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Long Wave Infrared Wavefront Reconstruction Through Complex Media

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Abstract: A novel broadband infrared (IR) speckle imaging system with a thin scatterer and an uncooled microbolometric camera is employed to encode wavefront phase variations as local speckle deformations. The phase reconstruction from speckle shifts using a fast diffeomorphic algorithm ultimately demonstrates IR wavefront reconstruction through complex media. © 2021 The Author(s)

1. Introduction

Long wave infrared (LWIR) radiation ($\lambda = 8-14 \mu\text{m}$) enables illumination-less passive thermal imaging, and precise chemical identification, besides atmospheric sensing, fault detection, and medical testing. Investigating far-field thermal emission from IR nano-antennas [1], and reconstructing thermal wavefronts from tunable free-form planar optics [2] has motivated our development of a novel broadband thermal wavefront sensing technique. Speckle imaging is widely used for intensity or phase imaging with broadband sources through complex inhomogeneous media at visible wavelengths [3], and recently in the infrared [4]. Visible speckle imaging has demonstrated the ability to encode the wavefront information in an intensity pattern [5], with the ability to reconstruct wavefronts by comparing a reference speckle to a deformed speckle [3]. We demonstrate LWIR wavefront reconstruction using a broadband speckle imaging setup comprising a thin scattering medium in front of an uncooled microbolometric camera. Our technique promises future imaging applications through visually opaque samples like semiconductor chips, solid-state nanoelectronics, and infrared optics, for defect characterization.

2. Speckle Imaging

Upon transmission through complex scattering media, a wavefront produces a unique speckle pattern. A local wavefront tilt produces a corresponding local deformation in the speckle pattern, which facilitates precise wavefront sensing as the speckle is a unique fingerprint of the incident wavefront. Assuming that θ , the tilt angle of the incident wavefront is small, the optical path difference δ and the tilt angle are related as $\theta \simeq \tan\theta \simeq \sin\theta = \|\nabla_{\perp}\delta\|$. The local displacement vector field of the speckle grains, \mathbf{s} , is proportional to the gradient of the optical path difference (δ) encountered by the beam:

$$\nabla_{\perp}\delta = \frac{\nabla_{\perp}\varphi}{k_0} \simeq \frac{\mathbf{s}}{d}, \quad (1)$$

where, d is the distance between the scatterer and the speckle imaging plane, φ is the phase of the wavefront, and $k_0 = \frac{2\pi}{\lambda}$ is the wavenumber. This equation gives access to the phase of the wavefront by computing the displacement \mathbf{s} over the entire field between the reference speckle and sample speckle image. The displacement map is estimated using the fast non-rigid diffeomorphic Demon's algorithm for image registration. [6] The gradient of this displacement vector field is integrated in 2-D to finally obtain the reconstructed wavefront.

3. Experimental Setup and Results

Our far-field LWIR speckle imaging setup consists of a Silicon carbide global blackbody source which is imaged using a Zinc Selenide (ZnSe) lens (7-12 μm) in a Köhler illumination scheme onto an iris for spatial filtering. The iris image then becomes a secondary source, which is collimated using another lens. This plane wavefront is incident on the complex medium, where it undergoes surface scattering. The transmitted light forms a reference speckle due to the inhomogeneous surface roughness of the scattering medium's exit surface. With a phase object, the plane wavefront is distorted and this produces a deformed sample speckle. The speckles formed 1mm away

from the scattering medium are imaged using a close-up lens of focal length $f = 62$ mm and magnification $M = 0.69$ onto the sensor of a FLIR A655sc uncooled microbolometric LWIR camera. Our imaging setup is therefore a broadband uncooled thermal speckle imaging system. To test the feasibility of LWIR wavefront reconstruction using speckle imaging, we use a ZnSe lens of focal length, $f = 1$ m, as a known phase object. This sample lens distorts the plane wavefront and produces a converging wavefront with a focus 1 m along the propagation axis. The local speckle grain shifts between the reference speckle and the sample speckle are computed using the rapid non-rigid image matching technique of diffeomorphic Demon's algorithm, which minimizes the mean squared difference function between the two images. The computed displacement vector field is then integrated in 2D in the Fourier domain to obtain the reconstructed wavefront. As evident from Figure 2, the reconstructed wavefront matches the phase values and the spherical profile of the ideal expected wavefront, which opens up the path towards precise quantitative LWIR wavefront reconstruction.

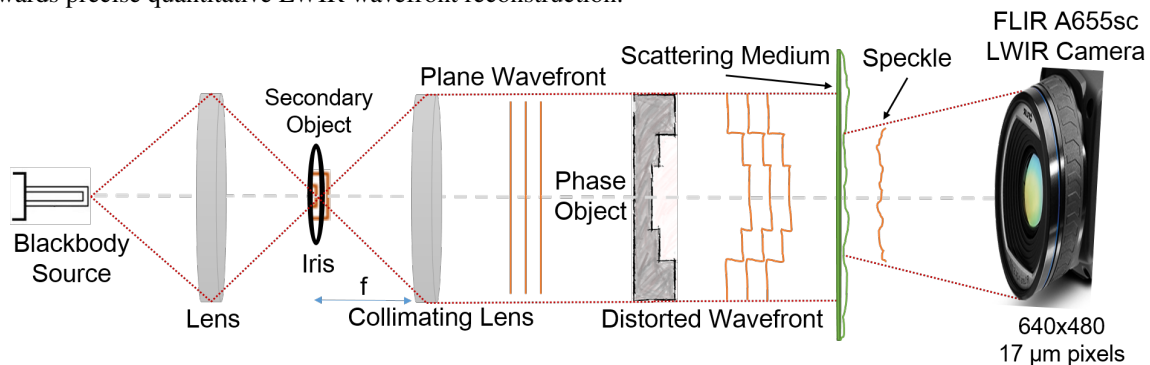


Fig. 1: Experimental Setup for LWIR Speckle Imaging

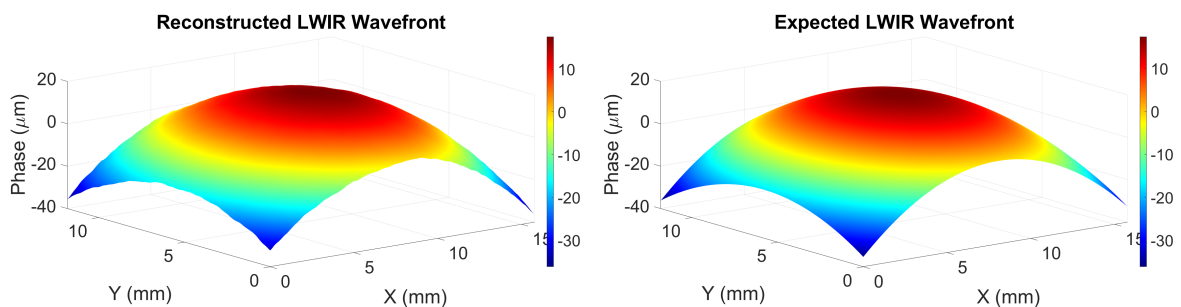


Fig. 2: LWIR Wavefront Reconstruction. Experimentally reconstructed (left) & ideal expected (right) wavefronts when a Zinc Selenide lens of $f = 1$ m is placed as a phase sample in the setup shown in Figure 1.

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