Nanometric Position Metrology with Topologically Structured Light

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We introduce a new ‘optical ruler’ concept, which allows for single-shot, real-time detection of nanometric displacements down to $\lambda/400$, through the visualization of singularities in a topologically structured optical field using a polarization-sensitive camera.

By analogy with a physical ruler, an ‘optical ruler’ is a complex electromagnetic field in which singularities serve as deeply subwavelength marks on the scale: The field is generated by the diffraction of light on a metasurface, and the scale of singularities is revealed by high-magnification interferometric observation. It can resolve deeply subwavelength lateral displacements between two platforms, *A* and *B* - one supporting a laser source, polarization optics and metasurface; the other, imaging optics and a camera. However, as originally conceived [1], each positional measurement requires the sequential recording of four diffraction patterns for four different polarization states of incident light (necessary for the *a posteriori* retrieval of the phase φ and local wavevector $\nabla\varphi$ of the super-oscillatory field). This is not only time-consuming but admits noise, and therefore measurement uncertainties, via: (i) errors in the repeated (re)setting of ½- and ¼-waveplate positions; (ii) laser power variations and thermomechanical fluctuations of instrumental hardware over the time interval required to capture the four images. Here we present a new implementation of the optical ruler paradigm with no moving parts in the beam path, which eliminates the above sources of instrumental error by capturing diffraction patterns for four different polarization states in a single shot, and in so doing also makes real-time measurements possible.

The enabling component in this configuration (Fig. 1a) is a polarization-sensitive camera with pixelated sensitivity to four linear polarization states at angles α = 0, 45, 90 and 135°. The metasurface is illuminated with a fixed linear polarization of light, whereby it transmits a plane wave with that polarization and an orthogonally polarized superoscillatory wavefront. These are converted to right-and left-circularly polarized states by a fixed ¼-waveplate in front of the camera. The intensity The intensity then detected in each linear polarization state is $I_\alpha = \frac{1}{2}(I_p + I_s + 2\sqrt{I_p I_s}\cos(\delta + 2\alpha))$, where δ is the phase difference between the incident circularly polarized super-oscillatory and plane waves, and $I_{p,s}$ are their intensities. From the set of four interferograms, the phase φ and local wavevector $\nabla\varphi$ of the super-oscillatory field can be calculated from $\varphi = \text{atan}(\frac{I_{135} - I_{45}}{I_{90} - I_0}) + k_0 z$, as shown in Fig. 1b. Figure 1c shows a representative measurement of piezoelectrically controlled displacement between platforms *A* and *B*, using an optical ruler operating at λ = 642 nm, with a magnification of 550× and an effective pixel size of 6 nm, achieving a precision (measurement standard deviation) of 1.6 nm.

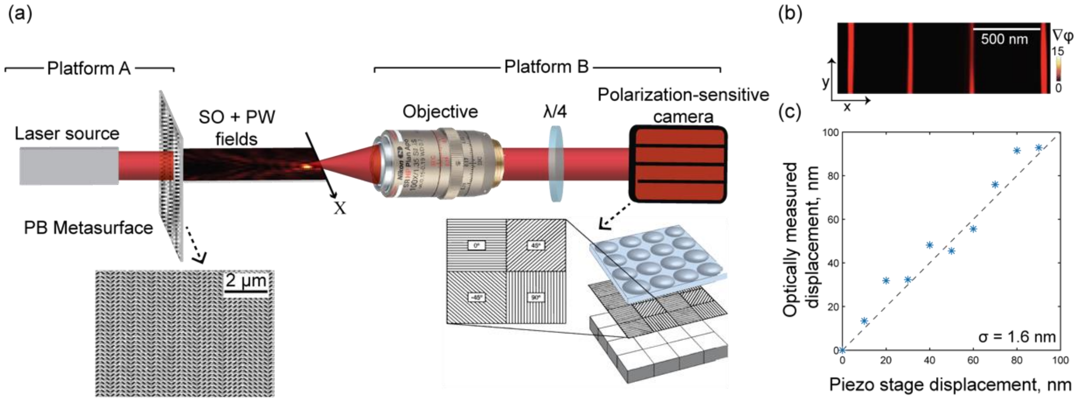

Fig. 1 Single-shot optical ruler. (a) Simplified schematic showing key components of the arrangement for measurement of nanometric displacement between the two platforms, *A* and *B*, in the *x* direction. Images below show detail of (on the left) the Pancharatnam-Berry phase metasurface which generates the superoscillatory field (SO), and (on the right) the camera’s arrangement of microlensed pixels, each equipped with a wire grid polarizer in one of four orientations. (b) *xy* map of local wavevector $\nabla\varphi$ retrieved from the set of four polarization-resolved interferograms, showing the singularity marks of the optical ruler scale. (c) Optical ruler measurement of piezoelectrically-controlled displacement between platforms *A* and *B*.

We further demonstrate a compact, reflection mode optical ruler, wherein all the source and detection optical components are mounted on the same (fixed) platform and only the metasurface is mounted on the second (moving) platform – a configuration better suited to many real-world metrology applications, and in which the optical ruler can be arbitrarily long as there is no offset in the beam path induced by relative displacement of the two platforms.

[1] G. H. Yuan, and N. I. Zheludev, "Detecting nanometric displacements with optical ruler metrology," Science **364**, 771 (2019).