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Formation of arrayed holes on metal foil and metal film by multibeam interfering femtosecond laser beams*

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We report on an optical interference method to fabricate arrayed holes on metal nickel foil and aluminum film deposited on glass substrate by means of five-beam interference of femtosecond laser pulses. Optical microscope and scanning electron microscope observations revealed that arrayed holes of micrometre-order were fabricated on both metal foil and metal film. The present technique allows one-step, large-area, micrometric processing of metal materials for potential industrial applications.

Keywords: array microstructure, interference, femtosecond laser, diffractive beam splitter
PACC: 4262A, 4225H, 4280W

In some technological implementations, the microfabrication of arrayed structures of micrometre-order is necessary. For metallic material with high heat conductivity the fabrication of micron-order structures by use of ultra-short pulse lasers have unique advantages. [1−3] By applying femtosecond (fs) laser pulses the size of the heat-affected zone is in the micron region, allowing the creation of small lateral structures. However, short-pulse irradiation is not necessarily enough to reach the micron region. The theoretical limit for the achievable smallest spot size is defined by the numerical aperture (NA) of the imaging optics and the wavelength of the laser radiation. By decreasing the wavelength, Békési *et al* employed UV fs laser to fabricated micron size holes on metal foil.[4] Here, we employ an alternative method, IR fs laser interference technique, to fabricate micrometre-order arrayed holes on metal foil and metal film.

Recently, much attention has been paid to the fs laser interference (FLI) technique[5−13] for the fabrication of periodic microstructures because it can produce a periodically modulated light intensity distribution with a period in the order of its wavelength. A periodically modulated microstructure can be obtained if the periodically modulated light intensity distribution is transferred to a photoreactive material. The interference of two beams creates a one-dimensional periodic pattern. By increasing the number of beams, in principle, two-dimensional and three-dimensional periodic patterns can be obtained. By this way, Kawamura *et al*,[6] Si *et al*[7] and Li *et al*[8] fabricated surface or volume micrograting in various materials. Qu *et al*[9] induced metal nanoparticle arrays in silicate glass. Kondo *et al*[10] and Shoji *et al*[11] demonstrated the fabrication of photonic crystals in photoresist and resin. Nakata *et al*[12] showed the fabrication of dot array on metal film. There are two kinds of beam delivery schemes which have been used in the aforementioned researches. The first is mainly composed of a beam splitter and an optical delay in order to achieve the spatial and temporal interference for fs laser pulses. The second is mainly composed of a diffractive beam splitter (DBS) and a confocal imaging system, in which no optical delay

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is needed. For the first approach, the needed precise adjustments of optical delay for each optical path are accomplished by observing the second-harmonic generation or third-harmonic generation[13] to obtain the temporal overlap of fs pulses. In addition, when multiple-beam (more than two beams) interference is used, a complicated optical setup is required and its precise adjustment is very difficult. For the second approach, the optical setup is quite simple and temporal overlap is achieved without any adjustment.

In this paper, we employ the FLI technique to fabricated arrayed holes on metal nickel (Ni) foil and metal aluminum (Al) film deposited on glass substrate. By five-beam interference of near-IR 800nm fs laser pulses, periodic holes of micrometre-order were successfully fabricated on both Ni foil and Al film. Morphology of the fabricated structures was investigated by optical microscope and scanning electron microscope (SEM). Also, the diffraction features of the structures on the metal film were evaluated.

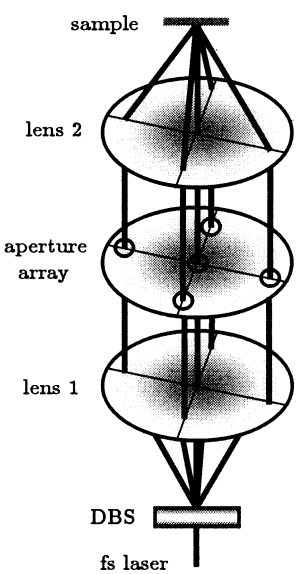


Fig.1. Schematic of the experimental setup.[10,11] DBS: diffractive beam splitter.

