Formation of Micro-lens Array using Femtosecond and CO_2 lasers

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Formation of micro-lens array (MLA) with various sizes and shapes has attracted many researchers as well as industries because of their wide range of applications, especially in the field of optical diffraction. Femtosecond laser pulses were irradiated on a glass sample to fabricate periodic micro-structures on the surface of a fused silica glass. Afterwards, we were shaping the micro gratings by several irradiation times of a CO_2 laser beam by focusing the laser beam on top of the micro gratings. Also, a flat top beam as a potential application of this micro-lens array was formed using the micro-lens array fabricated by using a He-Ne laser.

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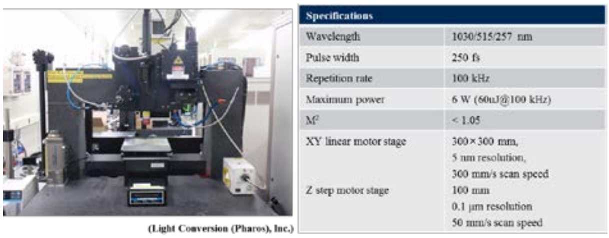
1. INTRODUCTION

A micro-lens is by defined a small lens with diameter of less than 1 mm. Importance of the micro-lens is growing with development of micro-scale optical devices and flourishing optoelectronic industry. In addition, applications of micro-lens can be easily found in many fields such as optical communication, display, optical storage and scanning technology. Conventional fabrication of micro-lens array is achieved by using reflow effect [1], surface tension [2] or mask lithography [3-8]. However, these methods suffer from sensitivity to heat, shock and environment changes. Moreover, each fabrication method has its limitation in terms of material and fabrication time. To address the issues, we demonstrate precise laser fabrication of micro-lens array on top of a silica surface [9-18]. Laser fabrication technology prevents deformation of fabrication material by circumventing the need for external force imposed on a sample. In addition, its capability to fabricate wide range of materials in sub-micrometer scale precision is another advantageous factor that allows its application in various fields. Employing the laser fabrication technique, lens can be fabricated on substrate of various material with the convenience of size and structure modification. In this research we fabricated micro-lens on silica substrate using femtosecond laser and CO_2 laser [19-23]. We tuned the lens curvature by varying cell size of array engraved on the silica substrate where different curvatures were formed by illuminating CO_2 laser on each cell. We compared the characteristics of our lens array with commercially available micro-lens.

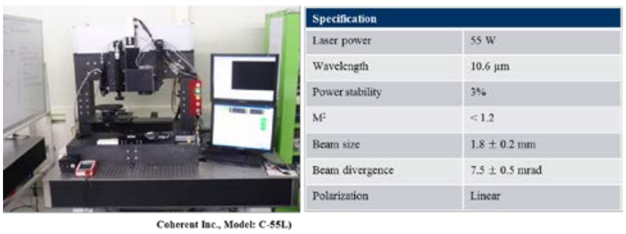
2. EXPERIMENTAL RESULTS

In order to fabricate micro-lens, we used a femtosecond laser (Light conversion, PHAROS) with repetition rate of 100 kHz in APRI, GIST to fabricate microstructure on a silica surface. The femtosecond laser has center wavelength of 1030 nm, pulse width of 250 fs, and maximum optical power of 6 W. Stage used in the experiment is linear motor stage in X and Y axis with 300 mm × 300 mm range of translation and 300 m/s maximum translation speed. Z axis has 100 mm range of translation with independent control. After the fabrication of microstructure, CO_2 laser beam was illuminated on the cell of the structure and introduces curvature. The CO_2 laser (COHERENT, C-55L) has center wavelength of 10.6 μm and maximum optical power of 30 W.



