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# Long Wave Infrared Wavefront Sensing through a Thin Diffuser

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## ABSTRACT

Long wave infrared (LWIR) radiation between 8-14  $\mu\text{m}$  allows imaging without external illumination, and is the fingerprint region for spectroscopic chemical species identification. Infrared (IR) imaging has wide-ranging applications in defense thermography, airborne sensing, structural fault detection, atmospheric measurements and non-invasive medical testing. The need to characterize infrared optics, and probe the thermal emission from controllable metasurfaces of IR nano-antennas,<sup>1</sup> has prompted our development of a high-resolution LWIR imaging methodology. The technique of speckle imaging enables the detection of phase or intensity through complex scattering media - at visible<sup>2</sup> and IR wavelengths.<sup>3</sup> One-shot speckle images of the light scattered through inhomogeneous complex media contain adequate information to enable scene reconstruction and for imaging around obstacles. In this paper, we describe a novel broadband LWIR speckle imaging configuration for wavefront sensing, utilizing a thin diffusive medium and an uncooled microbolometric camera. The thin diffuser has a high angular memory effect, which produces deformations in the speckle image when the locally varying phase of the impinging wavefront is scattered by the diffuser. The spatial shifts of the speckle grains in the images are registered using a rapid diffeomorphic image registration algorithm, generating a high-resolution map of the local phase gradients. The local phase gradients are then integrated in 2-D to reconstruct the wavefront profile. We demonstrate thermal wavefront reconstruction through the LWIR speckle imaging technique in IR optical samples, with promising future applications for imaging through visually non-transparent media like semiconductor wafers, engineered nano-electronic surfaces, and infrared optics.

**Keywords:** Phase imaging, Infrared imaging, Wavefront sensing, Surface scattering, Complex media, Broadband imaging

## 1. INTRODUCTION

All matter with temperature above absolute zero Kelvin emits thermal radiation, which emerges from the conversion of the kinetic energy of motion of its constituent particles into electromagnetic energy. Thermal radiation provides a way to investigate thermal sources, while the development of tailored unconventional thermal sources<sup>4</sup> enable the altering of thermal emission for innovative applications like creating more energy efficient materials.<sup>5</sup>

Thermal sources are typically broadband with low spatial and temporal coherence, thus radiating near-isotropically over a broad angular range and spectrum. Sub-wavelength structuration on polar and plasmonic materials have been successfully developed to control and alter the emitted thermal radiation.<sup>6,7</sup> Recently, metasurfaces composed of sub-wavelength Metal-Insulator-Metal (MIM) resonators of various geometries have enabled spatial and spectral control of infrared radiation.<sup>8</sup> These atypical thermal sources thus necessitate the need to characterize the Infrared (IR) emitters themselves. Our specific interest lies in investigating the thermal emission from IR nano-antennas in the far field, and reconstructing thermal wavefronts using imaging.

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Thermal radiation from objects near room temperature fall in the sub-band of infrared radiation known as the Long wave infrared (LWIR), with photon wavelengths from 8 to 14  $\mu\text{m}$ . This makes the LWIR spectrum particularly relevant for thermal imaging, as objects can be imaged solely due to their emitted thermal radiation without being externally illuminated.<sup>9</sup> The overlap with the transmittance window of the earth’s atmosphere makes the LWIR useful for atmospheric and space applications<sup>10</sup> as well.

To carry out thermal wavefront sensing, it is necessary to encode the phase of the IR radiation in an intensity pattern since it cannot be directly measured by a camera. IR holography<sup>11</sup> is a possible technique, but the difficulty of sourcing optical components in the IR and its careful alignment demand an alternative approach. Visible wavefront sensors<sup>12</sup> map the local wavevectors directly onto a two-dimensional image to obtain a phase map. Self-referenced techniques for wavefront sensing encode the phase in an intensity image by having an optical mask before the camera,<sup>13</sup> where small deformations due to local phase gradients allow the reconstruction of the incident wavefront with high fidelity.<sup>2</sup> In this communication, we augment the IR speckle imaging configuration developed in<sup>14</sup> for wavefront sensing. Our setup with a thin diffuser and uncooled thermal camera allows us to demonstrate quantitative LWIR wavefront reconstruction, which can potentially lead to thermal wavefront sensing of more complex samples.

