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Laser micro machining using a photonic nanojet controlled by incident wavelength

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Abstract

A novel laser micro machining method using a photonic nanojet (PNJ) is investigated. For a high resolution control of a feature size, it is necessary to control the intensity distribution of a PNJ in sub-micrometer scale. In this paper, we investigated the control of the intensity distribution of PNJ by the incident wavelength. Three-dimensional finite-difference time-domain (3D-FDTD) simulation clarified that a silica particle with the diameter of 8 µm illuminated by laser with the wavelength of 700 nm can generate a PNJ at the beam diameter of 526 nm at the highest intensity position. Similarly, a silica particle illuminated by 800 nm laser can generate a PNJ at the beam diameter of 598 nm. Hole diameter of 376 nm was obtained when the incident wavelength was 700 nm. Similarly, the hole diameter of 498 nm was obtained when the incident wavelength was 800 nm. A PNJ controlled its intensity distribution by incident wavelength can be beneficial to a high-resolution laser micro machining in sub-micrometer scale.

Laser micro machining, Photonic nanojet, FDTD simulation

1. Introduction

In conventional laser micro machining using a focused laser beam, a high numerical aperture objective lens is needed to get a sub-micrometer scale beam diameter. In this case, the beam diameter suddenly expands with defocus because of a small depth of focus. Thus, a focused laser beam is not appropriate for three-dimensional laser micro machining.

We propose a laser micro machining method using a photonic nanojet (PNJ) [1]. A PNJ is a high intensity beam generated from a dielectric microsphere illuminated by a laser. A PNJ has smaller beam diameter than the incident wavelength. Moreover, a PNJ can propagate much longer than incident wavelength while maintaining a smaller beam diameter than 1 µm. These specific properties of a PNJ enable three-dimensional laser micro machining in sub-micrometer scale.

For high resolution control of the feature size, it is necessary to control an intensity distribution of a PNJ in sub-micrometer scale. An intensity distribution of a PNJ can be controlled into the following ways: either by the wavelength and polarization of the incident laser or by the diameter and refractive index of the dielectric microsphere [2]. An incident wavelength control is effective in high resolution control of an intensity distribution of a PNJ by using a tunable laser.

In this paper, we investigated the intensity distribution control of a PNJ by incident wavelength. 3D-FDTD simulations and experiments were carried out by the control of the incident wavelength to investigate the relationship between the intensity distribution of PNJ and feature size of laser micro machining using a PNJ.

2. 3D-FDTD simulations of PNJs

Intensity distribution analyses of PNJs were carried out by changing the incident wavelength with 3D-FDTD method. Simulation conditions were the same as the experimental conditions described later. The incident wavelengths were set 700 nm and 800 nm, which was assumed to use a tunable femtosecond laser. Incident laser was x axis polarized gaussian beam with the beam diameter ($1/e^2$) of 16 µm. The diameter of the microsphere was set to 8 µm. The refractive index was set to 1.455 at wavelength of 700 nm and 1.453 at 800 nm, which was considered dispersion of fused silica [3]. The refractive index of medium surroundings (air) was set to 1.000.

Figure 1(a) and (b) show the intensity distributions of PNJs in xz plane calculated by 3D-FDTD simulations. A small beam diameter and a long beam without divergence could be confirmed. Figure 1(c) shows the x direction beam profiles of PNJs at the highest intensity position. The beam diameter defined as full width at half maximum (FWHM) was evaluated based on the beam profile in the x direction. The statement x =

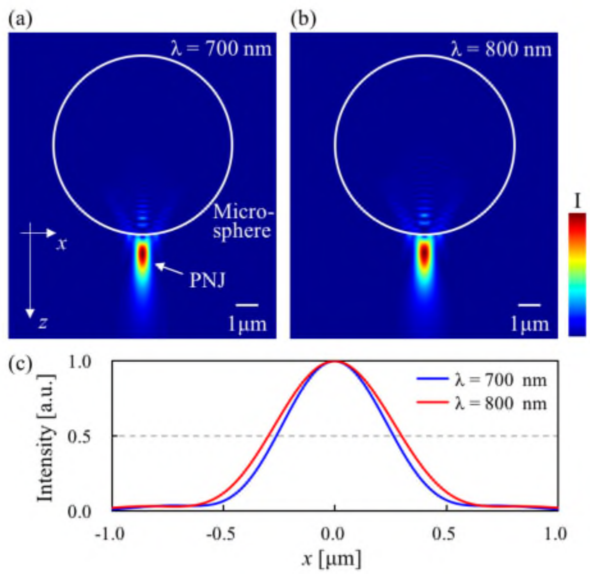

Figure 1. PNJs calculated by FDTD simulation. Intensity distributions of PNJs when the incident wavelength are (a) 700 nm and (b) 800 nm. (c) Beam profile in y direction at the strongest intensity position in the z direction.

0 represents the center position of the PNJ. The FWHM was 526 nm at wavelength of 700 nm, and 598 nm at wavelength of 800 nm. Smaller FWHM can be obtained when the incident wavelength is shorter.

By control of the incident wavelength, high resolution control of FWHM of PNJ is possible in sub-micrometer scale. This means the feature size of laser machining can be controlled in sub-micrometer scale.