Specifications	
Wavelength	1030/515/257 nm
Pulse width	250 fs
Repetition rate	100 kHz
Maximum power	6 W (60uJ@100 kHz)
M^2	< 1.05
XY linear motor stage	300×300 mm, 5 nm resolution, 300 mm/s scan speed
Z step motor stage	100 mm 0.1 μm resolution 50 mm/s scan speed

Fig. 1 Femtosecond laser micro-machine system



Specification	
Laser power	55 W
Wavelength	10.6 μm
Power stability	3%
M^2	< 1.2
Beam size	1.8 ± 0.2 mm
Beam divergence	7.5 ± 0.5 mrad
Polarization	Linear

Fig. 2 CO_2 laser polishing system

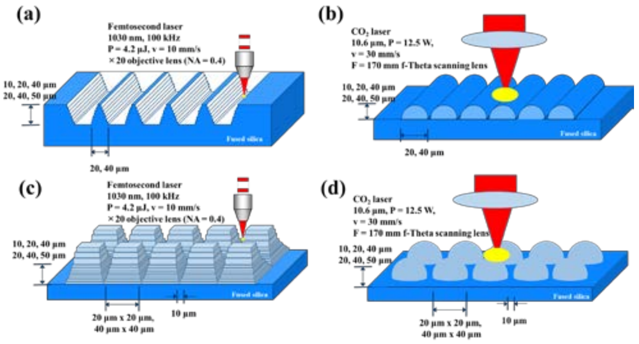


Fig. 3 Schematic of fabrication process using femtosecond and CO_2 lasers. (Fabrication and polishing of cylindrical and dome type micro-lens structures, (a) and (c). Fabrication of cylindrical and dome type structure using the femtosecond laser, (b) and (d) Surface polishing process using a CO_2 laser.)

In order to make micro-lens array, microstructure is fabricated on silica surface with a femtosecond laser and curvature is introduced by melting the surface with CO_2 laser. Figure 3 shows schematic of micro-lens fabrication process that allows production of various curvature.

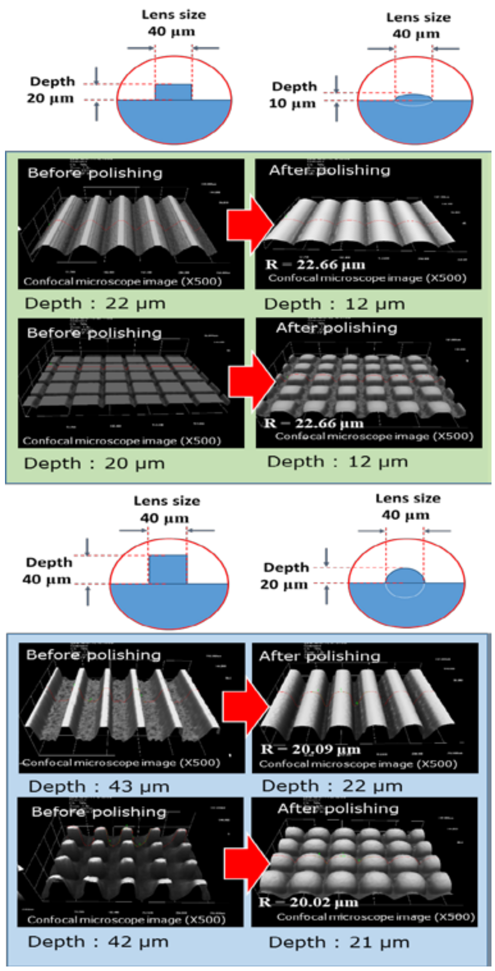


Fig. 4 Image of fabricated structure using a femtosecond laser and polished surface using a CO_2 laser. (Before polishing: 40 µm of structure size and ablation depth of 20 µm and 40 µm; After polishing: 40 µm of structure size, fabrication depth of 10 µm and 20 µm).

