

Scattering media as random micro-phase-pinhole arrays for incoherent information transmission

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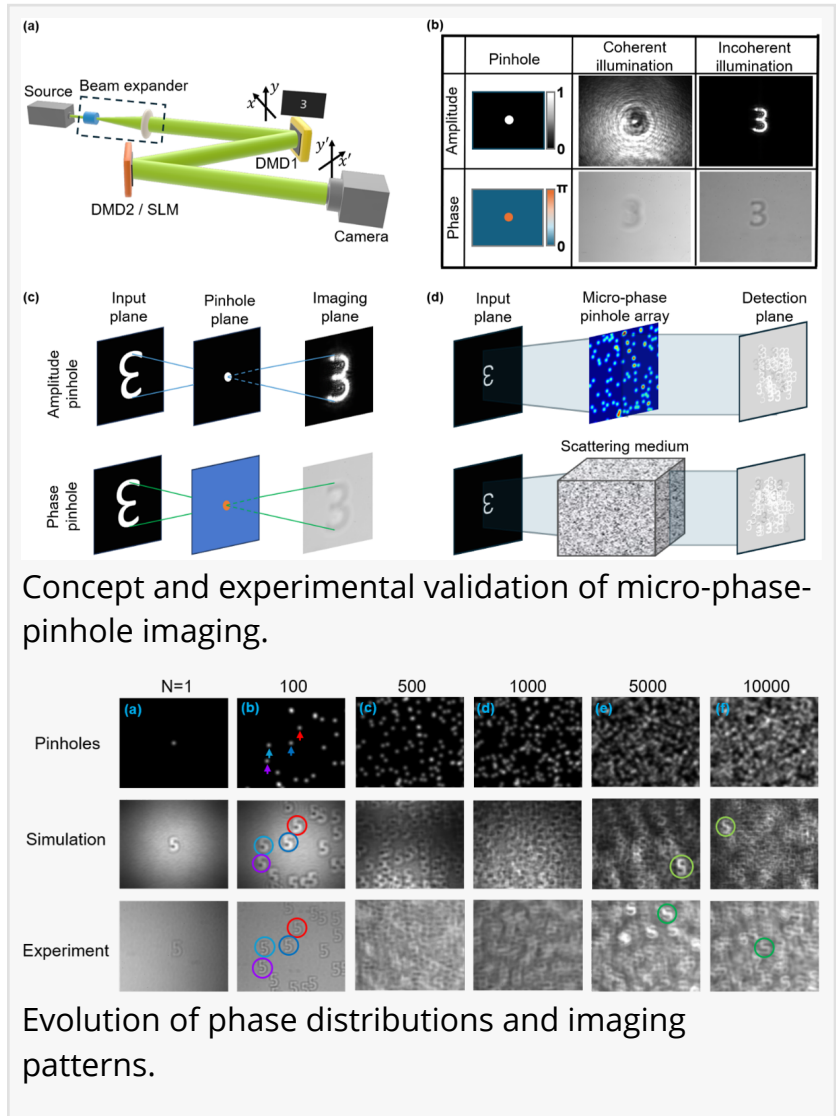
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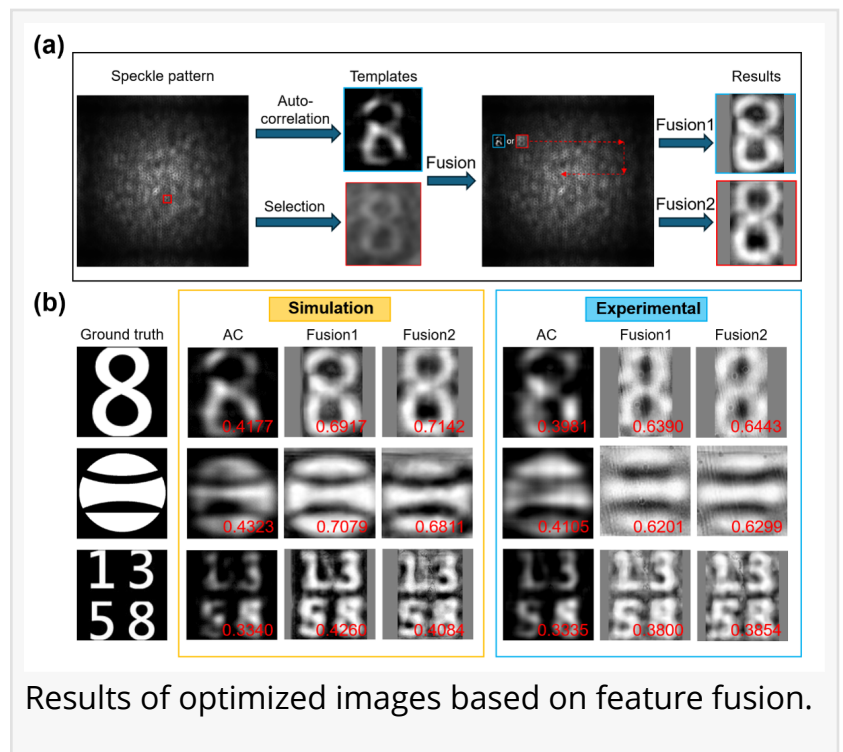
Researchers from Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, The Hong Kong Polytechnic University, and University of Shanghai for Science and Technology have proposed a groundbreaking micro-phase-pinhole model for imaging through scattering media. By conceptualizing disordered media as deterministic imaging channels rather than a stochastic black box, the team reveals that random pinhole combinations spontaneously generate high-fidelity images. Using a novel feature fusion algorithm, this work greatly enhances imaging quality.

