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# Four-beam Interference Optical System for Laser Micro- structuring Using Picosecond Laser

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A four beam interference optical system for laser micro structuring using a pulse laser was demonstrated. The four beam interference optical system using a pulse laser(picosecond laser) can fabricate micro structure on mold material(NAK80) directly. Micro structure on the polymer can be reproduced economically by injection molding of the micro structure on the mold material. The four beam interference optical system was composed by the DOE(Diffractive Optical Element) and two lenses. The laser intensity distribution of four beam interference was explained by an interference optics point of view and by the image optics point of view. We revealed that both views showed the same result. The laser power distribution of a 1 μm peak pattern was made by the four beam interference optical system and measured by the objective lens and CCD. A 1 μm pitch dot pattern on the mold material was fabricated and measured by SEM(Scanning Electron Microscopy).

*Keywords* : Four beam interference, Laser ablation process, DOE(Diffractive Optical Element), Mold surface micro pattern

*OCIS codes* : (320.0320) Ultrafast optics; (320.5390) Picosecond phenomena

## I. INTRODUCTION

The laser ablation process which is a micro-scale ablation process using the high intensity energy produced by focusing a pulse laser beam has been the subject of many studies recently.[1-4] The laser ablation process is applicable to various materials, environment-friendly, and simpler than a photolithography process. Because the laser ablation process is non-contacting, it is less influenced by thermal impact and produces less thermal and mechanical deformation. It also enables micro-processing without a mask by using a laser direct writing method. However, due to the characteristics of the laser micro-machining where surface is processed with a focused laser beam, the fabrication width cannot be smaller than the diffraction limited focus spot diameter.[5] When focusing a laser beam using a focusing lens, the size of the focused beam cannot be smaller than the limit in diffraction. To reduce the size of the focused beam, the size of the incident beam to the focusing lens can be enlarged, the wavelength of the incident laser can be reduced, or a focusing lens having shorter focal length can be used. The size of the incident beam can be enlarged using a beam expander, however, there is a limit in expanding the incident beam size. The method of shortening the wavelength of the incident laser beam is limited by the price of the laser source. Using a short-focal length lens can reduce the focused-spot size, but the ‘depth of focus’ also is reduced resulting in difficulty in processing. [6] The problem of irregular processing caused by insufficient depth of focus may be prevented by using an auto focusing unit, however, the auto focusing unit adds complexity to the laser process machine. The short-focal length lens may be damaged by the particles generated in ablation.

In order to cope with the diffraction limit, optical systems using an interference effect are studied. A CW (continuous wave) laser having good coherence can be used when exposing photo resistive material. But pulse lasers are required for an ablation process which requires higher fluence. As the temporal and spatial coherences of pulse lasers are not as good as those of CW lasers, which leads to poor contrast of interference power distribution, pulse lasers are disadvantageous to micro-proc-

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essing using interference effects. But the most important reason that interference patterns should be processed using pulse laser is that micro patterns can be processed on mold material in a single process. While the photo resistive material exposing method requires chemical etching and electroforming processes to produce micro-patterns on mold material, the laser ablation process can produce micro-patterns on mold material in a single process.