The experimental setup is similar to previous researches of Kondo *et al* and Shoji *et al*,[10,11] as shown in Fig.1. A commercial regeneratively amplified 800nm Ti: Sapphire laser was used to produce 120fs, 1kHz, mode-locked pulses, which were split into five beams by a DBS (MEMS Optical, Inc.). The split five beams were made parallel by a lens with focal length of 100mm, then collected to the sample by a 20× optical objective lens (Nikon 20MI, NA 0.45), where the temporal and spatial overlap of the pulses of the five beams was perfectly achieved. The four outer beams with equal intensity were symmetrically placed around the central beam, and make an angle (θ) of 12° with it. The intensity of the central beam was 10 times higher than that of the other beams. The typical input laser power (incident on DBS) and exposure time were set as 150mW and ~10s, respectively. The material used in the experiments was commercial nickel foil of thickness 20μm. Al film of thickness 200nm was prepared by evaporation on silica glass substrate. All experiments were carried out at room temperature in ambient atmosphere.

The structures fabricated on the Ni foil by five-beam interfering fs laser pulses are shown in Figs.2(a) to 2(d). In Fig.2(a), a spot with a diameter of about 300μm was fabricated by five-beam interfering fs pulses in a one-step exposure process (~10s). By scanning the Ni foil, the fabricated spots align into a line. The detailed structures in the spots are shown in Figs.2(b) and 2(c), observed by SEM and optical microscope, respectively. Fourfold-symmetric arrayed holes were induced on the Ni foil. The period of the array is about 2.5μm, which is in agreement with the calculated value of $\lambda/(\sqrt{2}\sin\theta)$.[10] The depth of ablated holes is about 10μm, measured by an optical microscope. Figure 2(d) is the magnified image of the structure of Fig.2(b). As can be seen, the well of holes is not very irregular, which may be the result of longer ablation duration. Based on the two-temperature diffusion and hyperbolic two-step heat conduction models, Chichkov *et al*[14] and Xu *et al*[15] have investigated the ablation behaviour of metal during fs laser irradiation. They suggested that the ablation process could be considered as a direct solid-vapor transition as very short time scales are involved in the ablation. In our case, the five-beam interference of fs laser pulses produces a periodically modulated light field with the distribution of enhanced and weakened intensity. The enhanced optical intensity heats the lattice on a picosecond time scale,[14] resulting in the creation of vapour and plasma phases followed by a rapid expansion and finally forming the periodic hole structures on the metal foil.

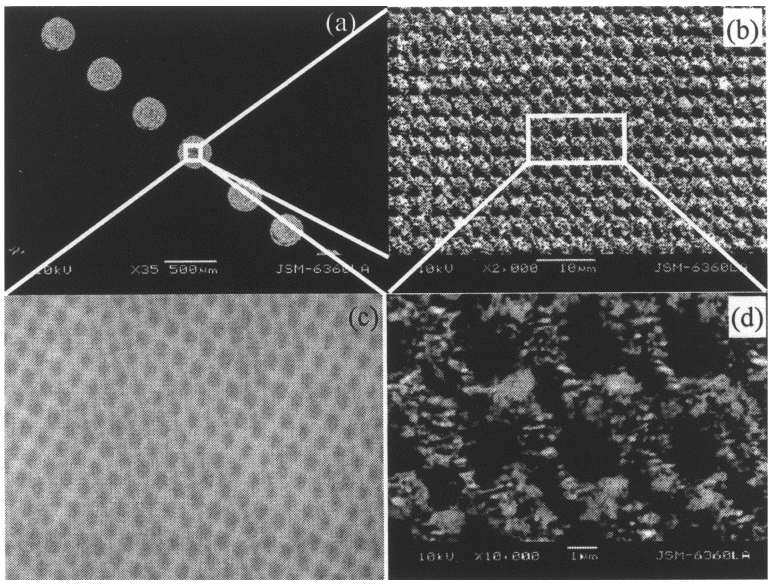


Fig.2. Optical microscope and SEM photographs of the fabricated array holes on Ni-foil by the interference of five-beam fs laser pulses. (a) Spots generated by interfering fs laser beams. (b) SEM images of arrayed holes in the spot shown in (a). (c) Optical microscope images of arrayed holes. (d) Magnified SEM images of holes shown in (b).

Figure 3 shows the optical and SEM images of the arrayed holes on the Al-film fabricated by five-beam interfering fs laser pulses. Similar fourfold-symmetric structures were formed on the metal film. The period of structures was about 2.5μm, too. Figure 3(b), the SEM image of the fabricated structure, demonstrates the details of Fig.3(a). A special "bead-in-hole" structure can be observed, which is similar to the result[12] demonstrated by Nakata *et al* through single interfering fs laser pulse. Bead with diameter less than 900nm is embraced in each hole. The special structure should be formed by surface tension. During ablation of Al-film by interfering fs laser pulses, the ablated areas of the film shrink and are torn off, forming the "bead-in-hole" structure.

