Metasurface-Based Optical Elements for Biomedical Applications

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Nanophotonic metasurfaces are a well-established technique for creating flat optical components with tailored functionalities. By manipulating light properties such as amplitude, phase, and polarization, metasurface-based optical elements enhance biomedical imaging instruments' performance. This work explores recent advancements in our laboratory applying metasurface optical components in biomedical instruments, including optical sectioning microscopy, light sheet microscopy, laser micro-profiling, and optical tweezers. Optical sectioning microscopy is vital for biomedical imaging. We integrated metalenses into two optically sectioned microscope modalities. Light sheet microscopy often requires special sample holders and faces spatial constraints between illumination and detection objectives. Metasurface-based flat optics help alleviate these limitations. A metalens for the light sheet fluorescence microscope enables high-resolution in-vivo imaging of live C. elegans without performance loss. We also show the benefits of using a variable focus metalens in a telecentric design with HiLo imaging for high-resolution optically sectioned images. The varifocal dielectric Moiré metalens delivers promising fluorescence imaging performance with standard test targets and biological samples.

Biophotonics applications require precise optical energy delivery to specific sites without affecting surrounding areas. Abrupt autofocusing (AAF) beams are ideal for laser-tissue interactions due to their high energy contrast between the input and focal plane. We present the design and implementation of a metasurface optical element for the AAF beam. Experimental demonstrations show fluorescence-guided laser micro-profiling of mouse heart tissue and photocoagulation in skin tissue using the AAF beam. These experiments highlight AAF beams' unique propagation and focusing properties, such as ballistic dynamics, high-intensity contrast, and self-reconstruction. Traditional bulky spatial light modulators can be replaced with metasurface optical elements in optical tweezers. We developed a two-dimensional Airy beam in the visible region for lateral shifting and guiding particles along the axial direction. Quantitative measurements for optical trap characterization demonstrate the potential of metasurface optical elements in miniaturizing optical tweezer setups. Implementing ultrathin optical devices in biomedical instruments opens new avenues for creating compact and high-performance systems. Our work has important applications in interdisciplinary research, including metasurface, optical microscopy, and biomedical optical instrumentation.