## 2. IMAGING THROUGH A DIFFUSER & PHASE ENCODING

The transmission of light through a thin scattering medium introduces random dephasing at the local scale due to the variable roughness of the thin diffusive medium on the order of a wavelength.<sup>15</sup> Visible speckle imaging has demonstrated the ability to carry out single-shot object reconstruction from speckle patterns.<sup>16</sup> This is due to the high degree of spatial correlation in the speckle images that is still preserved after transmission through the thin diffuser, as seen in the high degree of similarity between the autocorrelation of a speckle pattern and the autocorrelation of the same object imaged by conventional lenses.<sup>13</sup>

The key to a thin diffuser’s high degree of spatial correlations in the speckle patterns is due to the phenomenon known as ‘Memory effect’. A small global tilt in the wavefront incident on a thin diffuser does not change the speckle pattern but only shifts it in the transverse direction by an amount proportional to the tilt angle  $\theta$ . However, a local tilt in the wavefront produces a local deformation of the speckle pattern, resulting in a distorted speckle, which enables precise wavefront sensing as the speckle becomes a unique fingerprint of the incident wavefront.

P. Berto *et al.* in 2017 demonstrated wavefront sensing using a thin diffuser in front of a visible camera, thanks to the memory effect of speckle correlations, and carried out high-resolution phase imaging.<sup>2</sup> Considering that the angle  $\theta$  between the local wavefront distortions is small, which is true for paraxial rays, the wavefront slope or the local phase gradient  $\varphi$  can then be calculated by computing the ratio of the local spot displacement,  $\mathbf{s}$ , to the distance between the wavefront and the sensor,  $\mathbf{d}$ .

$$\theta \simeq \tan\theta \simeq \sin\theta = \|\nabla_{\perp}\delta\| \quad (1)$$

$$\nabla_{\perp}\delta = \frac{\nabla_{\perp}\varphi}{k_0} \simeq \frac{\mathbf{s}}{d}, \quad (2)$$

where,  $d$  is the distance between the diffuser and the speckle,  $\varphi$  is the wavefront’s phase, and  $k_0 = \frac{2\pi}{\lambda}$  is the wavenumber. This relation connecting the phase of the wavefront to the speckle grain displacement allows the phase to be computed from the intensity images themselves. In our case, we use the diffeomorphic Demon’s algorithm to compute the minuscule displacements of the speckle grains between the reference and sample speckle images, as shown in [Figure 2](#).<sup>17,18,19</sup> Obtaining the local displacement vector field and integrating it in 2D gives access to the reconstructed wavefront.

### 3. EXPERIMENT & RESULTS

To carry out speckle imaging for thermal wavefront sensing in the far field, we have developed a broadband LWIR speckle imaging setup using a thin diffusive medium and an uncooled microbolometric camera, as shown in Figure 1 and described in a previous communication.<sup>14</sup> In our experiment, we typically capture 100 frame movies at 25 Hz, and average them before processing. At first, a reference speckle due to the plane wavefront is acquired. Subsequently, a Zinc Selenide plano-convex lens of focal length 1 metre is placed as a test phase object, which alters the plane wavefront and produces a converging wavefront that has a focus 1 metre away. The distorted speckle due to the converging wavefront is then captured as the sample speckle image.

