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EDITORIAL

Achieving superresolution imaging via k-space superoscillation

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Abstract

The inability to resolve closely spaced objects fundamentally limits the information accessible to optical imaging systems. In a recent study, a *k*-space superoscillation framework is introduced as an alternative route to far-field superresolution imaging. By engineering a nonlocal, angle-dependent transmission function, the approach effectively redistributes spatial-frequency content in momentum space, enabling enhanced separation of image features without narrowing the point spread function. Implemented via an inverse-designed multilayer metastructure, the concept is experimentally validated at microwave frequencies, achieving an approximately twofold improvement in resolution. By suppressing real-space sidebands and concentrating energy into the focal region, the *k*-space approach addresses key limitations of conventional real-space superoscillation. Despite remaining challenges, such as scalability and bandwidth constraints, this work highlights the growing role of inverse design in enabling unconventional optical functionalities and offers a promising pathway toward practical superresolution imaging systems.

The inability to resolve closely spaced objects sets a fundamental limit on the detail an imaging system can access or deliver. Advances in achieving higher spatial resolution have therefore driven both scientific discovery and technological progress. Over centuries, improvements in microscopy and telescopy have expanded our view of the natural world, from revealing the laws of gravitation to uncovering the unique structure of DNA, across scales from the nanoscale to the astronomical. Today, imaging technologies underpinning extreme ultraviolet (EUV) lithography continue to sustain Moore's law, supporting the rapid expansion of the information age and serving as a technological backbone of morden society, particularly in the era of artificial intelligence (AI).

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From the perspective of wave physics, the spatial resolution of an imaging system is fundamentally constrained by the probing wavelength and the range of spatial frequencies it can capture, as described by Abbe's theory of image formation [1]. Accordingly, strategies for enhancing resolution fall into two broad categories. One employs shorter-wavelength (higher-energy) probes, from ultraviolet photons and X-rays to electron beams. The other extends the accessible spatial-frequency bandwidth by capturing high-frequency components, for example through high-refractive-index environments, synthetic apertures, or near-field techniques that collect evanescent waves.

Nevertheless, in practice, many applications are constrained by factors such as sample damage under high-energy illumination, throughput requirements, and system cost and footprint. These limitations raise a fundamental question: how can spatial resolution be further improved when the probing wavelength and numerical aperture are fixed? This challenge has inspired a range of approaches that effectively circumvent Abbe's diffraction limit by deconvolving the blurred image either physically, as in structured illumination [2], stimulated emission depletion [3], and superoscillation [4, 5], or digitally, as in stochastic optical reconstruction microscopy [6] and AI-driven superresolution methods [7].

Different strategies offer distinct trade-offs and are suited to specific scenarios. In principle, image deconvolution is straightforward once the point spread function (PSF) is known, but in practice it is fundamentally limited by noise, making the signal-to-noise ratio (SNR) as critical as spatial resolution. This limitation is particularly evident in superoscillation-based imaging, which, despite enabling label-free, far-field superresolution without post-processing, suffers from intrinsically low focusing efficiency, degraded SNR, and a limited field of view (FOV).

In a recent study [8], *Far-field superresolution imaging* via *k-space superoscillation*, the authors propose an alternative route to overcome the low efficiency that has long limited superoscillation-based imaging by shifting the fast-oscillating components from real space into momentum (k) space. The idea builds on a deceptively simple premise: if the point spread function (PSF) can no longer be narrowed under fixed wavelength and aperture constraints, can one instead increase the effective separation of objects in the image plane? In this framework, achieving a twofold enhancement in angular magnification, as illustrated in Fig. 1a, requires an angle-dependent transmission function of the form $T(x\prime, k_x) = T_0 e^{-\frac{j\pi x\prime^2}{\lambda f} + 2\times jk_x x\prime}$, in contrast to the conventional lens response $T(x\prime, k_x) = T_0 e^{-\frac{j\pi x\prime^2}{\lambda f} + jk_x x\prime}$. Here, T_0 denotes the transmission amplitude, k_x the transverse wavevector, $x^{\prime}$ the lens output plane coordinate, λ the wavelength, and f the focal length. This formulation naturally raises key questions: what is the physical interpretation of such a transformation, whether it is experimentally realizable, and, if so, what trade-offs must be made.