Imaging through strong scattering media such as biological tissues, clouds, smoke, and turbid water has long been a persistent challenge that modern optical research has strived to address. When light propagates in such media, the random distribution of spatial refractive index causes chaotic scattering of light rays, which severely disrupts the original spatial information distribution and results in messy speckle patterns on the detection surface.

Over the past two decades, researchers have proposed and developed various technologies



—including wavefront shaping, scattering matrix measurement, and speckle autocorrelation—to mitigate the impact of scattering on imaging, achieving remarkable progress. However, most mainstream studies treat scattering media as a "black box", relying heavily on empirical input-output mapping and global statistical correlation of speckles, rather than elucidating the specific physical process occurring within the media. As the thickness of the medium increases, the imaging quality of traditional technologies degrades sharply, eventually leading to complete failure. To fundamentally solve the problem and open the "black box", it is essential to clarify the propagation mechanism of spatial information in scattering media and the characteristics of scattering channels.



To achieve this goal, a joint research team led by Liu Honglin from Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Lai Puxiang from The Hong Kong Polytechnic University, and Zhang Dawei from University of Shanghai for Science and Technology proposed a brand-new scattering medium model: equating the scattering medium to a random array of phase pinholes, each serves as an independent information transmission channel. Based on this model, the research team initially revealed the internal information transmission mechanism of scattering media.

The research team first completed the theoretical modeling of the phase pinhole channel model, and through rigorous theoretical derivation, they proved that the scattering medium can be equivalent to a random array composed of phase pinholes. Then, through systematic simulation and experimental verification, the researchers found that a single phase aperture can form an inverted real image, and the imaging quality depends on the object-image distance, aperture size, and phase profile, which directly affect the channel capacity of the phase pinhole channel. In further research, the team confirmed from both theoretical and experimental perspectives that the speckle pattern on the detection surface is essentially the superposition of the responses from all phase pinhole channels.

A key finding of this study is the "lucky" cluster of apertures: among numerous randomly distributed aperture combinations, a specific aperture distribution can directly generate high-quality target images in the speckle field, thereby optimizing the capacity of the combined channel. Guided by this physical mechanism, the research team developed a feature fusion

algorithm. By scanning the speckle pattern and applying dual strict screening criteria (structural similarity index SSIM greater than 0.5 and the number of feature point matches not less than 5), the algorithm accurately locks onto high-capacity phase pinhole channels, and finally synthesizes high-fidelity images by fusing high-quality speckle segments of the corresponding channels.

This random array model of phase pinholes can not only explain the core reason why the depth of field of scattering imaging is not limited by traditional imaging, but also provide a concise physical explanation for the thickness bottleneck of scattering imaging from the angle of the geometric limitation of the microchannel field of view (FOV). The conceptual breakthrough of this model offers a new perspective for understanding the propagation law of spatial information in complex media, and also opens the door for the development of new technologies.

Keywords: micro-phase-pinhole array, speckle pattern, scattering media, incoherent information transmission, feature fusion

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Liu Honglin: Associate Researcher and Master's Supervisor at the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences. She has long been engaged in research on image information transmission and reconstruction in complex channel environments, including light field remote sensing through clouds and fog, non-destructive optical imaging of biological tissues, and high-fidelity image transmission through multimode fibers. She has published more than 50 research papers in journals such as Nature Photonics, Advanced Photonics, PhotoniX, and Advanced Science.

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