



Integrated laser processing platform based on metasurface

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Laser processing technologies enable the precise fabrication of arbitrary structures and devices with broad applications in micro-optics, micro-mechanics, and biomedicine. However, its adoption is limited by the large size, complexity, high cost, and low flexibility of optical systems. Metasurfaces enable precise multidimensional control of light fields, aligning well with the development trend toward compact, high-performance optical systems. Here, we review several recent studies on the application of metasurfaces in laser processing technologies, including 3D nanolithography, direct laser writing, and laser cutting. Metasurfaces provide an integrated operational platform with exceptional performance, poised to disrupt conventional laser processing workflows. This combination presents significant cost efficiency and substantial development potential, with promising applications in areas such as imaging, optical storage, advanced sensing, and space on-orbit manufacturing.

Keywords: laser processing; two-photon polymerization; direct laser writing; laser cutting; metasurface

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Introduction

Laser processing technologies are driving a transformation in modern manufacturing, playing a pivotal role in key sectors such as semiconductors, aerospace, and nanorobotics^{1–6}. While high resolution and throughput remain core objectives, recent advancements in laser processing technologies have shifted focus toward miniaturization and cost reduction to lower entry barriers and facilitate broader adoption^{7–11}. Specifically, existing laser processing systems are heavily dependent on intricate and expensive optical modules, including focusing lenses, beam expansion systems, and optical field modulation components (e.g., diffractive optical elements, spatial light modulators, digital micromirror devices, etc.), along with other essential optical elements. These systems are commonly characterized by their large size and

high cost, leading to significant challenges. In particular, switching between different processing functions becomes extremely complicated, requiring extensive time and effort to recalibrate the optical configuration. Metasurfaces present an innovative ultralightweight solution with substantial potential to overcome these obstacles and advance the field^{12–16}.

In a study published in *Laser & Photonics Reviews*, Hui Gao, Wei Xiong, and their colleagues proposed an ultra-compact metasurface-based two-photon polymerization (M-TPP) technique as an alternative to conventional optical setups¹⁷. By incorporating a holographic multi-focus metalens into 3D nanolithography, they developed a miniaturized and simplified TPP system capable of achieving high-uniformity multi-focus parallel processing. Experimental results demonstrated that M-TPP

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enables the fabrication of 3D micro/nanostructures with sub-diffraction-limited feature sizes. The lateral and axial sizes of the thinnest linewidth were 100.8 nm and 159.7 nm, respectively. To validate its practical potential, a microlens array device with a hexagonal topology was successfully fabricated using this technique. Specifically, a metasurface was employed to replace multiple light field modulation components in a traditional multi-focus TPP system, including a beam splitter, a dispersion compensating system, a beam expanding system, and an objective lens (Fig. 1(a,b)). The metasurface, specifically designed as a multi-focus metalens (MFM) with a high numerical aperture, significantly reduced the size and weight of the system. The replaced optical components and their associated optical paths spanned several centimeters transversely and tens of centimeters axially, with a combined weight of several kilograms. In contrast, the effective transverse diameter of the MFM was only 1 mm and the effective axial size was only 1.15 μm , with a total weight of just 0.00025 kg, including its glass substrate. Compared to traditional multi-focus TPP systems, the MFM reduced the optical setup volume by at least one million times and its weight by at least one thousand times. Figure 1(c) showcases the printing process of a 3D micro/nanostructure array using the MFM, which

achieved a sevenfold increase in processing throughput compared to traditional single-focus methods while maintaining high morphological uniformity among the structures. Figure 1(d) compares the planar optical device metalens with a conventional objective lens, demonstrating the MFM is significantly smaller and lighter. Furthermore, advancements in fabrication technology are expected to significantly lower the manufacturing cost of the MFM, enhancing its practicality and scalability.

