Direct laser writing method for micro-lens fabrication on the fiber facet

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Abstract. We present a way for micro-lens and micro-lens array fabrication on the fiber facet by direct laser writing (DLW) method. The proposed setup for DLW printing on the fiber facet can protect objective lens and makes it possible to safely using a wide range of resists. Micro-lens fabricated on the single-mode optical fiber facet is demonstrated. Based on lens-on-fiber system we proposed concept of the micro-lenses on baseplate array printed on the multi-core fiber, where each lens is rigidly aligned with the core. One of the possible micro-lenses on the baseplate array is presented and its optical properties such as focal spot size and resolution are investigated. The possible application of the proposed micro-lens array is complex optical elements, such as micro-objectives with optimized optical design. Moreover, suggested freeform lens array can find application in high-accuracy wavefront sensing.

1. Introduction
Nowadays, direct laser writing (DLW) method is commonly used for micro-optical elements fabrication. This state-of-the-art technology gives sub-micrometer accuracy and makes it possible to fabricate complex freeform 3D polymer structures. DLW opens large possibilities for fabrication high quality freeform micro-lenses and micro-objects for wavefront transformation, such X-ray parabolic compound refractive lenses with curvature radius up to 5 μm at the paraboloid apex [1]. Also, the efficient single-photon source consisting of QD with a micro-lens, whose emission is collimated by the on-chip micro-objective has been demonstrated recently [2]. Moreover, DLW enables to combine polymer structures with optical fiber [3] or to create elements directly on the fiber facet [4], which is promising for sensing and imaging.

Here we demonstrate free-form micro-lens array on baseplate for MCF fiber and micro-lens on single-mode fiber facet fabricated by DLW and perform its optical characterization.

2. Experimental section
For the micro-lenses fabrication by direct laser writing method we used commercial 3D two-photon lithography system (Photonic Professional, Nanoscribe GmbH). The development for both micro-lens on the cover glass and micro-lens on the fiber facet were performed according to standard protocol (PGMEA 25 min, IPA 5 min).

2.1. Single micro-lens design and realization
For lens printing with DLW method we prepared the adaptive model with variable slicing and hatching distances in order to reducing RMS roughness. The different design (spherical and aspherical) with radius in the range from 10 to 150 µm were used for lenses fabrication. In order to reduce the focal spot size and improve the quality of light coupling we optimized the micro-lens shape to aspherical using optical design software Zemax. Also the geometry optimization takes into account the dispersion of the refractive index of the polymer. It should be noted that combining micro-lenses which consists of a wide range of photosensitive compositions with different dispersion characteristics makes it possible to optimize such parameters as a chromatic aberration. As a transparent material for lenses fabrication, commercial IP-L resist (refractive index 1.52 @ 532 nm, [5]) and custom resists, such as acrylate with imidazole photoinitiator [6] were used. After fabrication we performed micro-lens characterization using setup that includes light source (white light or green laser), micropositioner and CCD camera. This setup makes it possible to examine the focal plane as well as to obtain an image of USAF target in order to estimate the resolution of micro-lens. The image of the USAF target (25 lp/mm) for optimized aspherical micro-lens is presented on Fig.1 (a). Also shape control of spherical and aspherical micro-lenses was conducted with atomic force microscopy (AFM) method. Besides lateral dimensions parameters measurements, AFM technique enables to control height, radius of curvature and surface roughness of the micro-lens.

![Image](image_url)

**FIGURE 1.** (a) The image of USAF target obtained with printed micro-lens. (b) Set-up for DLW printing on the facet of optical fiber (not to scale). (c) Micro-lens fabricated on the single-mode optical fiber rigidly alignment with the core (optical microscopy image)

### 2.2. Printing micro-lens on the fiber facet

For DLW printing on the optical fiber facet we used custom-made fiber holder combined with Nanoscribe (Fig.1 b). This set-up makes it possible to print elements on the optical fiber facet throw cover glass that protects the objective lens from mechanical damage, provides easy way to find the resin-glass interface and ability to use chemically aggressive resists. Before the printing process, the single mode telecom fiber were cleaved, cleaned and mounted into a holder. The image of the fabricated lens on the fiber facet is presented on fig.1 (c).

### 2.3. Lens on baseplate concept for multi-core fiber tools

In order to improve the quality of light coupling in optical waveguide we present an idea of baseplate with different controllable height (fig. 2 a). Holes in baseplate are made to allow the resist to flow out of the structure during development and reduce the fabrication time. Proposed approach of the micro-lens on baseplate is promising for fabrication a micro-lens array combined with multi-core fiber, where each lens is rigidly aligned with its core with sub-micron precision (Fig. 2 b). Microlens-array can significantly increases light coupling efficiency by focusing light directly into each single core of multicore fiber (as a commercially available MCF with 7 cores and cladding diameter of 125 µm). Moreover, the efficiency of coupling can be controlled by varying the shape of both sides of the lens and height of the baseplate (i.e. lens-facet distance). As a demonstration we fabricated the proposed multi-lens system and investigated its optical properties (Fig. 2 c).
3. Results and discussion
We designed and fabricated such optical components as single micro-lens, micro-lens array and micro-lens on the optical fiber facet. Also we presented the concept of the micro-lens on the baseplate array printed on the fiber facet, which makes it possible to control intensity and other characteristics of light coupling. Also this approach combined with methods of computer vision and correlation analysis can find application for improving the resolution of image systems (e.g. increasing depth of field). The system of such micro-lens array with 7 lens on baseplate is fabricated and its optical properties are measured. The obtained typical size of the focal spot is about 2 µm and the cross-section is Gaussian. It can be seen that the FWHM of the focal spot of single micro-lens is less than the typical core size of single-mode fiber (5-10 µm), which indicates the possibility of using proposed micro-lenses system for multi-core fiber assisting. DLW fabrication method on baseplate makes it possible to fabricate both plano-convex and convex-concave micro-lenses in order to improve quality of the wavefront conversion. In this way, one of the possible application of the proposed micro-lens array is complex optical elements, such as micro-objectives with optimized optical design.

4. Conclusion
The presented concept of micro-lens and micro-lens array fabrication on the fiber facet by direct laser writing (DLW) method is of great interest. The concept could be used for devices similar to fibre bundle for quantum correlation enhanced super-resolution microscopy. Suggested freeform lens array can find application in high-accuracy wavefront sensing, endoscopic systems and spatially-resolved spectroscopy.

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