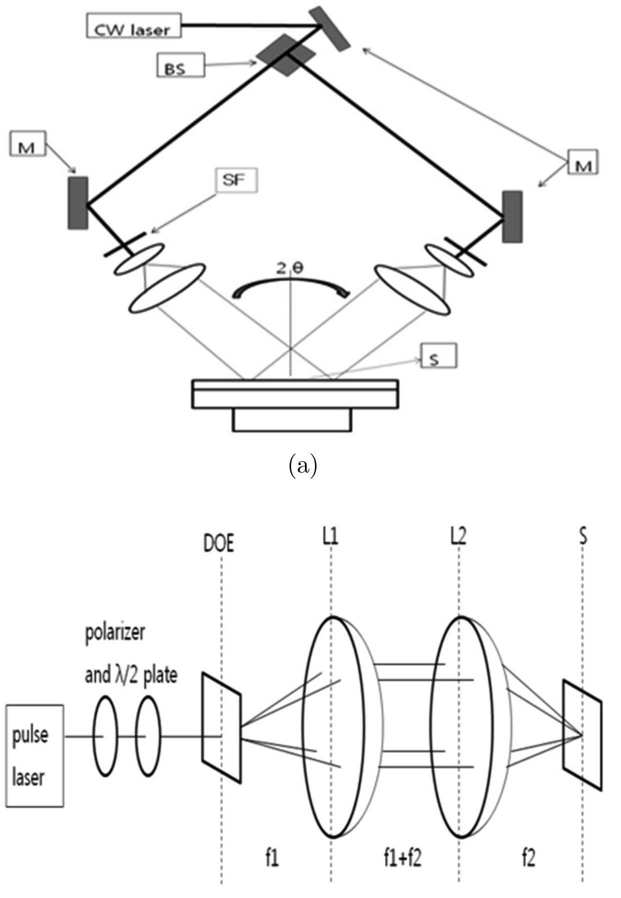
In an optical system using interference effect, the laser beam is divided into 2 split beams using a beam splitter, then irradiates the specimen to produce an interference pattern and to perform processing. The interference pattern of the two split laser beams are a line pattern. However, to produce a dot pattern instead of a line pattern using interference effects, four beams instead of two beams have to be combined. It is very difficult for an optical system using a beam splitter to make four beams interfere together. To simplify such complexity of the optical system, studies are being conducted on the systems using DOE (Diffractive Optical Element) and lenses. [7-11]

In this study, using a pulse laser with 12 picoseconds of pulse duration in an interference optical system implemented with DOE and lens, micro patterns were directly processed on NAK80 mold material. To the best of my knowledge, there is no report about the micro structuring on the mold material with four beam interference using a picosecond laser. The performance of the interference optical system was evaluated by measuring the light distribution of the interfering light with objective lens and CCD. Using the interfered light distribution, micro dot pattern whose pattern size was 1 μm or less was processed.

## II. EXPERIMENTAL CONDITION

The picosecond laser used in the experiments was a diode-pumped mode-locked Nd:YVO4 laser with a pulse duration of 12 ps. The fundamental wavelength is 1064 nm. The laser is equipped with second harmonic generators to make laser wavelengths of 532 nm. In the experiments, we used the laser wavelength of 532 nm. The diameter of the laser beam was 1.5mm. A half wave plate and a polarizer were used to control the laser power. Instead of a mechanical shutter, an external TTL signal served as a shutter for laser pulses. This prevents extra irradiation of laser pulses onto the specimen caused by the time delay of a mechanical shutter at every end point of laser beam path.

Fig. 1(b) presents the configuration of the interference optical system in this study. The system comprised a DOE which splits the laser beam into 4, lens 1 which makes the split beams parallel with each other, and the lens 2 which converges the 4 parallel beams. The focal lengths of the lens 1 and lens 2 were 150 mm and 75 mm, respectively. To make the 4 beams split by the DOE to propagate parallel to each other, the distances between the DOE and lens 1 was set to 150mm. The distance between the lens 1 and lens 2 was set to 225 mm.



(a)

(b)

FIG. 1. The schematics of interference optical system (a) Two beam interference system using beam splitter: BS; Beam splitter, M; Mirror, SF; Spatial Filter, S; Specimen, (b) Four beam interference system using DOE(Diffractive Optical Element) : L1; Lens1, L2;Lens2, S; Specimen

In this study, the processing material was NAK80, a mold steel with a uniform hardness of approximately 40HRc throughout: which does not require stress relieving, even after heavy machining. It has uniform grain structure with no pin holes, inclusions or hard spots. This material can be machined to obtain a mirror-surface. Due to these features, NAK80 is widely used for lens molds. If patterns can be made on NAK80, they can be replicated on a plastic surface, which means that mass production is possible at a very low cost. The surface morphology was investigated by scanning electron microscopy (SEM) with JEOL JSM-6300.