Taking the Fourier transform of the required angle-dependent transmission function yields $T(x\prime, x) = T_0\delta(x - 2x\prime)e^{-\frac{j\pi x\prime^2}{\lambda f}}$, indicating that the transmitted field at position $x^{\prime}$ on the output plane is governed by the incident field at $x = 2x^{\prime}$ on the input plane. This implies an extreme degree of nonlocality in the system response. At first sight, such a relation appears paradoxical, as it seems to require collecting photons from regions of the input plane that lie beyond the physical

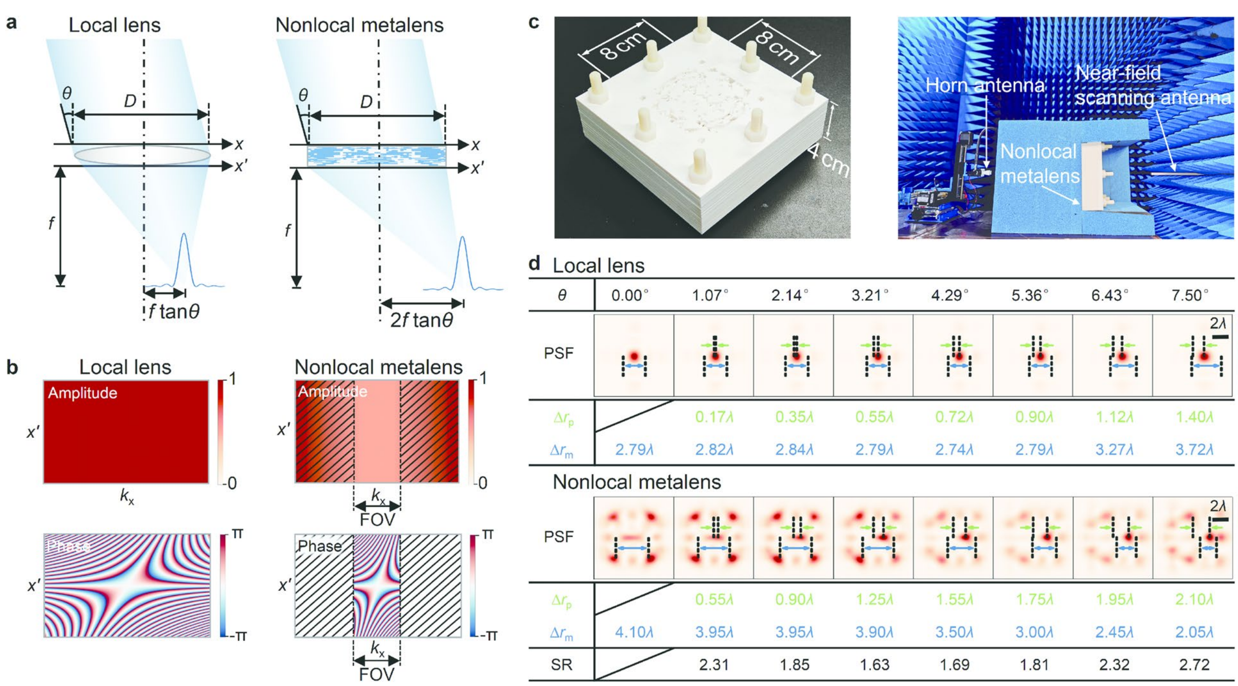

Fig. 1 Working principle behind superresolution imaging using a nonlocal metalens via k-space superoscillation. **a** Schematic of a local (left) and nonlocal (right) 1D cylindrical lens with a focal length *f* that focuses a plane wave with an incident angle *θ* to a spot located at *f* tan*θ* (left) and 2*f* tan*θ* (right) from the optical axis in the focal plane. **b** Complex amplitude and phase of angle-dependent transmitted field (left: amplitude, right: phase) of a local (left) and nonlocal (right) 1D cylindrical lens. **c** Photograph of the 3D-patterned metalens made of 24 layers of polypropylene sheets (left) and the microwave measurement setup with part of the absorbing material removed (right). **d** Measured PSF as a function of the angular position of the point source for the local lens (up) and the nonlocal metalens (down). The observed sidelobes at the four corners are due to the truncation of the diffracted wave by the absorbing material, which are fundamentally different from the sidebands encountered in real-space superoscillation

aperture. The resolution lies in recognizing that such a nonlocal lens encodes a rapid variation of the transmission function with respect to k_x, which can only be sustained over a finite spatial-frequency bandwidth (Fig. 1b). This constraint mirrors the real-space behavior of superoscillation, where rapid oscillations arise at the expense of a reduced FOV. Consequently, such a transformation is physically realizable, although it is intrinsically accompanied by a fundamentally limited angular FOV.

Because there is no straightforward route to realize such a nonlocal response, the authors resort to inverse design to optimize the structure within a "black-box" framework. They implement a three-dimensional, multilayer metastructure operating at 30 GHz, a choice that facilitates fabrication. The resulting prototype consists of 24 layers of low-loss polypropylene, with an overall footprint of approximately $4 \times 8 \times 8\,\lambda^3$. Experiments reveal a clear superresolution factor of about two within the designed angular field of view, in good agreement with simulations. In a subsequent two-point source measurement, the nonlocal metalens achieves a resolution 2.1 times higher than that of a conventional local lens.

