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Ultra-compact metalens-based phase shifting interferometry for surface metrology

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Abstract

The transition toward Industry 4.0 has created a significant demand for compact, integration-ready optical sensors capable of enabling on-machine measurement and closed-loop process control. Conventional optical metrology systems remain limited by bulky and heavy refractive components, which restrict their deployment in space-constrained manufacturing platforms. This paper reports on the design, fabrication, and experimental validation of a high-performance GaN-based metalens doublet and its implementation in an ultra-compact phase shifting interferometry system. The metalens doublet was designed with a 2 mm field of view within a total axial length of 11.5 mm. Phase modulation is achieved through a truncated optical waveguide mechanism, where nanopillars (750 nm height, 70–180 nm radius) are etched into a GaN layer on an Al_2O_3 substrate and arranged in a 450 nm square lattice. By tailoring pillar dimensions, full 2π phase coverage is realised at a design wavelength of 660 nm. Optical simulations and experimental characterisation confirm high-quality imaging performance suitable for objective lens applications. The metalens doublet is integrated into a phase-shifting interferometric module with a total optical footprint of 6.25 mm × 9.5 mm × 5 mm. Surface measurements of a calibrated 43.7 nm step-height standard show strong agreement with results obtained from a commercial white-light interferometer, demonstrating nanometre-scale measurement capability. These results establish metasurface-based optics as a viable platform for compact, robust, and integration-ready metrology systems for advanced manufacturing environments.

Keywords: metasurfaces, optical metrology, on-machine measurement, phase-shifting interferometer

1. Introduction

The rapid evolution toward smart, interconnected manufacturing under the Industry 4.0 paradigm has increased the demand for compact, integration-ready metrology systems capable of operating directly within production platforms [1]. In-process and on-machine measurement enable closed-loop control, reduced downtime, and enhanced product quality. However, conventional optical metrology instruments remain constrained by bulky refractive components and complex assemblies. These limitations hinder seamless integration into confined manufacturing platforms and restrict their deployment in distributed sensing architectures.

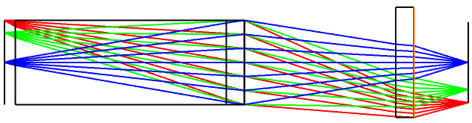
In recent years, metasurfaces have emerged as a viable technology for achieving the functionality of conventional refractive optics without the associated size and weight. Composed of arrays of nanostructures, often referred as meta-atoms, metasurfaces provide precise control over the phase, polarisation, and amplitude of incident light [2]. By spatially arranging these elements, desired optical functions equivalent to the combined effect of multiple traditional components can be realised within a single planar device. This capability enables substantial reductions in system size and weight, opening the path toward ultra-compact, lightweight optical sensors suitable for smart factories.

In this work, we present the design, fabrication, and experimental validation of a high-performance metalens doublet and its implementation in an ultra-compact phase shifting interferometry system. The metalens doublet was designed with a 2 mm field of view (FOV) within a total axial length of only 11.5 mm. To verify practical utility, the doublet is integrated into an ultra-compact phase-shifting interferometric module with a total optical footprint of 6.25 mm × 9.5 mm × 5 mm. Phase shifting was implemented using a simple mechanical translation of the tested sample as a proof-of-concept demonstration. Surface measurements of a calibrated step-height standard (VLSI Standards) show strong agreement with those obtained using a commercial white-light interferometer, confirming the viability of metasurface-enabled optical sensors for high-resolution surface metrology.

2. Metalens doublet design

One of the key elements for microscopy based optical sensors is the objective lens, which provides high resolution imaging across the field of view (FoV). While a single metalens can achieve compact focusing, off-axis aberrations often limit usable field of view. To address this, we designed a metalens doublet configuration. The first metasurface performs the primary wavefront shaping required for focusing, while the second metasurface compensates for residual aberrations, thereby extending the field of view to 2 mm. To facilitate subsequent integration in a metrology system, a glass plate with a thickness of 5 mm serving as a beamsplitter was incorporated into the optical design to optimise imaging performance.

As shown in Figure 1, the complete optical system has a total axial length of 11.5 mm. Ray-tracing simulations performed in Zemax OpticStudio confirm near diffraction-limited performance across the full FoV. The spot diagrams indicate a root mean square (RMS) spot radius ranging from 1.3 to 2.6 µm, which is suitable for surface imaging and metrology applications.