## III. EXPERIMENT RESULTS AND DISCUSSION

Fig. 1 shows the schematics of a two beam interference optical system using a beam splitter and a four beam interference system using DOE. In a two beam interference system, the laser beam is split using a beam splitter and combined on the specimen again to cause interference. It is difficult in this method to implement high laser fluence on the specimen. This is because, to realize high laser fluence, the split beams have to be irradiated on the specimen using a focusing lens, however, this optical system is not easy to implement. Furthermore, to make 4 split beams interfere together, more optical elements are involved and their optical alignment is very difficult. On the other hand, since the four beam interference system using DOE splits laser beam into 4 using a simple DOE element and focuses the beams using a lens system, this system is very useful for the implementation of high laser fluence by interfering 4 beams together. The first lens makes the 4 beams parallel with each other and the second lens focuses them, giving higher laser fluence.

The Equation (1) below expresses the 4 split beams;

$$\begin{aligned}\overrightarrow{E_1} &= |E_1|\exp\left[i(\overrightarrow{k_1}\bullet\vec{\gamma}+\phi_1)\right]\\ \overrightarrow{E_2} &= |E_2|\exp\left[i(\overrightarrow{k_2}\bullet\vec{\gamma}+\phi_2)\right]\\ \overrightarrow{E_3} &= |E_3|\exp\left[i(\overrightarrow{k_3}\bullet\vec{\gamma}+\phi_3)\right]\\ \overrightarrow{E_4} &= |E_4|\exp\left[i(\overrightarrow{k_4}\bullet\vec{\gamma}+\phi_4)\right]\end{aligned} \tag{1}$$

Where $\overrightarrow{k_n}$ is the 2πλ , λ is the wavelength, $\phi_n$ is the phase constant and n=1,2,3,4

When these 4 beams interfere together, the light distribution can be expressed with the Equation (2) below;

$$\vec{E} = \overrightarrow{E_1}+\overrightarrow{E_2}+\overrightarrow{E_3}+\overrightarrow{E_4} \tag{2}$$

The intensity of the light having the electric field as above equation can be expressed with the Equation (3) below;

$$\begin{aligned} I &= C\epsilon_0\left\{\left(\overrightarrow{E_1}+\overrightarrow{E_2}+\overrightarrow{E_3}+\overrightarrow{E_4}\right)\bullet\left(\overrightarrow{E_1}+\overrightarrow{E_2}+\overrightarrow{E_3}+\overrightarrow{E_4}\right)\right\}\\ &= C\epsilon_0\left\{\frac{1}{2}|E_1|^2+\frac{1}{2}|E_2|^2+\frac{1}{2}|E_3|^2+\frac{1}{2}|E_4|^2+\right.\\ &\quad |E_1||E_2|C_{1-2}+|E_1||E_3|C_{1-3}+|E_1||E_4|C_{1-4}+\\ &\quad \left.|E_2||E_3|C_{2-3}+|E_2||E_4|C_{2-4}+|E_3||E_4|C_{3-4}\right\}\end{aligned} \tag{3}$$

Where $C_{i\text{-}j} \equiv \mathrm{COS}\left\{(\overrightarrow{k_i}-\overrightarrow{k_j})\bullet\vec{\gamma}+(\phi_i-\phi_j)\right\}$(i, j = 1~4)

Here, the period of the light distribution can be expressed with the Equation (4) below;

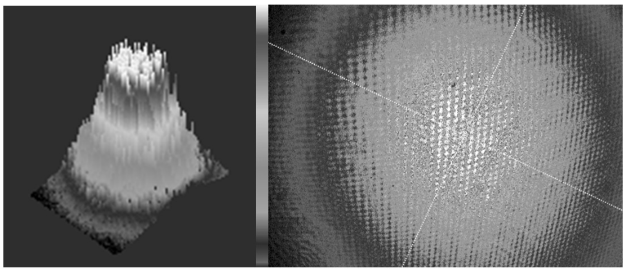

(a) (b)