The structures in Fig.3 work as a diffractive beam splitter, as shown in Fig.4. To investigate the diffraction characteristics of the structures, we coupled a diode-pumped all solid state laser of wavelength 532nm with an optical objective lens onto the structures on metal film and the diffraction patterns were recorded by a digital camera, the experimental scheme is shown in Fig.4(b). Figure 4(a) shows the diffraction patterns of the periodic structure on metal film. Diffraction spots with four orders were observed for the array holes. Here, we define the diffraction efficiency as the ratio of the averaged power of each order diffraction to the power of the incident light. The measured diffraction efficiency of each order diffraction spot is shown in Fig.4(c).

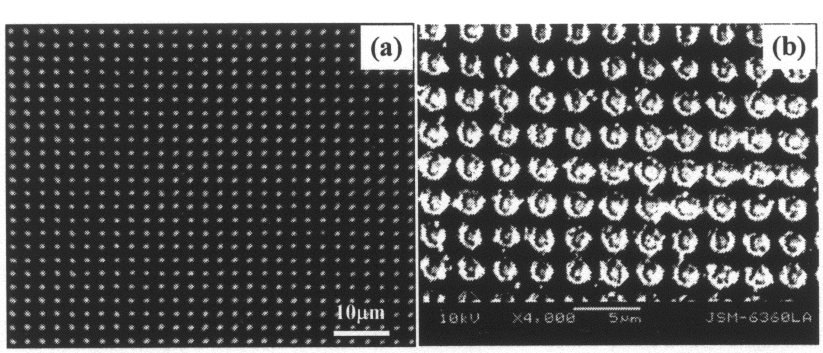


Fig.3. Optical microscope (a) and SEM (b) photographs of the fabricated array holes Al-film by the interference of five-beam fs laser pulses.

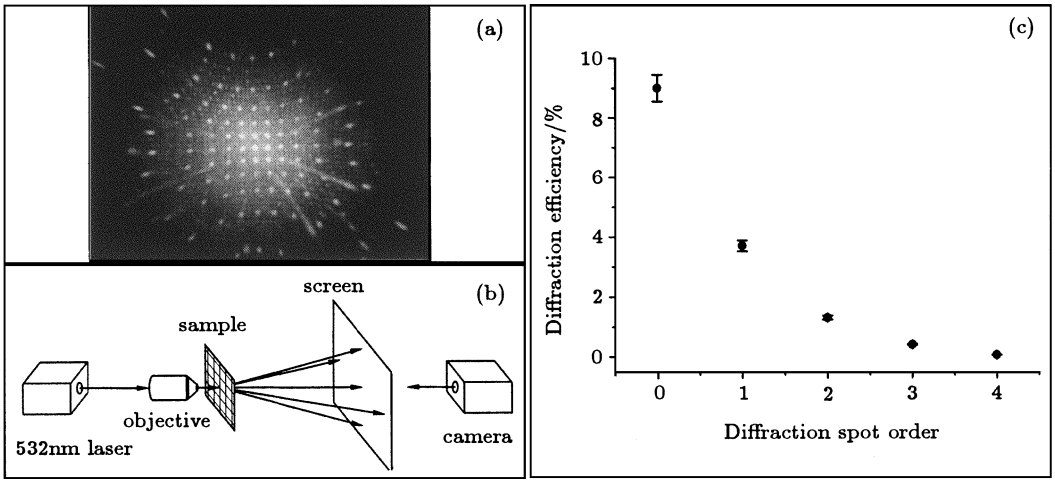


Fig.4. (a) Diffraction patterns produced by the structures. (b) Scheme for testing the diffraction. (c) Diffraction efficiency vs diffraction spot order.

In summary, arrayed holes of micrometre-order on Ni foil and Al film deposited on glass substrate have been fabricated by means of five-beam interference of fs laser pulses. By adjusting laser energy, angle of the beams, focal length, irradiation time, and laser wavelength, etc, the fabricated structures can be changed in period and shape. The present technique allows one-step, large-area, micrometric processing of metal materials for potential industrial applications.

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