Compared with conventional real-space superoscillation imaging, the *k*-space approach offers several notable advantages. By transferring the constraint to the momentum space, it avoids the formation of sidebands in the image plane, as angular spectrum components beyond the aperture limit are naturally suppressed. This effectively enlarges the FOV for a given region of interest. The absence of sidebands also leads to a substantial improvement in focusing efficiency, by up to one order of magnitude for a given superresolution factor, because the transmitted energy is concentrated into the focal region. We note, however, that this gain still comes at the cost of a reduced transmission amplitude within the bounded FOV to satisfy the weak measurement condition, where a post-selection in momentum space is applied. In addition, because the nonlocal metalens operates at the diffraction limit, it retains a level of robustness comparable to that of a conventional lens, and is less sensitive than real-space superoscillation schemes that rely on finely weighted superpositions of spatial frequency components.

Nevertheless, the demonstrated prototype still exhibits several limitations, as noted by the authors. Some arise primarily from technical constraints, including artificial sidelobes introduced by the experimental setup, the relatively low numerical aperture (~0.2) adopted for design simplicity, and the difficulty of scaling the approach to optical frequencies. In principle, these challenges may be mitigated with more advanced implementations, albeit at increased cost and complexity. More fundamentally, however, other open questions relate to the intrinsic limits of optical systems engineered to perform arbitrary nonlocal transformations. These include whether the required transfer functions can be realized over a broad bandwidth, and how extreme the angle-dependent transmission function can be distributed so that the superresolution ratio, focusing efficiency, and the FOV can be improved further.

Over the past fifteen years, inverse design [9] has profoundly reshaped our understanding of what is achievable in optics and photonics. The nonlocal metalens demonstrated here, enabling *k*-space superoscillation, represents another compelling example along this trajectory. Looking ahead, the rapid expansion of computational capabilities, which is further accelerated by advances in artificial intelligence, is likely to continue unlocking optical functionalities that remain inaccessible to conventional design paradigms. At this juncture, however, it remains essential to keep two fundamental questions in focus: what is physically possible, and why; and what constitutes a meaningful figure of merit. Although significant progress has been made, the space of opportunities continues to expand, with much still left to explore.

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