Laser beam was incident on silica surface where ablation depth was controlled for fabrication of micro-lens with different size and structure. Micro-lens size of 20 µm and 40 µm was produced with ablation depth of 10, 20, 40 µm and 20, 40, 50 µm respectively. When the surface ablation at a certain depth is completed, the height in Z-axis was translated down repetitively for additional ablation. 20× objective lens (Mitutoyo, NA=0.4) was used for structure fabrication on silica surface with femtosecond laser. Femtosecond laser beam was fixed in position and the sample was scanned with translating stage. Pulse energy was 4.2 µJ and fabrication speed was 10 mm/s throughout the fabrication stages. CO_2 laser beam was incident on the microstructure formed by the femtosecond laser. CO_2 laser beam was scanned over the structured sample placed on fixed stage. F-theta lens with focal length of 170 mm, optical power of 12.5 W and scanning speed of 30 mm/s were the configuration parameters for polishing the microstructures on the silica substrate. Focal spot size of CO_2 laser was approximately 200 µm. Figure 4 shows schematic of micro-lens fabrication process where femtosecond laser introduce array structure on the silica sample and CO_2 laser polishes each cell into a micro-lens.

Cylindrical and dome type micro-lenses were fabricated by using femtosecond laser and CO_2 laser. Size of the lenses were 20 µm and 40 µm and we measured the structure of micro-lens prior to polishing and after the polishing by using confocal microscope (OLYMPUS, OLS3100-Universal type-100). Size and depth of array structure fabricated with femtosecond showed good agreement with the fabrication settings. Also, the ablation roughness and size of the lens were measured for the femtosecond and CO_2 laser fabrication process. Surface roughness was about 4.277 µm after the femtosecond laser fabrication and was reduced to 0.783 um after the surface polishing by CO_2 laser.

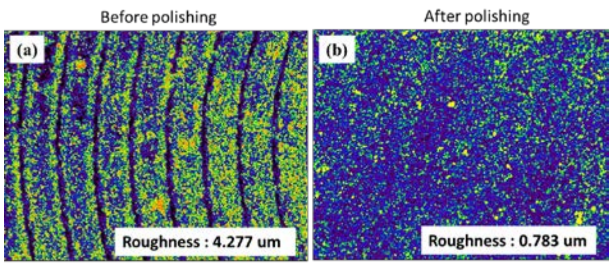


Fig. 5 Comparison of surface roughness before and after the polishing step. (a) Before polishing: 4.277 µm. (b) After polishing: 0.783 µm.

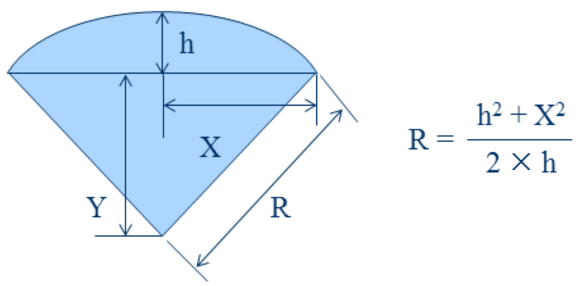


Fig. 6 Radius of curvature equation

We found optimum fabrication condition and calculated curvature of each micro-lenses by series of structure measurements of micro-lens structures produced at different fabrication conditions. Radius of curvature equation shown in Figure 6 was used for calculation of micro-lens curvature. Size and depth of each micro-lens array were found with confocal microscopy and the radius of curvature was acquired from the measurement. We found that the radius of curvature decreases with deeper groove of the array.

We characterized the cylindrical and dome type micro-lens array produced with laser fabrication system. A He-Ne laser was transmitted through the micro-lens and the beam profile at the focal point of micro-lens was acquired with CCD. Micro-lens array with size of 40 µm, cylindrical and dome type micro-lens with radius of curvature of 20.09 and 20.02 µm respectively were used for the experiment. He-Ne laser (THORLABS, HRP020) had center wavelength of 633 nm and the optical intensity was controlled with two polarizers after the laser. We identified the beam patterns at the focal point that matched with the corresponding micro-lens array type.

