

# Integration of micro-optical elements with top-end of fibers via focused ion beam direct fabrication

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**Abstract:** Integration of micro-optical elements (MOEs) with optical fiber at top-end was realized by use of focused ion beam (FIB) direct milling. The designed MOEs (micro-refractive lens, micro-diffractive lens with continuous relief, and micro-gratings) were directly milled by the FIB with ion energy and ion beam current of 40 keV and 569 pA, respectively, in the core area of both single mode fiber and multimode fiber for dispersion and focusing uses. The integrated fibers can be used in microspectrometer, optical fiber sensors, and micro-optical systems for biochemistry analysis.

**Keywords:** Diffraction gratings; Diffractive optics; Fiber design and fabrication; Microstructure fabrication; FIB

## 1. Introduction

Optical fiber is a key component for optical communication, optical sensor, and biochemistry analysis systems. With the tendency of integration and miniaturization, the optical systems become smaller and smaller, such as micro-optical electronic mechanical systems (MOEMS). However, R & D of current micro-optical systems was limited by the problem of separate components in the systems, which is a bottleneck for the miniaturization of optical systems. M. Prasciolu reported a method of fabrication the micro-diffractive lens on-fiber by e-beam lithography.<sup>1</sup> Eisenstein reported their conical lens on-fiber by use of chemically etching.<sup>2</sup> In this paper, we focus on the point of integration of MOEs with optical fibers. The MOEs (micro-refractive lens, micro-diffractive lens with continuous relief, and micro-gratings) were directly integrated at core area of top-end of the fibers (both single mode and multimode fibers) by directly writing of the FIB. Before this, we studied the fabrication and integration of MOEs with edge-emitting laser diode and vertical cavity emission laser diode (VCSEL) by use of FIB technology with both functions of direct milling and deposition of SiO<sub>2</sub>.<sup>3-9</sup> These works show that the FIB technology is a practical way for the integration of MOEs with laser diodes for beam collimation and focusing. Our experiments were carried out with both single-mode and multimode fibers from Corning company (SMF28-8.3/125, and MMF 50/125). A micro-grating was directly milled at core area of the single-mode fiber, and micro-diffractive lens with continuous relief and micro-refractive lens were milled at core area of the multimode fibers, respectively, by the FIB milling.

## 2. Experimental setup

The milling experiments were carried out by our FIB machine (FEI Quanta 200 3D) with ion source of liquid gallium, integrated with scanning electron microscope (SEM). This machine uses a focused Ga<sup>+</sup> ion beam with energy of 5~30 keV, a probe current of 1 pA~20 nA and beam limiting aperture size of 25µm~350 µm. For the smallest beam currents, the beam can be focused down to 10 nm in diameter at full width and half maximum (FWHM). The ion beam is focused on the sample surface with normal incident angle. The ion beam scan in the defined area of 64.5×64.5 µm<sup>2</sup> for the micro-grating and 75×75 µm<sup>2</sup> for the diffractive lens, respectively, with the milling process parameters of ion dose, raster mode scanning frequency, pixel space, overlapping, and beam current, are 0.3 nC/µm<sup>2</sup>, 2 Hz, 45 nm, 50%, and 1 nA, respectively.

The diffractive structures can be milled by the FIB using its programming function.<sup>3-9</sup> A computer program can be written (using the machine provided commands instead of the commonly used computer languages) in terms of the

designed parameters and discrete data. Then run the program in a defined milling area. The manufacturing procedures are as follows:

- Discretizing the relief curves according to selected ion beam spot size and feature size of the diffractive lenses.
- Selecting suitable ion energy (ion dose) and dwell time in terms of discrete relief height and curvature of the spherical lens so as to determine the total milling depth for each step (see Fig. 1 and Fig.2 (a) and (b)).
- Programming and optimizing the parameters.
- Milling the relief microstructures by running the designed computer programs.
- Measuring the accuracy of the relief profile and form by interferometers or atomic force microscopy (AFM) or optical interferometer, e.g. WYKO NT 2000.
- Revising machining parameters and recycling above procedures until fabrication accuracy of the diffractive lens reaches the design's.