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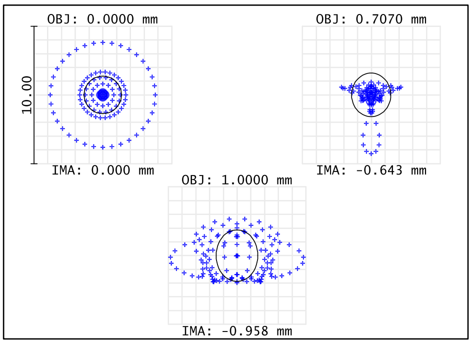


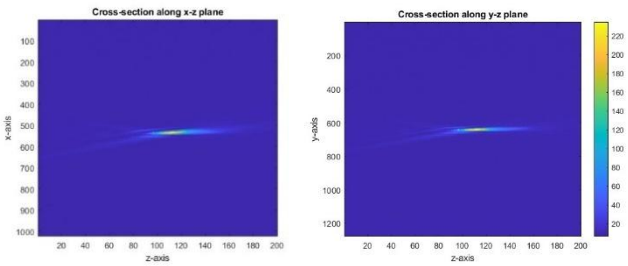
(b)

Figure 1. Metalens doublet design: (a) optical layout, (b) spot diagram.

3. Fabrication and Characterisation

The metalenses were fabricated using electron-beam lithography and dry etching. The nanopillars were etched to a depth of 750 nm into a 4.5 µm-thick GaN layer grown on an Al_2O_3 substrate with a thickness of 430 ± 25 µm. For ease of manufacture the pillars are restricted to a set with radii ranging from 70 nm to 180 nm in 10 nm increments [3].

A 50× microscopy setup was constructed to characterise the focal spots of the metalens doublet by scanning along the optical axis. Figure 2 shows the cross-section beam profiles in the x–z and y–z planes for point sources positioned at different field locations (0 mm and 1 mm). The measured maximum full width at half maximum (FWHM) is less than 4 µm, demonstrating the good focusing performance of the metalens doublet.



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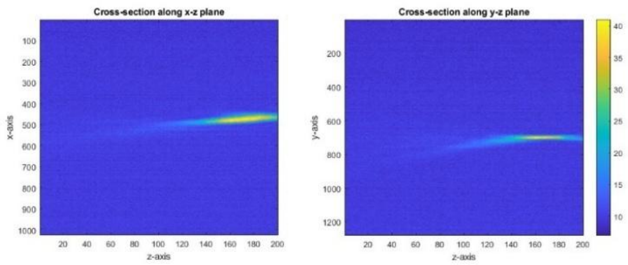

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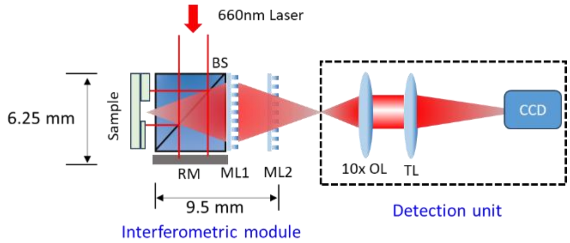
Figure 2. Cross-section beam profiles: (a) on-axis field position (0 mm); (b) off-axis field position (1 mm).

4. Metalens-based phase shifting interferometer and results

A compact metasurface-based phase-shifting interferometric module was constructed using the fabricated metalens doublet, together with a reference mirror bonded to a 5 mm beamsplitter using optical adhesive. The resulting interferometer module has an optical footprint of just 6.25 mm × 9.5 mm × 5 mm. An experimental setup was constructed in which the module was illuminated with a 660 nm light source (Figure 3(a)). Phase shifting was achieved by translating the sample in four discrete steps, each corresponding to λ/8 [4]. A calibrated standard sample with a 43.7 nm step height was measured, and the resulting interference fringes were captured using a 10× microscope system to magnify the surface features. The measured mean step height of 43.11 nm (Figure 3(b)) closely matched those obtained using a commercial white-light interferometer.



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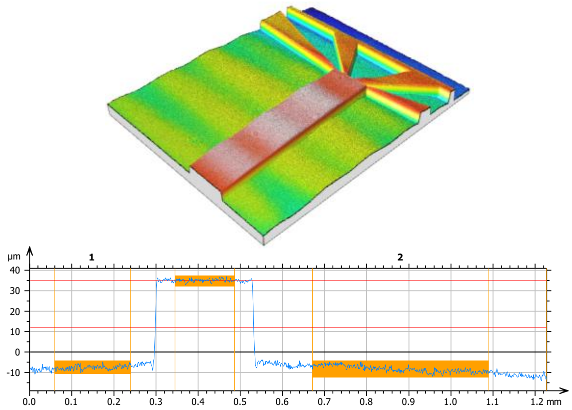

(b)

Figure 3. Demonstration of Metalens-based phase shifting interferometer: (a) schematic of the experimental setup; (b) reconstructed surface topography and extracted line profile.

5. Conclusion and future work

This work demonstrates the design, fabrication, and experimental validation of a GaN-based metalens doublet and its implementation for ultra-compact interferometric surface metrology, establishing metasurface optics as a viable platform for compact, mechanically robust, and integration-ready metrology systems. Future work will focus on the development of mechanically free phase-shifting approaches for metalens-based interferometry, as well as long-term stability testing under manufacturing environments.

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