV and operating temperature range. The design result is a WFWC-AIIS with a two-element lens, where three aspheric surfaces are introduced to reduce optical off-axis aberrations and a cubic surface is introduced to achieve athermalization. The optimally designed phase mask containing an aspheric surface and a cubic surface is manufactured. This paper further develops a WFWC-AIIS and its FoV and operating temperature range are validated.

This paper is organized as follows. Section 2 discusses the design and manufacture of our WFWC-AIIS. The developed WFWC-AIIS is validated in Section 3. The conclusion is presented in Section 4.

2. Development of our WFWC-AIIS

2.1. Design

Cathey and Dowski previously proposed the wavefront coding technique to extend depth of focus [19]. This technique firstly was used to extend field depth of a microscope [20] and then researchers explored this technique to athermalize infrared imaging systems [5,15]. This technique mainly includes two stages of optical coding and digital decoding. By mounting a purposely designed optical phase mask in a pupil of a conventional imaging system, the incident rays are wavefront modulated. Consequently, the near focal plane array (FPA) rays focus on an axial range other than a focusing point (as shown in Fig. 1) and the coded image becomes blurred. The focusing range causes that the intermediate coded image is insensitive to misfocus-related (or thermal defocus) aberrations. Then, the intermediate coded image is digitally decoded to output a decoded image with sharpness.

Based on the principle of wavefront technique, to meet requirements for wide FoV, wide operating temperature and low weight of an infrared imaging system, the motivation of this work is to develop a WF-AIIS using a two-element lens. The other parameters are also required. The expected full FoV is greater than 25°, F number is less than 2.0, and the expected temperature range covers −20 °C to +70 °C. A long-wave infrared (LWIR) FPA of 640 × 512 pixels on a 17um pitch is preferred. This infrared detector has an operating spectral range of 8–13.5 μm.

For a WFWC-AIIS, off-axis aberration causes optical transfer function (OTF) differences between FoV areas. Those differences will degrade the image quality of a decoded image and increase the difficulty of digital decoding [6]. In order to realize that a central-FoV PSF is utilized to decode all the areas of an intermediate coded image which is captured under a wide operating temperature range, optical PSFs should be kept invariant in radial and axial directions. Difference between PSFs lies in aberrations. Relative to an ideal image plane, one spatial point near focal plane array (FPA) in a wavefront coding imaging system, revolves three types of optical aberrations. They are geometrical aberrations, defocus aberrations, purposely introduced wavefront-coded aberrations. Commonly, an introduction of aspheric surfaces is an effective way to correct geometrical aberrations (aspheric surface is mostly effective in correcting on-axis aberrations). Aspheric surfaces also help to reduce the lens number and increase the compact. The introduced wavefront-coded aberrations are effective to reduce the impact of thermal defocus aberrations. Note that to keep PSFs invariant only by introducing large wavefront-coded aberrations will seriously lower MTF of a wavefront coding optical system.

Therefore, in our design, both the aspheric surface and wavefront-coded surface are jointly utilized to keep PSFs invariant in radial and axial directions. Aspheric optical surfaces correct off-axis aberrations of the WF-AIIS. Wavefront-coded surface is mainly responsible for the athermalization of the WF-AIIS. The design procedure of our WFWC-AIIS mainly consists of two stages.

Stage I This stage is to optimize an aspheric infrared optical system at +25 °C by a commercial optical design software such as ZEMAX, CODE V and OSLO, regardless of the athermalization feature. Fig. 2 shows the resulted raytrace diagram. The optical system includes two pieces of aspheric lenses that are made of Ge material. As a temporally set plane, the fourth surface (from left to right) is located at the pupil stop and left for the wavefront coding surface. After optimization, the parameters of three aspherical

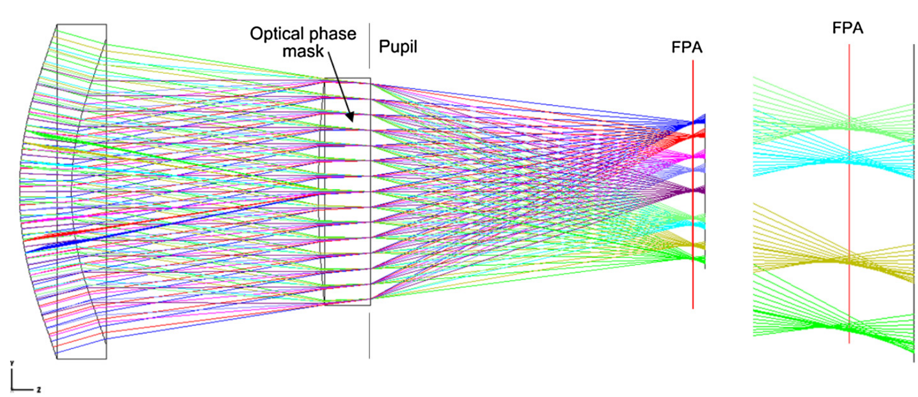

Fig. 1. Raytrace diagram of a wavefront coding infrared imaging system.