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Cascaded metasurfaces for adaptive aberration correction

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Aberration-corrected focus scanning is crucial for high-precision optics, but the conventional optical systems rely on bulky and complicated dynamic correctors. Recently, Shiyi Xiao's group proposed a method using two rotating cascaded transmissive metasurfaces for adaptive aberration correction in focus scanning. The optimized phase profiles enable precise control of the focal position for scanning custom-curved surfaces. This concept was experimentally validated by two all-silicon meta-devices in the terahertz regime, paving the way for high-precision and compact optical devices in various applications.

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Results

Dynamic light focus control has garnered significant interest for both scientific research and practical applications, such as bioimaging, laser processing, and optical tweezers. One major challenge is scanning aberrations, where the focal deviation from target surface compromises focus quality (intensity and shape), limiting the optical scanning precision[1,2]. To solve the problem, conventional methods rely on extra optical components and external control algorithms for correction, resulting in bulky and inefficient systems.

In recent years, metasurfaces composed of precisely engineered planar meta-atoms have enabled ultra-compact and high-efficiency focal control[3,4]. Tunable metasurfaces achieve dynamic electromagnetic (EM) response modulation by integrating active elements such as PIN diodes, varactors, graphene, and semiconductors into meta-atoms[5–8]. Building on this capability, researchers have explored aberration-free focus control by dynamically shaping local phase distributions[9]. Though promising designs have been existing in the microwave regime, high-performance meta-devices for eliminating the scanning aberrations in higher frequencies (e.g., Terahertz, infrared, visible light) remain unrealized. This limitation arises primarily from the lack of efficient active materials and the inherent complexity of point-by-point control of meta-atom's EM responses in the high frequencies, ultimately restricting the precise manipulation of optical wavefront.

More recently, cascaded metasurfaces have emerged as a promising approach for dynamic EM wave control[10–12], enabling a wide range of advanced manipulation effects. However, they encounter significant challenges in eliminating the scanning aberrations and achieving the high-precision optical control. The primary limitation stems from their global phase-tuning mechanism, which constrains the precise local adjustments essential for the high-accuracy dynamic EM wave generation.

In a recent paper published in *Opto-Electronic Advances*[13], Prof. Shiyi Xiao and his colleagues proposed a method utilizing two cascaded transmissive metasur-

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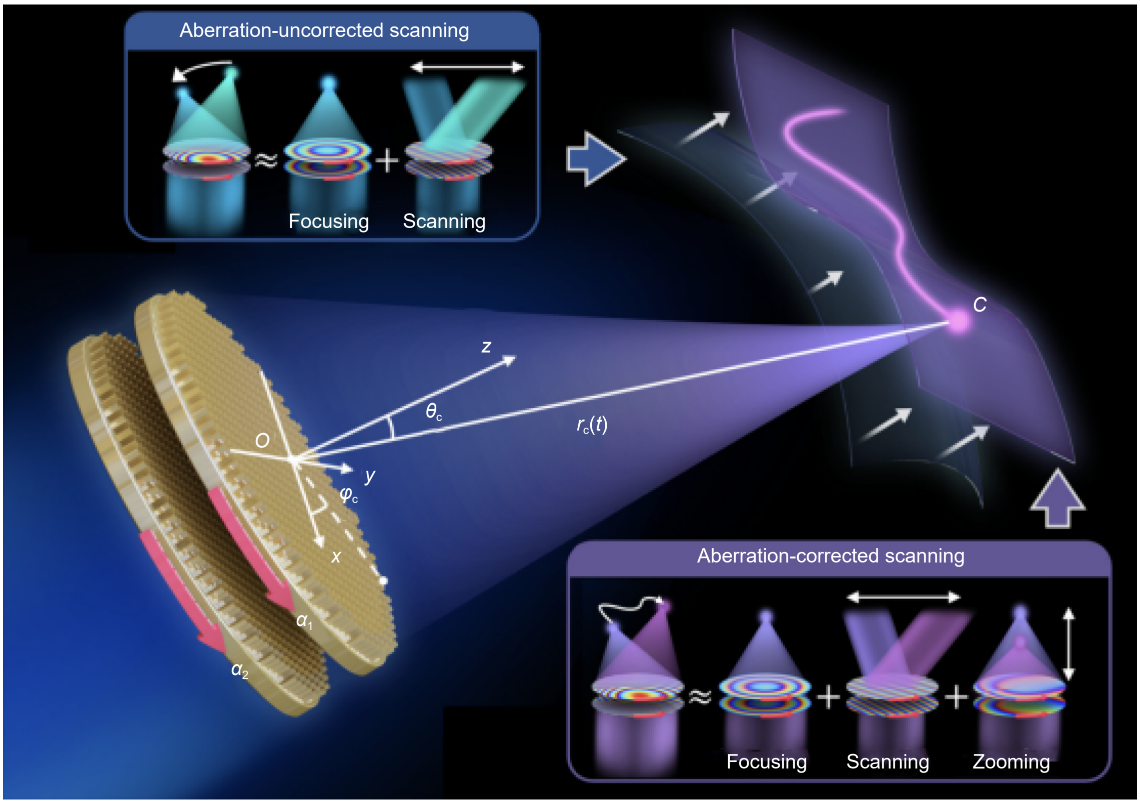

Fig. 1 | Schematic of the cascaded metasurfaces for adaptively aberration-corrected focus scanning via mechanical rotation.

faces for adaptive aberration correction in coordination with focus scanning. As shown in Fig. 1, the proposed meta-device comprises two mechanically-rotated transmissive metasurface layers, each with a predefined phase distribution and a specific rotation angle. The aberration correction is achieved by simply rotating the cascaded metasurfaces with precisely engineered phase distributions, which can eliminate the need for additional optical elements or external control algorithms. The authors also developed a general parameter-solving method to optimize the phase-profile parameters to move a focal spot across custom-designed curved surfaces, thereby improving both intensity and shape during scanning.

Two all-silicon terahertz meta-devices were designed and fabricated to validate this concept. Experimental results show that the first meta-device can scan a focal spot on a planar surface with an average aberration of 1.18% within a ±30° scanning range, offering a 5.56-fold improvement over the hyperbolic scanning lens. The second meta-device successfully scans two focal points: one on a planar surface and the other on a conical surface, with the average aberrations of 2.5% and 4.6%, respectively.

Compared to the scanning lenses with hyperbolic or quadratic phase distributions, the proposed method offers greater flexibility in both surface shapes and number of focal points. Additionally, it can be extended to other frequency bands, including microwave, near-infrared, and visible light. Overall, this versatile method provides a new perspective for designing meta-devices with adaptive dynamic control, catering to the high-precision demands in applications such as laser processing, lithography, and optical tweezers.

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