In a similar study published in *Opto-Electronic Science*, a supercritical lens (SCL) operating at 405 nm (h-line) was proposed for direct laser writing (DLW) lithography¹⁸. In comparison to traditional Fresnel zone lenses (FZLs), the supercritical metalens offers a smaller full width at half maximum, an extended depth of focus, and controlled side lobes. To address the ultraviolet environment, the researchers used aluminum nitride to fabricate metalenses, a material known for its high refractive index and low optical losses across the ultraviolet-visible spectrum. Three types of metalenses were designed: SCL05 (the ratio of the intensities of the first side lobe and the central peak is 5%), SCL10 (the ratio of the intensities of the first side lobe and the central peak is 10%), and a traditional FZL. These were incorporated

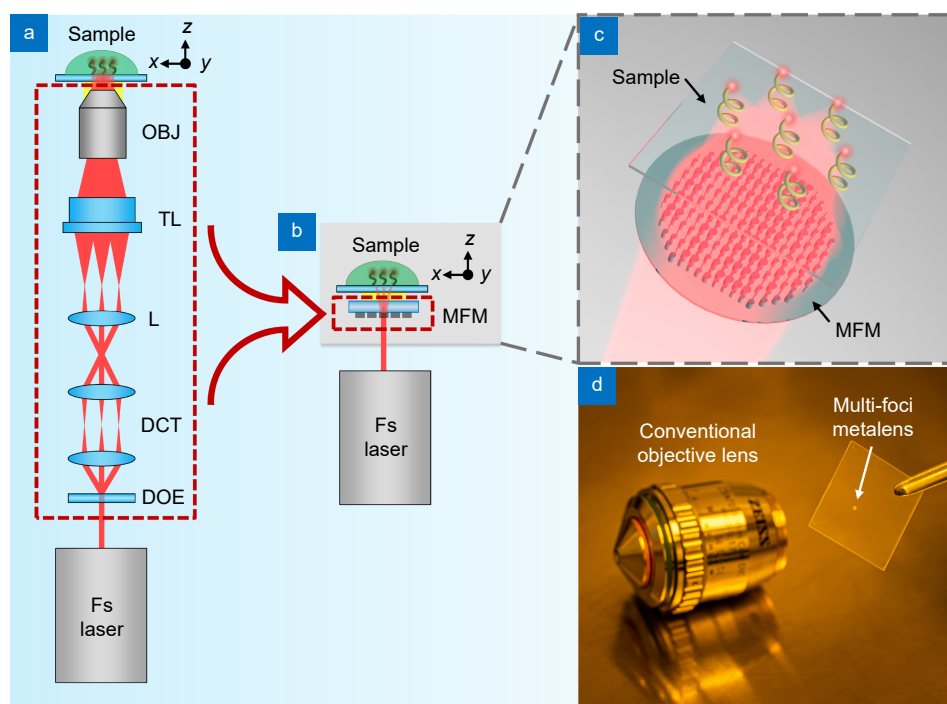


Fig. 1 | Design concept of M-TPP. (a) Schematic diagram of traditional multi-focus TPP system. (b) Schematic diagram of M-TPP system. (c) Printing process of an array of 3D micro/nanostructures using an MFM. (d) Contrast diagram of the conventional objective lens and the MFM. Figure reproduced from ref.¹⁷, John Wiley and Sons.

into a DLW system, as illustrated in Fig. 2(a). Figure 2(b) presents DLW experiments conducted with the three metalenses, where five sets of gratings were written on the commercial photoresist ma-N 1405. Each set consists of six 4 μm -long lines, with their full pitches ranging from 680 nm to 560 nm, from left to right. The SCLs demonstrated significantly better performance in producing high-resolution patterns compared to the FZL, as all grating patterns created by the SCLs exhibited higher contrast than those produced by the FZL. For instance, in the fifth set, the pattern generated by the SCL was clearly resolvable, whereas the FZL pattern was almost indistinguishable. The resolutions of the FZL, SCL05, and SCL10 were approximately 540 nm, 500 nm, and 480 nm, respectively. Compared to the FZL, the resolution of the SCLs was improved by nearly 10%.

More recently, in a study published in *Advanced Materials*, a silicon carbide (SiC) metalens with exceptional thermal stability was employed in laser cutting to mitigate the thermal drift effects induced by high-power laser irradiation¹⁹, as illustrated in Fig. 2(c). The metalens was fabricated from 4H-SiC, a material renowned for its high refractive index, low optical losses across the visible to near-infrared spectrum, remarkable mechanical hardness, chemical resistance, and significantly high thermal conductivity at room temperature. Under a 1030 nm pulsed laser at 15 W for 1 h, the SiC metalens exhibited a

minimal temperature increase of 3.2 $^{\circ}\text{C}$ and a tiny focal shift of 14 μm (relative to 0.1%), which was only 6% of the shift observed with conventional lenses. Laser cutting tests, shown in Fig. 2(d), revealed that the SiC metalens maintained stable cutting performance after 60 minutes of operation, whereas the focus of the objective lens shifted noticeably towards the substrate after just 30 minutes. After 1 h of operation, the change in cutting depth of the SiC metalens was only 11.4% of that of the objective lens.