3. Experiments

Hole machining experiments were carried out by PNJ controlled its intensity distribution by the incident wavelength. The sample was a silicon substrate.

Figure 2 shows schematic diagram of the experimental setup. The highest intensity of PNJ emerges at a position away from the microsphere bottom surface as can be seen in figure 1(a) and (b). To use the peak intensity effectively, the relative position between the microsphere and Si substrate must be controlled. A micropipette was introduced to hold the microsphere and control its position. Thus, the distance *h* between the microsphere bottom surface and the Si substrate surface can be controlled.

A femtosecond laser with the wavelength of 700 nm and 800 nm, pulse duration of 100 fs, and repetition rate of 80 MHz illuminated the microsphere with the diameter of 8 µm held by micropipette. Incident laser, which was x axis polarized, was focused by an objective lens with the numerical aperture of 0.5 to increase the incident intensity and defocused by 16 µm. The distance h was set to working distance, which is the distance from the microsphere bottom surface to the highest intensity position of the PNJ, based on the intensity distribution in the z direction of the PNJ calculated by FDTD method. The incident fluence, which is the intensity per pulse, was set to 3.9 mJ/cm^2. The number of pulses was set to 160,000.

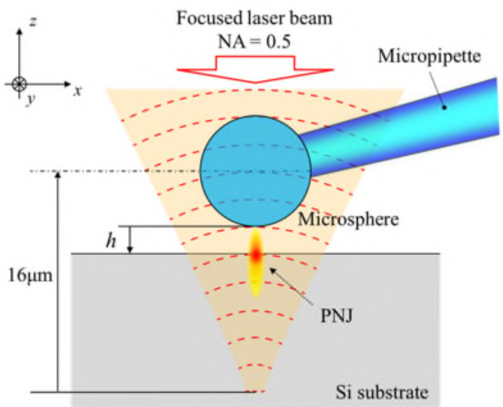

Figure 2. Experimental setup

4. Results and discussions

Machined holes were measured by an atomic force microscope (AFM), and evaluated the hole diameter and hole depth based on the cross-sectional profile. Figure 3 shows the measurement results of hole machining experiments by control of the incident wavelength. Based on the average height (i.e. reference height z = 0) of the region around the machined hole, the hole diameter and depth were defined. The distance between the intersections of the reference height and the cross-sectional profile is defined as the hole diameter. The distance from the reference height to the deepest position in the z direction is defined as the hole depth.

Hole diameter of 376 nm and hole depth of 113 nm were obtained when the incident wavelength was 700 nm. On the other hand, hole diameter of 498 nm and hole depth of 117 nm were obtained when the incident wavelength was 800 nm. Smaller hole diameter was obtained when the incident wavelength was shorter. It is generally known that the hole diameter is determined by the relationship between the beam profile of laser irradiated on the sample and the ablation threshold that is the inherent value of the sample. Considering the simulation results of PNJs, these experimental results are reasonable because the PNJ with the incident wavelength of 700 nm had smaller beam diameter.

Based on these results, the way to control the incident wavelength is of use to high resolution control of the feature size in sub-micrometer scale.

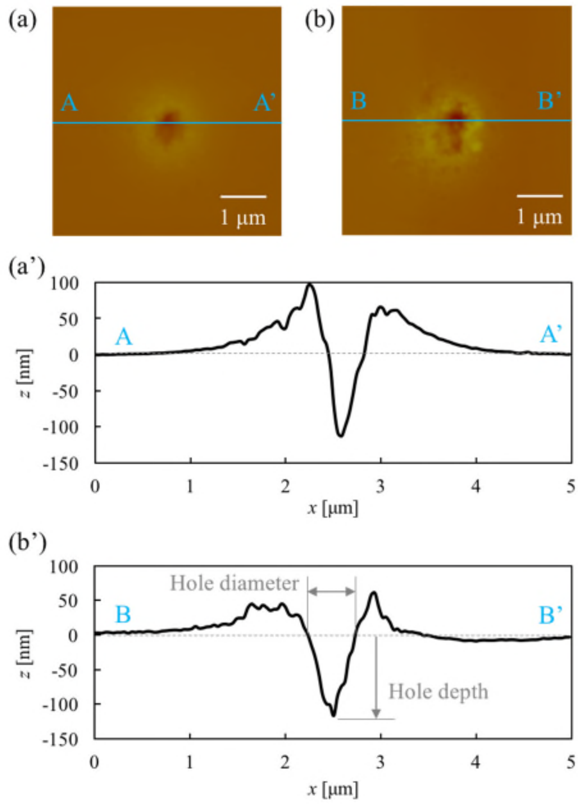

Figure 3. Experimental results. AFM images when the incident wavelength were (a) 700 nm and (b) 800 nm. (a') and (b') cross sectional profiles of each machined hole.

5. Conclusion

In this paper, we propose a laser micro machining method using a PNJ in sub-micrometer scale. We investigated the control of the intensity distribution of PNJ by incident wavelength.

Smaller hole diameter of 379 nm was obtain when the incident wavelength was 700 nm compared to the hole diameter of 498 nm when the incident wavelength of 800 nm. The intensity distribution control of PNJ by incident wavelength is effective in high resolution control of the feature size in sub-micrometer scale.

In the future, there is some possibility of higher resolution control of the feature size by polarization of incident laser.

References

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