The designed continuous profile of the micro-lens is divided into many thin layers with the circular shape slice with different diameters for the sake of fabrication, which compose of the lens 3 dimensional profiles using the discrete layers. Each layer is rectangular, with a different size for each different section.

The FIB also can fabricate the microlens on the top end of the fibers by deposition (additive material).<sup>[10]</sup> SiO<sub>2</sub> can be deposited directly to form a required pattern by FIB deposition. The source gas is decomposed by an ion beam and adsorbed on the surface of the substrate. The entire process is controlled by a computer program, generally based on the relationship between ion-beam energy and deposited thickness. The whole process can be carried out automatically using the software program, as shown in Fig.3 and Fig.4. By changing the dwell time under different beam-limiting aperture sizes and controlling the actual beam current error to be less than 10% of the corresponding theoretical value, different deposition results were obtained with precursor gases of 1,3,5,7 tetramethylcyclotetrasiloxane (TMCTS) and H<sub>2</sub>O for the SiO<sub>2</sub> microlens deposition. The accelerating voltage used was 50 kV, and the chamber base pressure was maintained at  $9.1 \times 10^{-6}$  Torr during the whole deposition process.

The designed continuous profile of the micro-cylindrical lens is divided into many thin layers for the sake of fabrication, which compose of the lens 3 dimensional profile using the discrete layers. Each layer is rectangular, with a different size for each different section. The micro-cylindrical lens is composed of many deposited rectangular SiO<sub>2</sub> films with different size and corresponding discrete thicknesses in terms of the sag of the lens, which overlap layer by layer. Finally, the microlens can be obtained by post-processing after completing the deposition of all layers, which are overlapped from bottom to top.

### 3. Experimental results and discussion

Two problems exist during the milling process: charging and polishing on the top of fiber. The former is caused by the accumulated positive ions on the insulate quartz of the fiber core and cladding. It deflected the beam during milling. Some FIB machine equipped with a part, called flood gun, to produce negative electrons to neutralize the positive ions. Unfortunately, our FIB machine (Quanta 200 3D) has no this part. To solve this problem, we wrapped the fiber with copper tape, see Fig.5 (a). The milling quality was improved greatly by this way. As we know, the specialized facility for polishing the top of fiber already appeared in some companies. But we have no this facility. In order to realize the polishing on top of fiber, we directly use FIB milling in the defined circular area with beam current as large as 20 nA. After 50 min., the top of the fiber was well polished, as shown in Fig.5 (b).

Fig.6 (a) is the micro-grating with designed depth and period of 527.8 nm and 3.1  $\mu$ m fabricated by the FIB direct program controlled milling on the top of single mode fiber with core diameter of 8.2  $\mu$ m. The integrated grating can be used as dispersion in micro-optical system. Fig.6 (b) is the micro-diffractive lens with four annulus fabricated by the FIB direct program controlled milling on the top of multi-mode fiber with core diameter of 50  $\mu$ m. The integrated diffractive lens can realize directly focusing the emitting light from the fiber.

Unfortunately, our machine (Micrion 9500EX) breakdown now, and the new machine (Quanta 200 3D) has not equipped with the deposition of SiO<sub>2</sub>. We have no results can show at here. For more information regarding the lens deposition, can see Ref. [10].

### 4. Summary

In summary, the FIB direct milling and deposition processes can be used to locally fabricate microlenses on top of the optical fibers for both single mode and multimode. It can realize integrated of microlenses with optical fibers and other optical waveguides to avoid misalignment error existed in conventional optical systems with separate components. Hopefully, it can provide another options for research and development of micro-optical systems.

## Acknowledgement

This work was supported in part by the Funding for Strategic Research Program on Ultra-precision Engineering from the A\*STAR (Agency for Science, Technology and Research, Singapore), and Innovation in Manufacturing Systems and Technology (IMST) Singapore-Massachusetts Institute of Technology (MIT) Alliance.