FIG. 2. The measurement result of laser power distribution of 1 µm peak pattern: (a) three dimensional laser power distribution, (b) two dimensional laser power distribution

$$(\overrightarrow{k_i}-\overrightarrow{k_j})\bullet\vec{\gamma} = (\hat{i}\,2k_0\sin\theta)\bullet(\hat{i}\,x+\hat{i}\,y) = 2k_0\times\mathrm{Sin}\theta = 2\pi \tag{4}$$

Therefore, the period of the light distribution can be expressed with the Equation (5) below;

$$x = \frac{\pi}{(k_0\sin\theta)}/=\frac{\lambda}{2n\ \sin\theta} \tag{5}$$

Where is Period of micro pattern, $k_0$ is $2\pi n/\lambda$, $\lambda$ is laser wavelength, $\theta$ is incident angle and $n$ is refraction index. In this paper $\lambda$ is 532 nm, $\theta$ is 15°, $n$ is 1 and x can be calculated into 1 µm.

While the Fig. 2b can be interpreted in the aspect of interference, however, it also can be interpreted as the image of the DOE element projected on the specimen. That is, the image created from the DOE element pattern through the two lenses is transcribed onto the specimen. In this interpretation, the interval of the image pattern gaps is determined by the Equation (6);

$$P = \frac{f_2}{2f_{1_o}}P_{DOE} \tag{6}$$

where $f_1$ is the focal length of the first lens, $f_2$ is the focal length of the second lens, $P_{DOE}$ is the pitch of DOE pattern, and $\frac{f_2}{2f_{1_0}}$ is the magnification factor of lens. In this paper, $f_1$ is 150 mm, $f_2$ is 75 mm, $P_{DOE}$ is 4 µm and $P$ can be calculated into 1 µm. The results show that the analysis in the interference aspect and projection aspect are identical with each other.

Fig. 2 shows the laser power distribution at the interfering part. The Fig. 2(a) shows three dimensional laser power distribution, and the Fig. 2(b) shows two dimensional laser power distribution. Red color represents higher fluence and purple represents lower fluence. As shown in the Equation (1), the laser beam profiler using conventional CCD is difficult to measure 1 µm -class

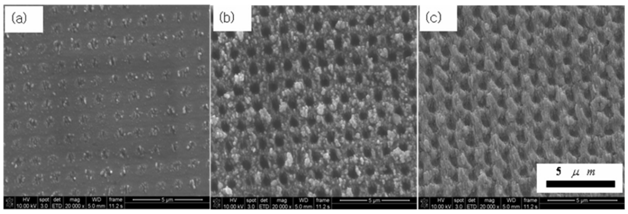


FIG. 3. SEM image of 1 μm pitch pattern on the mold material: (a) 500 pulses shot, (b) 1000 pulses shot, (c)3000 pulses shot

laser power distribution, because the pixel size of conventional CCD is 5 μm or larger. It is not possible to measure 1 μm-scale laser power distribution using a CCD whose pixel size is 5 μm or larger. Therefore, 1 μm-class laser power distribution needs to be magnified. In this study, an objective lens (Nikon Plan Fluor 10x working distance 16 mm) was used to enlarge 1 μm-class laser power distribution, and the enlarged image was measured with CCD (Ophir Beamstar-fx50), while the laser power was reduced to minimum using polarizer and wave plate to protect the CCD. In the measurement result, the contrast of the 1 μm peak pattern was not satisfactory, because the contrast of the actual interference laser power distribution itself was not good enough. It is because both the temporal and spatial coherences of the pulse laser were not good compared with CW laser. In addition, it was thought that the measurement values in the Fig. 2 contained the error of the measurement instrument itself, including the aberration of the objective lens and the measurement error based on the resolution of the CCD.