In conclusion, metasurfaces present a promising operational platform for laser precision processing applications across a range of applications, including laser ablation, laser modification, laser cutting, two-photon polymerization, and more. They enable richer and more flexible processing functionalities while maintaining system miniaturization and low cost. More importantly, metasurfaces are set to surpass the limitations of traditional laser modulation technologies. Their small pixel size, multidimensional modulation capabilities, and high information capacity position metasurface platforms to usher in entirely new paradigms in laser processing. This advancement is particularly significant for modern applications demanding compact, lightweight, and cost-effective optical systems, such as aerospace, lab-on-fiber, and nanorobotics.

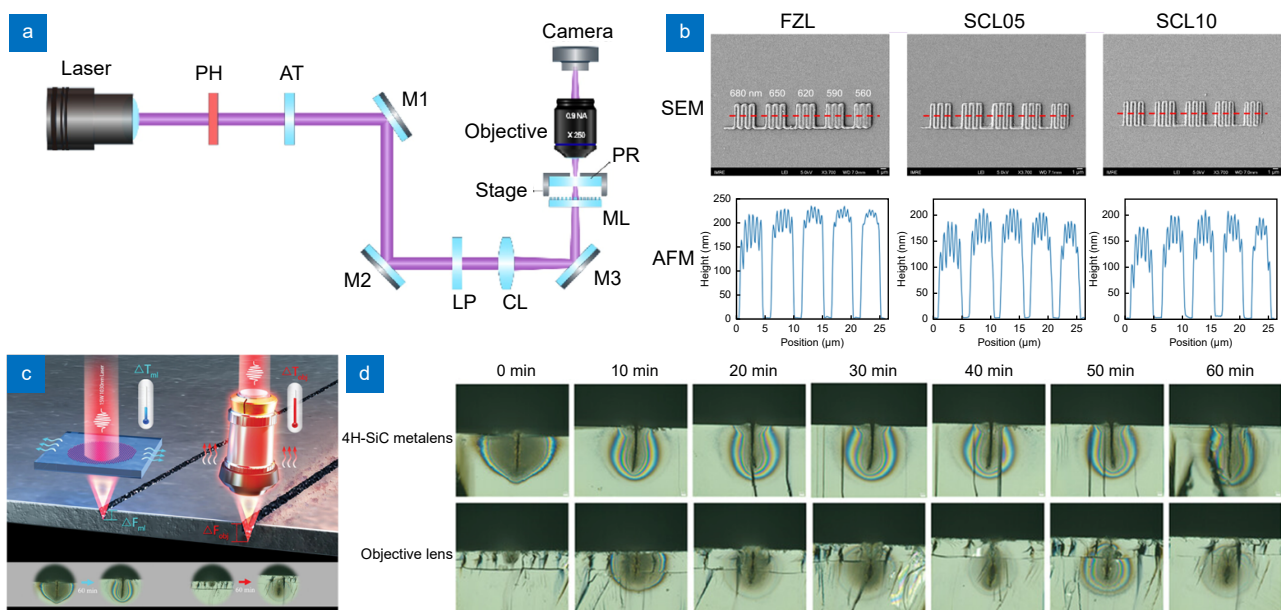


Fig. 2 | DLW lithography and laser cutting using metalenses. (a) Schematic of the DLW lithography system. (b) Grating patterns produced by DLW with the FZL and the SCLs. (c) Schematic of the thermal drift effects of the SiC metalens (left) and the traditional objective lens (right). (d) Cross-sectional images of 4H-SiC substrates after 60 minutes of laser cutting with a 15 W, 1030 nm laser. Figure reproduced from (a, b) ref.¹⁸, under the terms of the Creative Commons CC BY license; (c,d) ref.¹⁹, John Wiley and Sons.

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