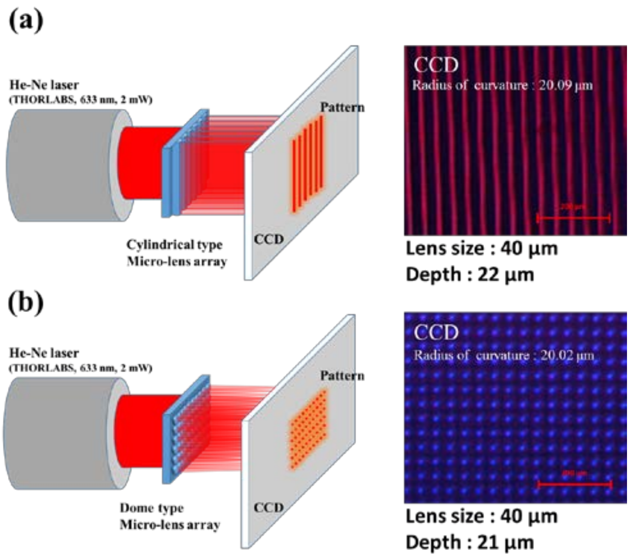


Fig. 7 Beam shape measurements of two different micro-lens array structures, (a) Cylindrical type, (b) Dome type

Also, dome type micro-lens array was characterized by image analysis. Optical microscope (ZEISS, Axioskop 40 Pol) and letters "APRI" formed by ablating the surface of aluminum coated acrylic plate was used for the image measurement. The dimension of the letters was 316 µm and 90 µm in horizontal and vertical direction respectively. Measurement was achieved by using CCD, micro-lens array. White light was illuminated from the bottom of the "APRI" letter sample and the image was formed on the CCD. The transmitted white light was propagated through the micro-lens array where the image on the CCD was acquired. We observed the "APRI" images were formed for each micro-lenses. The size of the images were 34 µm in horizontal direction and 10 µm in vertical direction which show demagnification from the original sample.

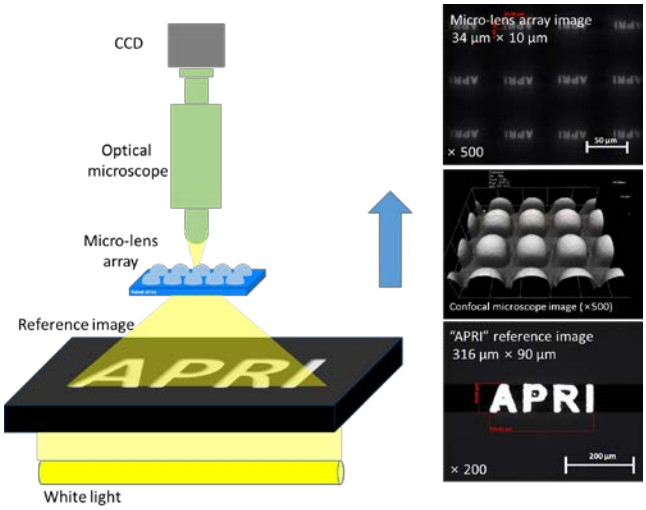


Fig. 8 Micro-lens array image measurement

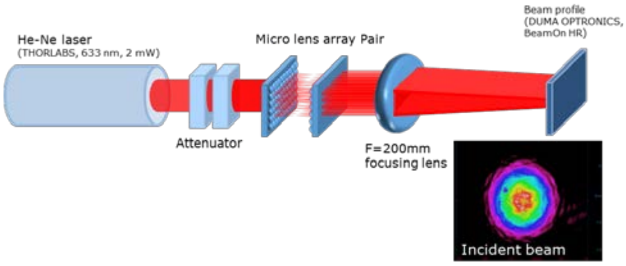


Fig. 9 Comparison of micro-lens array beam profile (commercial type & laser processed type)

In order to compare our micro-lens array with commercial product, we characterized conventional micro-lens array by SUSS MicroOptics where the size of the micro-lenses were 500 µm. Figure 8 shows the schematic of the experiment to compare the characteristics. We placed two same-sized micro-lens array at each focusing position and acquired the transmitted laser beam pattern with a beam profiler. Two of the commercial micro-lens arrays and two of the fabricated micro-lens arrays were used in the experiment.

