COMMENTARY

Picophotonics goes to higher dimensions

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The van der Waals diameter of a silicon atom is 220 pm, more than three orders of magnitude smaller than the wavelength of visible light. It is a common belief that events on a picometer scale cannot significantly influence light with wavelengths thousands of times larger. However, rather than using conventional light, the recent works demonstrated that topologically structured light offers the possibility of metrology at subatomic scale.

By passing light through elaborately designed metasurfaces or manipulating wavefront with spatial light modulators, one can generate a nontrivial superoscillatory light fields with subwavelength energy localizations, high phase gradients zones of energy backflow, and topological features, such as phase singularities.[1] Mapping the superoscillatory fields enables the singularities to serve as marks on the scale of the "optical ruler" and to measure subnanometer displacements with light.[2] Figure 1(a) shows a schematic of the optical ruler instrument that monitors the mutual position of two platforms, one with a laser and a metasurface generating superoscillatory light and the other with a polarization-sensitive microscope interferometrically retrieving positions of singularities in the superoscillatory field.

Furthermore, even much higher resolution has been achieved in localization metrology of nanoscale objects using a deep-learning analysis of scattering patterns of topologically structured light on the object. At a wavelength of $\lambda = 488$ nm, sub-Brownian motion metrology with $\sim\lambda/5300$ absolute errors has been demonstrated to open a range of opportunities to study phenomena down to a fraction of the typical size of an atom.[3] Further research demonstrated that a neural network can be trained to robustly quantify picometric displacements of a target against orders-of-magnitude larger background fluctuations, opening up a range of application opportunities, for example, in the optical study of nanostructural dynamics, stiction, material fatigue, and phase transitions.[4]

The recent study by Ma et al. reported in *Nature Communications* extends the singularity-based picometer scale optical ruler metrology from 1D to 3D.[5] This technique exploits the sharp phase gradients of the optical vortices,[6] which are localized in a tightly focused structured light field generated with a spatial light modulator through a four-wave interference. The sharp phase gradient peak results in a high sensitivity of the metrology to both transverse and longitudinal displacements [see Fig. 1(b)]. The position of the singularity is modulated by the spatial light modulator (SLM) system in 3D, allowing localization precision of 60 pm in 3D. Although this study presents a significant step toward 3D picometrology, challenges such as long data acquisition time of about 10 min per measurement and environmental instabilities remain.

The implications of picophotonic metrology are far-reaching. 1D metrology with a million measurements per second has already been demonstrated.[7] Extension of this to two and three dimensions will open

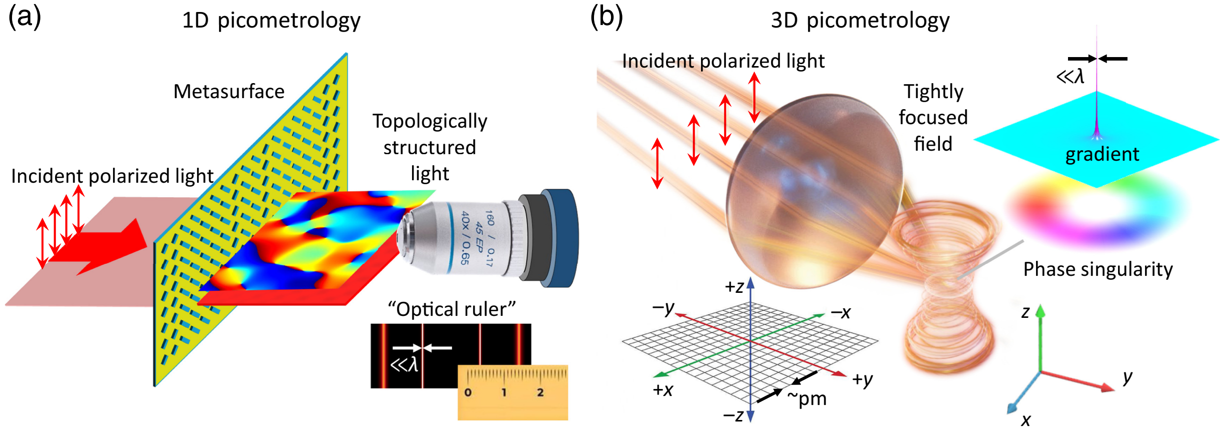

Fig. 1 (a) 1D optical ruler displacement picometrology uses phase singularities of a superoscillatory light created by the Pancharatnam–Berry phase metasurface as marks. (b) 3D displacement picometrology uses a tightly focused structured light created by interference of four beams as a mark in three dimensions.

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opportunities to sense and monitor processes in micro-electro-mechanical systems (MEMS) and nano-electro-mechanical system (NEMS) devices, to study the dynamics of nanoscale active matter and to investigate viruses.[8] Such metrologies can be used in high-precision smart manufacturing and could be considered for the detection of gravitational forces.

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