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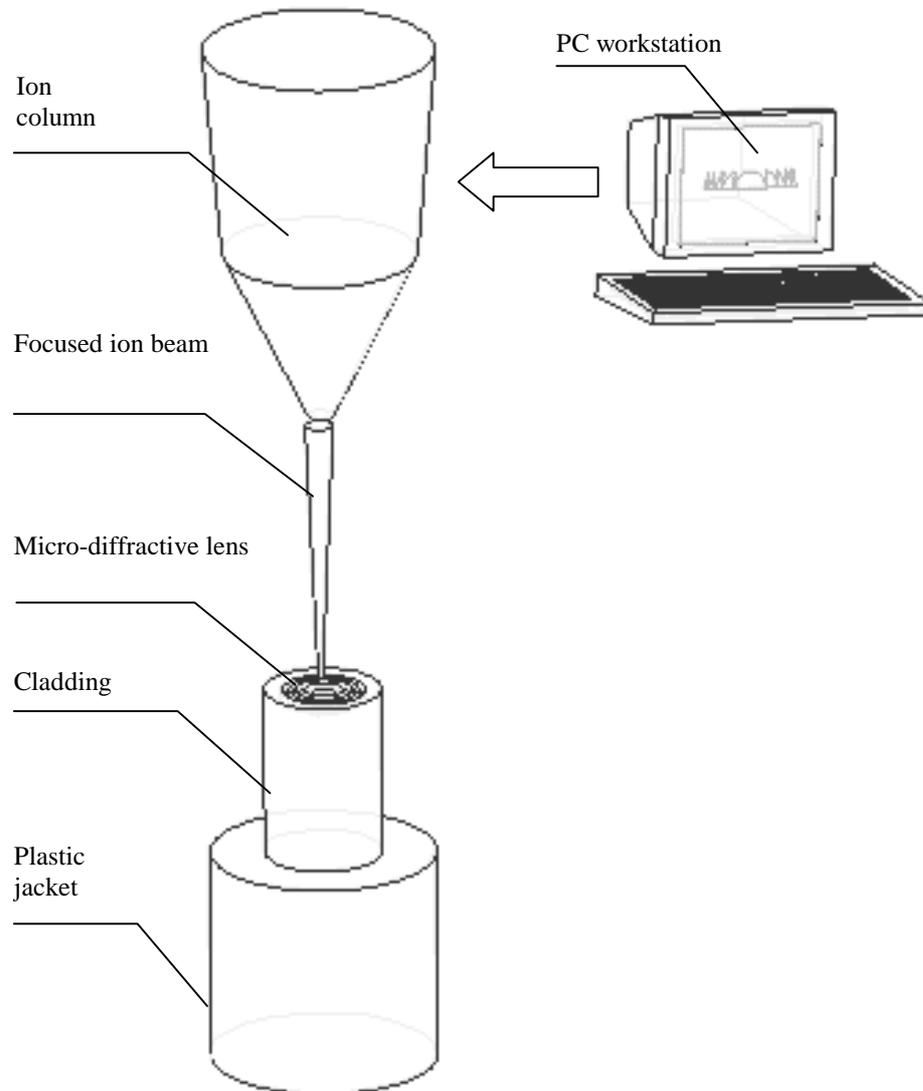


Fig.1 Schematic of micromachining of diffractive lens by computer program controlled focused ion beam