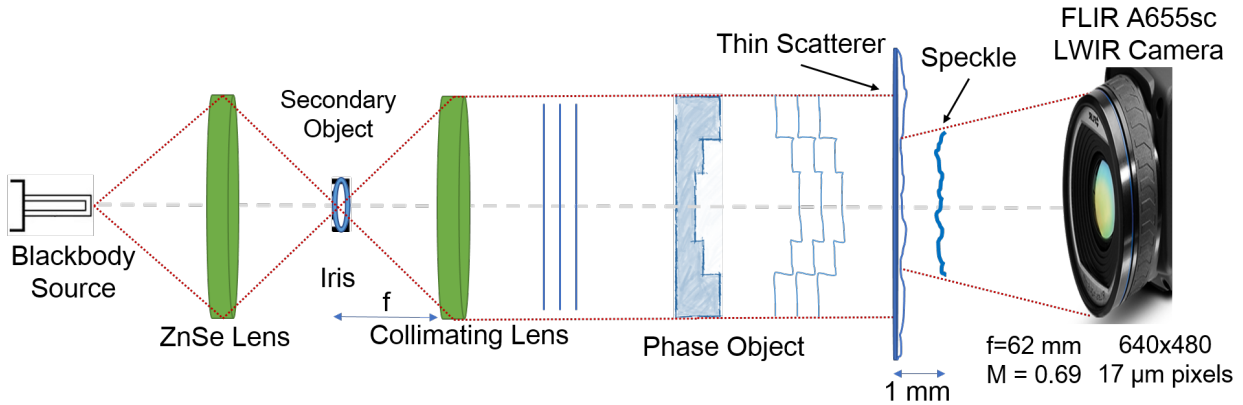


Figure 1: LWIR Speckle Imaging Experimental Setup. A Silicon Carbide globar source is heated to about 1000 K, and imaged onto an iris to control its spatial extent. The homogeneous secondary source is then collimated to produce a plane wavefront, which impinges on a phase object that distorts the wavefront. The distorted wavefront is incident on the thin surface scatterer, forming a speckle in transmission that is imaged using an objective lens onto the 0.3 Megapixel sensor of a FLIR uncooled microbolometric LWIR camera.

The minuscule displacements of the speckle grains between the reference and sample speckle are computed using the diffeomorphic Demon's algorithm. The algorithm uses effectors known as Demons to alter a deformable grid of the sample image to diffuse through the contours of the static reference image, ultimately trying to match the two. The deformations produced by the Demons are used to compute a displacement field which is integrated in the Fourier domain to obtain the reconstructed wavefront.

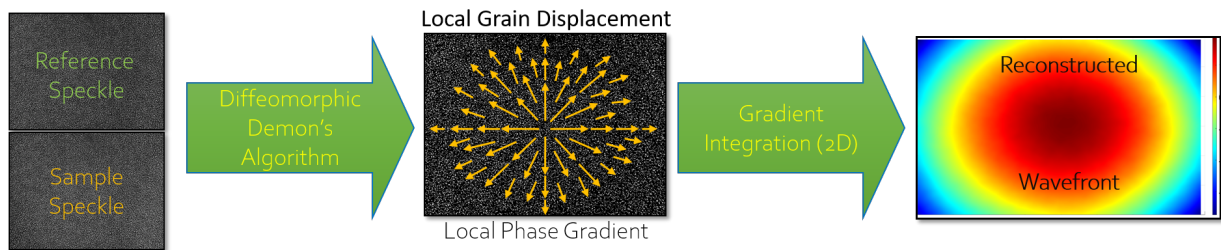


Figure 2: Thermal Wavefront Reconstruction from LWIR Speckles - Diffeomorphic Demon's Algorithm. The algorithm takes as input the reference speckle and the sample speckle and a small number of parameters, then computes a local displacement vector field map from the local speckle grain shifts between the two images, and produces the phase map or reconstructed wavefront to be detected.

The plane wavefront becomes a converging wavefront after passing through the sample lens, and ideally, we expect to reconstruct this spherical wavefront that is incident on the scattering medium, as seen in Figure 3.