Figure 10 shows the beam profile images of commercial and fabricated micro-lens array. We found that Gaussian beam of the a He-Ne laser was transformed into square-shaped beam profile. The commercial micro-lens array exhibit clear square beam profile whereas the fabricated micro-lens shows artifacts of diffraction located outside of the square region. Although the diffraction effects were present in the fabricated lens array, the characteristic of micro-lens array was confirmed to be a square profile. We assume the artifact arises from the incomplete polishing of arrays where the roughness results in diffraction of light. In our later studies we anticipate fabrication of micro-lens array with characteristics comparable to commercial product by reducing the roughness and diffraction effect.

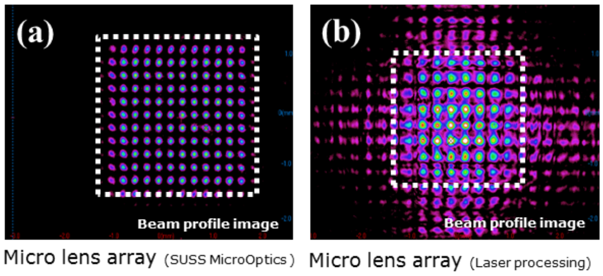


Fig. 10 Beam profile images of commercial and fabricated micro lens array (a) SUS MicroOptics MLA, (b) Fabricated MLA

3. CONCLUSION

We have demonstrated fabrication of micro-lens array using femtosecond and CO_2 lasers, and analyzed the characteristic of the micro-lens array. Also, we have compared the fabricated micro-lens array with commercial micro-lens array. Array corresponding to size of lens was fabricated on surface of silica with femtosecond laser. Structure of micro-lenses was formed by CO_2 laser polishing. Array on the silica surface was fabricated by translating the laser beam in Z direction and the depths were chosen according to the size of the array. Surface polishing using CO_2 laser was achieved by scanning over the sample. Micro-lens arrays with various size were produced according to the depth of the array. Structure of the fabricated micro-lens arrays were measured by confocal microscopy and the curvature was analyzed by using radius of curvature formula.

Beam profiles at the focal point for cylindrical and dome type lenses each with radius of curvature of 20.09 and 20.02 μm were measured with CCD. The beam patterns were identified for each lens type. Also, we perform image analysis of dome type micro-lens. Letter sample “APRI” was fabricated and the white light transmitted through the micro-lens array were acquired as image. We observed demagnification of original sample for acquired images. We compared our fabricated micro-lens array with commercial product (SUSS MicroOptics). Micro-lens arrays with identical size were aligned carefully and corresponding beam profiles were acquired. We observed transformation of original Gaussian beam profile into square array of circular dots.

We fabricated micro-lens array with similar dimension using laser fabrication system. At similar experiment configuration, the square array beam pattern was reproduced. However, the beam artifacts arising from diffraction were found outside of the square region. We assume that the effect is due to incomplete polishing of the array. We prospect enhanced polishing condition in the future with optimum CO_2 laser polishing settings where the characteristic may improve to be comparable to the commercial micro-lens array. In order to complement our fabrication process, we are planning to employ flat top laser beam for our fabrication. We anticipate that our laser fabrication process allow for more convenient micro-lens array production with various dimensions and furthermore we may find possibility for fabrication of sub-micrometer scale lens array. Also, the laser fabrication technique can be employed in variety of fields not only limited to manufacturing of optoelectronic devices.

Acknowledgments and Appendixes

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