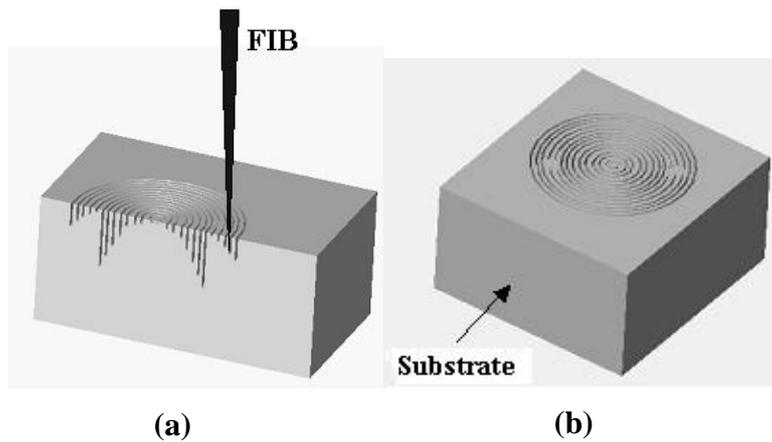


Fig.2 Schematic of programming controlled FIB milling for the diffractive structures with continuous relief. (a) cross-section of the FIB milling circle-by-circle, different circles correspond to different milling depth; (b) top view of the Fresnel structure. It is the same principle for milling of blazed grating; only substitute the circles with straight lines.

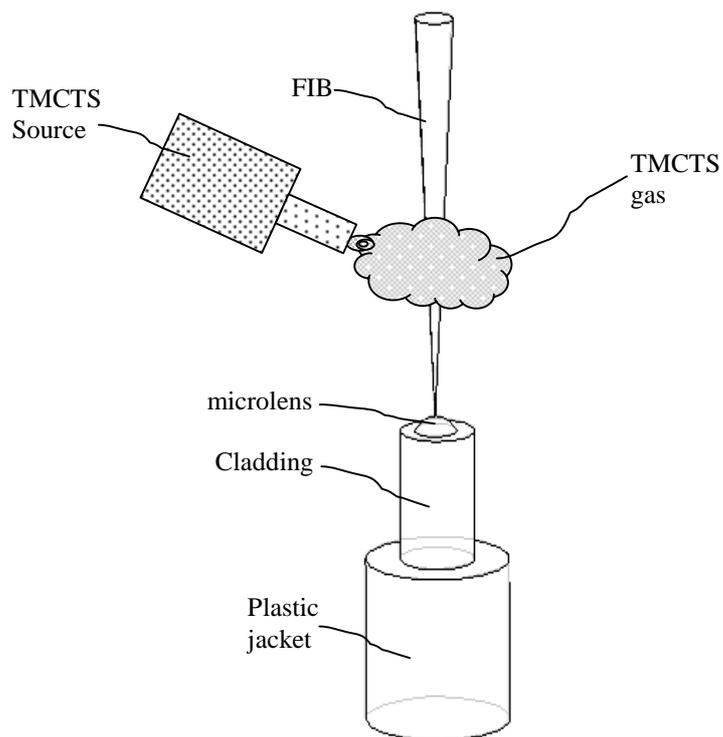


Fig.3 Schematic of deposition of microlenses by chemical gas of TMCTS via focused ion beam scanning. The whole process can be carried out by computer program or manual.

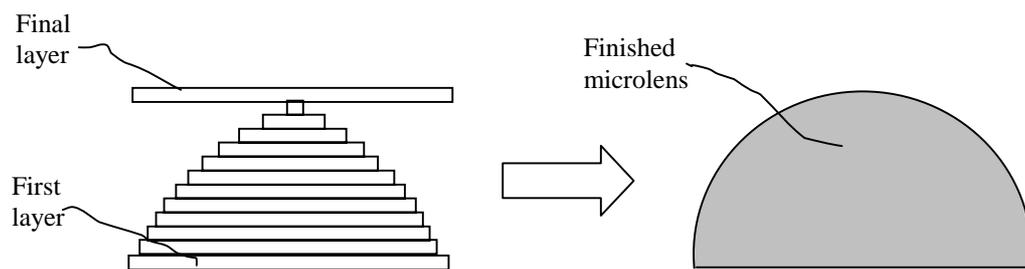


Fig.4 Schematic of microlens deposition through the method of layer-by-layer. Final layer was used for the post-processing.