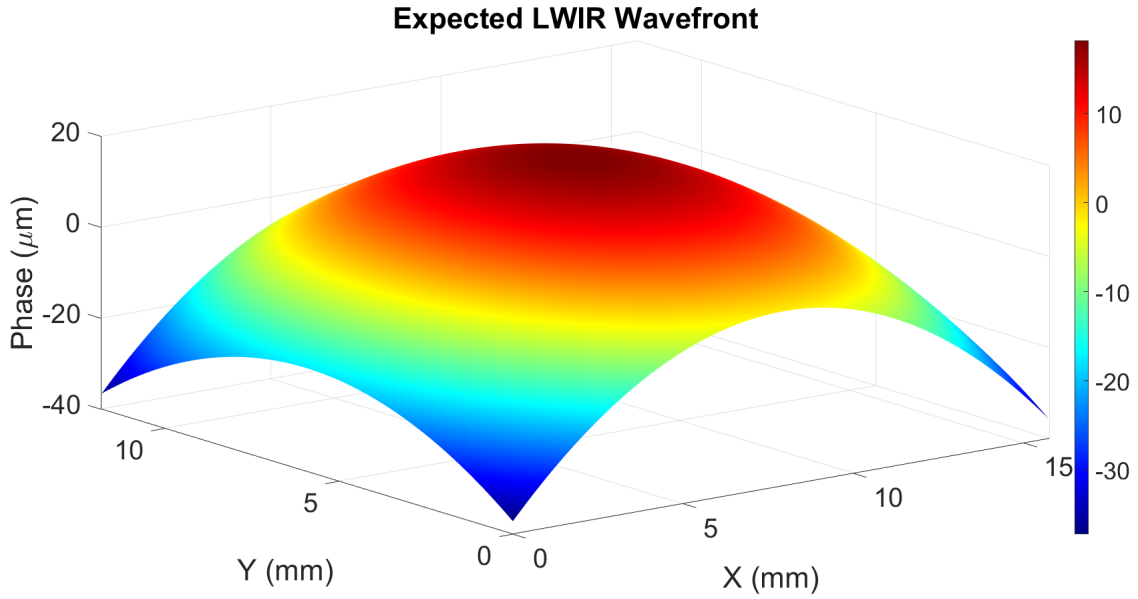


Figure 3: LWIR Ideal Expected Wavefront

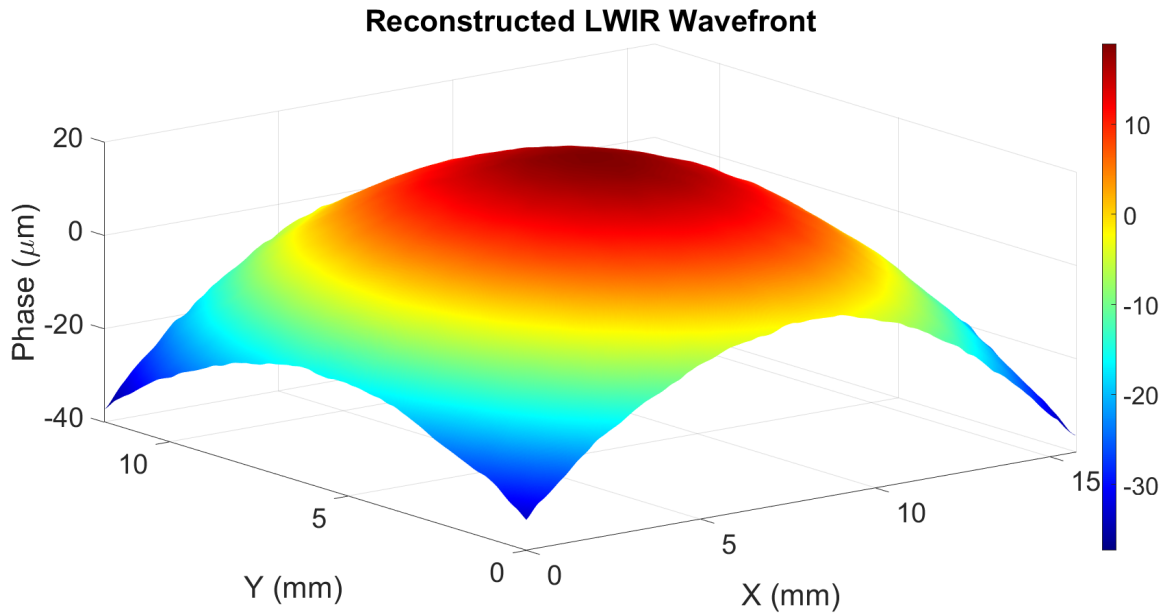


Figure 4: LWIR Reconstructed Wavefront

We can finally see in [Figure 4](#), that the reconstructed wavefront matches the spherical shape of the expected wavefront above. This similarity of the symmetric spherical profile of the reconstructed and ideal expected wavefront demonstrates qualitative phase reconstruction in the longwave infrared. We also fit the reconstructed wavefront to a spherical profile,  $z(x, y) = \frac{x^2 + y^2}{2R}$  to estimate the radius of curvature of the wavefront. The reconstructed radius of curvature turns out to be 93.5 cm while the ideal expected radius of curvature is 98 cm, with a difference of 4.6%. This promising result opens up the avenue towards quantitative wavefront reconstruction of more complex phase samples in the longwave infrared.

## 4. CONCLUSION

We have demonstrated thermal wavefront reconstruction in the LWIR for a phase modifying sample, using our simple broadband speckle imaging setup that consists of a thin diffuser and an uncooled thermal camera. The memory effect of the thin diffuser and the efficient diffeomorphic Demon’s algorithm allow us to carry out LWIR wavefront reconstruction that is compact and fast, while the uniqueness of the speckle patterns also avoids reconstruction artifacts in the reconstruction.

In the future, we seek to improve our LWIR wavefront sensing technique for more precise quantitative phase reconstruction of phase samples with increasing complexity. The experimental technique can then be used to image visually opaque samples like semiconductor circuits, and IR optics for wavefront sensing and defect detection.

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