Direct Visualization of the Axial Phase Evolution of Light Fields Emerging from Microstructures

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Summary

We investigate the axial phase evolution of light emerging from microstructures. The high-resolution interference microscope (HRIM) allows to record three-dimensional (3D) phase distributions in differential and propagation modes along the longitudinal direction. We apply this differential-mode HRIM to study the axial phase evolution of particular cases of microstructures, for instance, the photonic nanojet generated by a diecectric microsphere and the spot of Arago created by a micrometer-size metallic disc.

Introduction

Specific microstructures often lead to a strong light confinement, which serves as an alternative sharper focus or a super-resolution spot. For the first example, when a plane wave impinges on a dielectric microsphere, a tiny bright hotspot appears on the shadow-side surface of the sphere due to a scattering effect, which is termed photonic nanojet [1]. Second, a circular obstacle of micro-size, such as a steel sphere or an opaque disc, creates a bright spot in its shadow, which is a pure demonstration of the diffraction of light at the circumference of the obstacle, named the spot of Arago [2]. For better understanding of such light interactions, we apply the differential-mode HRIM to investigate light fields emerging from microstructures. The longitudinal-differential phase distributions directly visualize the peculiar axial phase evolutions like a Gouy phase anomaly, which is discovered by Gouy for the focused Gaussian beam in 1890 [3].

Experiment and results

The HRIM is basically an optical microscope with a 100X/NA0.9 objective combined with a Mach-Zehnder interferometer, as shown in Fig. 1(a). Details of the experimental setup are reported in our previous papers [4, 5]. In the object arm of the interferometer, a sample (microstructure) is illuminated at normal incidence with a plane wave of 642 nm wavelength. A z-axis piezo stage, which has a scan range of 500 µm and an accuracy of 1 nm, scans the sample along the longitudinal direction to record the 3D amplitude and phase distributions. Contrary to the arrangement with an oil immersion objective in Fig. 1(b), when a dry objective is applied as shown in Fig 1(c), the optical path length (OPL) of the interferometer stays constant during the this *z*-axis scanning. Under this condition, the phase of a plane wave appears as a constant along the propagation direction. The phase of light perturbed by the microstructures is recorded as the difference from the constant phase

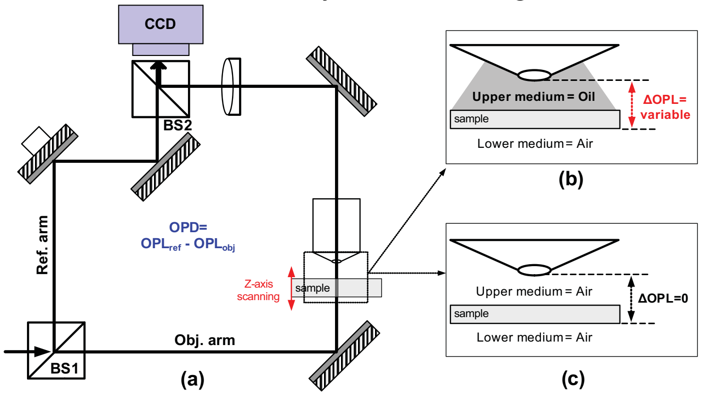

Fig. 1 (a) Simplified schematic of the HRIM. Close-up diagrams of the observation space (b) in oil and (c) in air.

of the plane wave. The longitudinal slices of such 3D phase data display the longitudinal-differential phase distributions.

Figures 2(a) and 2(b) present the measured longitudinal-differential phase distributions of the photonic nanojet and the spot of Arago, respectively. In Fig. 2(a), the photonic nanojet created by a 4-μm glass sphere exhibits the axial phase evolution. The on-axis phase deviation demonstrates the existence of the Gouy phase anomaly in the photonic nanojet [5]. The spot of Arago, which appears in the center of the shadow of the obstacle as shown in Fig. 2(b), is originated to the constructive interference of the diffracted light from each point of the circumference of the obstacle. The axial phase deviation of such a bright spot represents the optical path difference (OPD) between a plane wave propagating along the normal direction and a diffracted light propagating from the edge toward the optical axis. Therefore, the maximum phase deviation occurs at z=0 μm, where is the surface of the disc, with an OPD of the radius of the disc. The measured on-axis phase shows a good agreement with OPD = $(r^2 + z^2)^{1/2}$, where r is the disc radius and z is the distance to the disc along the z-axis.

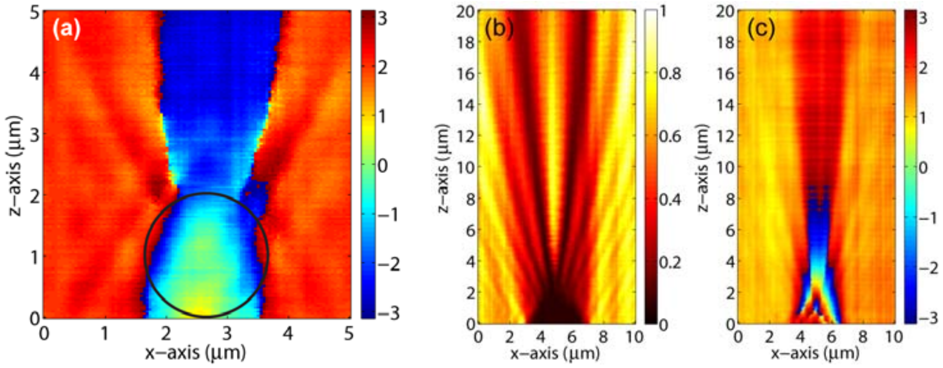

Fig. 2 (a) Measured longitudinal-differential phase distributions of the photonic nanojet created by a 4-μm glass sphere. (b) The longitudinal intensity and (c) the phase distributions of the spot of Arago created by a 4-μm metallic disc.

Conclusions

We demonstrate a new high-resolution experimental method to investigate the axial phase evolution of light interaction with microstructures. The differential-mode HRIM allows to record the longitudinal-differential phase distributions, which reveal specific axial phase features. The Gouy phase anomaly in the photonic nanojet and the axial phase shifts of the spot of Arago have been for the first time directly visualized in this manner.

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