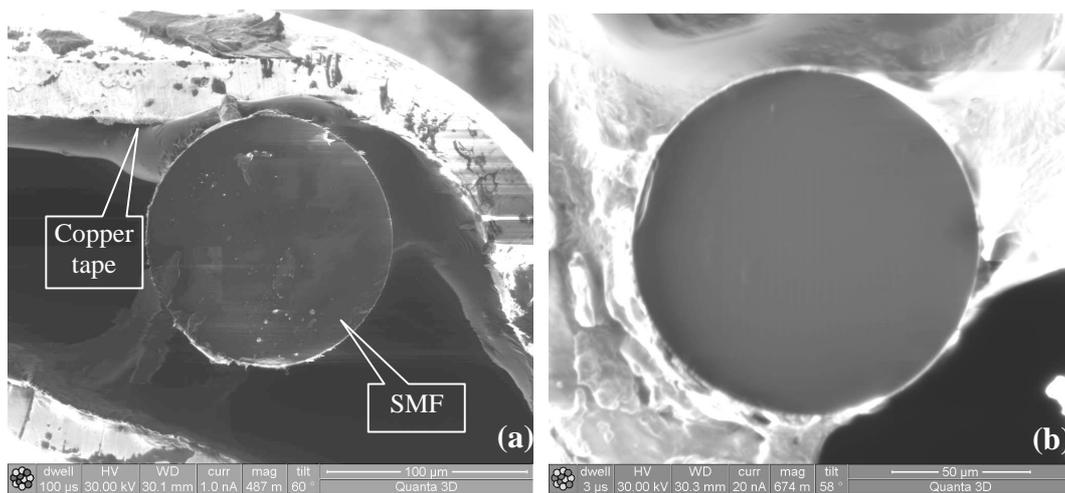


Fig.5 Results of FIB polishing on the top end of fiber. Micrograph of the fiber, (a) before FIB polishing; (b) after FIB polishing

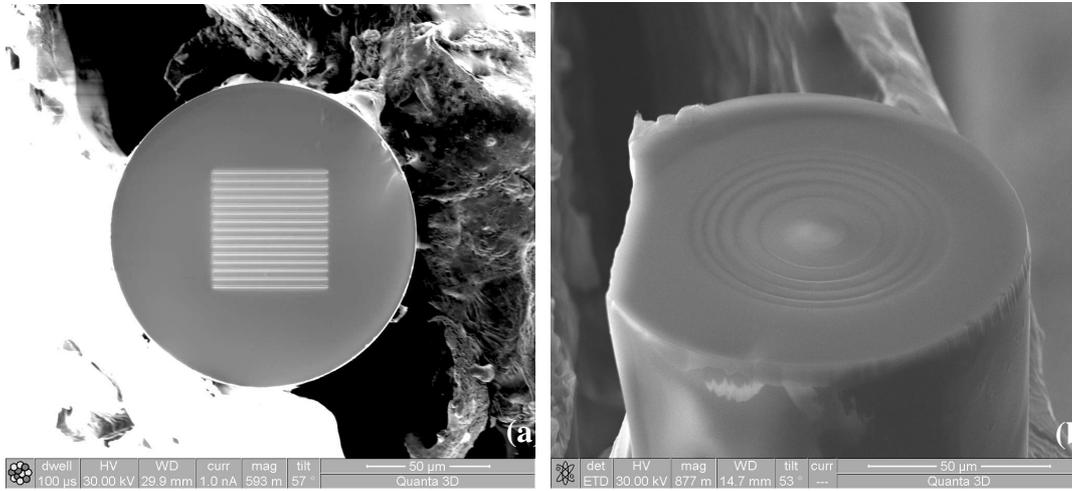


Fig.6 Results of fabrication of grating and diffractive lens on the top end of fiber. Micrograph of the fiber, (a) micro-grating by the FIB milling; (b) diffractive lens by the FIB milling without polishing before the fabrication.