Fig. 3 shows the results of 1 μm-class micro-patterning on mold material (NAK80) by four beam interference using DOE and picosecond laser. The average laser power at the focus of the 4 beams was 2W, the focused spot size was 60 μm, the repetition rate was 50kHz, and the laser fluence was 1.4 J/cm$^2$. The laser ablation process was conducted in ambient condition, without using blowing gas. The Fig. 3a is the case of 500 pulses, Fig. 3b is the case of 1,000 pulses, and the Fig. 3c is the case of 3,000 pulses. It can be seen that the increase in the number of pulse results in deeper patterns. However, as the number of pulse increases, the boundary between the processed and unprocessed parts becomes unclear, due to the heat affection zone generated in the laser ablation process. Even when the contrast of the light pattern is very high, larger HAZ(heat affection zone) is formed when more energy is used in the process. The HAZ can be reduced by using ultrashort pulse laser whose pulse duration is between 10 femtosecond to 20 picoseconds. [12] The energy of the laser irradiating the material is used to excite the electrons in the initial phase, and then the excited electrons transmit energy to the solid lattice. In this process, complicated reactions including electron emission, melting, vaporization, phase explosion, pallation, and electrostatic ablation, occur and the material begins to be removed. The detailed ablation mechanism is still under investigation. The ablation mechanism differs according to laser parameters (fluence, wavelength, pulse duration, et cetera) and material. In an ordinary pulse laser, the pulse duration is some tens of nanoseconds. Such a pulse laser induces large heat affection zones in the material removal process because during the tens of nanoseconds of irradiation, energy is transferred to the lattice. On the other hand, when using ultrashort laser beam, the electron energy is not transferred to the lattice because the laser irradiation is cut-off after exciting the electrons and no more energy is transferred to the lattice of the material. This is because it takes normally some tens of picoseconds for the electron energy to be transferred to the lattice of the material, though the transferring time from electron to lattice differs by material. This enables clean ablation, that is, processing with reduced heat affection zone. [13] However, the interactive mechanism between ultrashort pulse laser and material has yet to be studied.

On the other hand, the laser coherence becomes worse as the laser pulse duration shorten in order to reduce the heat affection zone. In particular, the pulse duration has to be reduced to reduce heat affection zone, but be increased to improve the peak contrast of interference laser power distribution. To this end, the pulse duration must be optimized. In this study, we chose the laser source of with pulse duration 12 picosecond. Though it would be impractical to process micro-structures having large aspect ratios (deep processing with narrow width) using interference optical system of pulse laser, the results of the experiment showed that micro-patterns can be easily produced on thin film using the interference of a pulse laser.

Another advantage of interference processing is the fast processing speed. In the process using focusing lenses, each pattern has to be processed one by one. However, in an interfering process, all the patterns within the spot size can be processed at the same time. Therefore, the processing speed is much faster than that using a focusing lens. For example, in the Fig. 3b where the material was processed using 1,000 pulses, 3,000 micro-dots of 1 μm size can be processed in 20 ms when using 50 kHz. Higher repetition rate than 50 kHz and the high speed of stage can be used to improve process speed.

## IV. CONCLUSION

In this study, about 3,000 micro-dots whose size was 1 μm or less were produced on NAK80 mold material in the process time of 20 ms, using a four beam interference optical system utilizing DOE and a picoseconds laser. In order to make the 4 beams interfere together using simple optics, the four beam interference optical system utilizing DOE was used and the picosecond laser was used to reduce the heat affection zone of the produced micro-structure. It was found that the pulse duration of the process laser should be determined to take the peak contrast of the interference light distribution and the heat affection zone into consideration. The light distribution of the four beam interference was analyzed in the aspect of image projection as well as in the interference aspect. The light distribution of the interfering beams was measured using an objective lens and CCD to evaluate the performance of the interference optical system.

The micro-patterns developed in this study can be applied in surfaces for reduced friction, such as car engines, surfaces for adhesion control or for increased absorbability. Especially, the micro-spike arrays produced by injection molding will provide super-hydrophobic surfaces at very cheap cost. [14-16]

## ACKNOWLEDGMENT

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