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Metal microneedle fabrication using twisted light with spin

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Abstract: Microneedle fabrication on a metal surface based on laser ablation using twisted light with spin was demonstrated, for the first time. The resulting needle showed a height of at least 10 μm above the target surface and a tip diameter of less than 0.3 μm . We also demonstrated the fabrication of a two-dimensional 5×6 microneedle array. The needles were uniformly well shaped with an average length and tip diameter of about 10 and 0.5 μm , respectively.

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OCIS codes: (140.3390) Laser materials processing; (140.3300) Laser beam shaping; (999.9999) Optical vortices;

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1. Introduction

Metal microneedles have attracted interest as electrodes for a variety of nanoscopic imagers. In particular, two-dimensional metal microneedle arrays should permit high-speed imaging. They could also be used for energy-saving field emission displays and bio-medical nano electro mechanical systems. Several fabrication methods for metal microneedles have been proposed. However, they usually involve a bottom-up technique requiring several chemical processes, so that their time and cost efficiencies are limited.

Laser ablation [1–3] is a promising top-down process for material processing and has been applied widely to microdrilling, cutting, and scribing of a variety of materials including metals, dielectric materials [4], and semiconductors [5]. But laser ablation, breaking a target down into its compositional elements, forming a plasma of ions and electrons, due to the high intense laser pulses, is unsuitable to gather compositional elements and fabricate structured materials.

In recent years, we have demonstrated laser ablation using nanosecond optical vortex pulses having a helical (twisted) wavefront, with orbital angular momentum (L) and an annular intensity profile owing to a phase singularity $L\varphi$ (where L is an integer and φ is the azimuthal angle) in the transverse plane. The surface processed using twisted light exhibited less debris in comparison with one using untwisted annular nanosecond pulses [6]. The laser-induced plasma acquires orbital angular momentum [7–9] from the twisted light, and it consequently starts to rotate along the intensity profile of the light, thereby assisting in the ablation process and resulting in a smoother surface. In this way the twisted light can directly control the plasma dynamics and improve the material processing with high accuracy and without needing expensive equipment such as ultrafast lasers [10]. It should also be applicable to the fabrication of structured materials.

In the present paper, we present a new metal microneedle fabrication method by a top-down laser ablation process based on circularly polarized optical vortices having nonzero total angular momentum, known as "twisted light with spin." This technique forms a metal microneedle by deposition of merely a few laser pulses onto a metal target, significantly improving the time and cost of fabrication of two-dimensional metal microneedle arrays. The resulting needle exhibits a height of at least 10 μm above the target surface and a tip diameter of less than 0.3 μm . We also demonstrate the fabrication of a two-dimensional 5×6 microneedle array. Such arrays fabricated by twisted light laser ablation with high cost efficiency could provide a next-generation technology for high-speed two-dimensional imaging systems at nanoscales [11–13], for energy-saving field emission displays [14], for plasmonic probes [15], for bio-medical nano electro-mechanical systems [16] or for living cell cages [17].

2. Experiments

2.1 Twisted light with spin

The circular polarization state provides spin (S) angular momentum to the light. The resulting circularly polarized optical vortex (twisted light with spin) has a total angular momentum (J) equal to the vector sum of the orbital (L) and spin (S) angular momenta [7]. When the direction of the vortex with $L = 1$ is the same as (or opposite to) that of the circular polarization, the total angular momentum of the twisted light is defined to be 2 (or 0), as shown in Fig. 1.

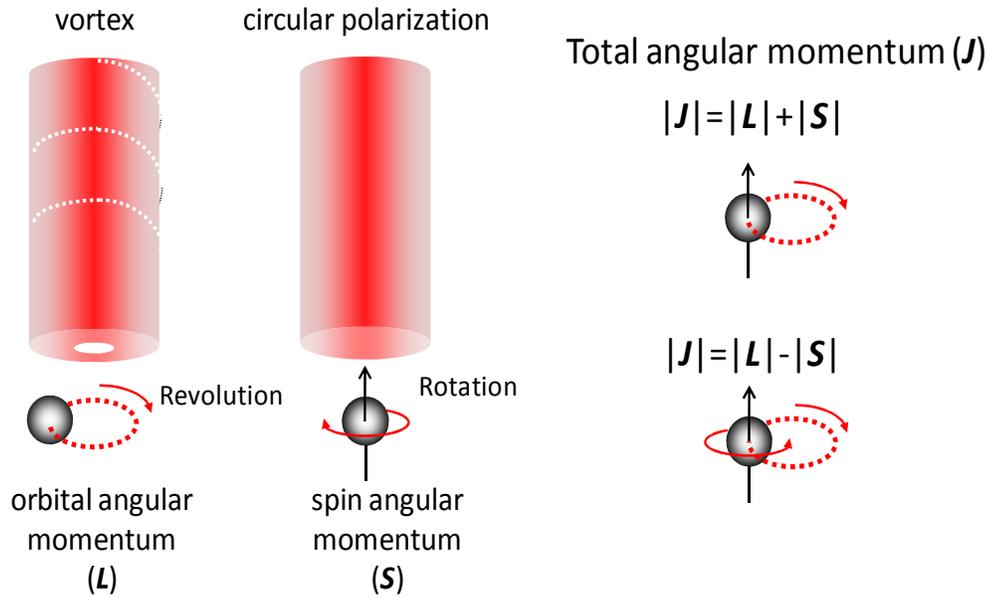


Fig. 1. Definition of the total angular momentum of twisted light with spin.

2.2. Experimental set up

Figure 2(a) shows a schematic diagram of an experimental setup for metal microneedle fabrication system using twisted light with spin. The target sample used was a ~1-mm thick polished tantalum plate, which has a relatively low ablation threshold in comparison with other metals [18].

The pump laser was a conventional Q -switched Nd:YAG laser (Quanta-Ray GCR190) with a wavelength of 1064 nm and a pulse duration of 30 ns. Its output was clipped by a 5-mm-diameter aperture in combination with a telescope, producing a Gaussian spatial beam. A spiral phase plate (SPP), fabricated by electron beam etching, was azimuthally divided into 16 parts using a $n\pi/8$ phase shifter (where n is an integer between 0 and 15). A quarter-wave plate was placed in the optical path between the SPP and an objective lens (M Plan Apo NIR, magnification factor 10, NA 0.26 from Mitutoyo co.) to control the polarization (spin angular momentum) of the twisted light. The output energy and spot diameter on the sample surface were fixed at 2 mJ and 130 μm , respectively. The experiments were performed at atmospheric pressure and room temperature. The ablated surface of the Ta plate was observed using a confocal laser-scanning microscope (Keyence VK-9700/VK9710GS) with a spatial resolution of 0.02 μm in both depth and transverse displacements.

The spatial form of the twisted light with $J = 2$ is annular and is identical with that of twisted light with $J = 0$, shown in Fig. 2(b). An interferogram formed by the twisted light and a plane reference wavefront exhibits fork-like fringes, illustrated in Fig. 2(c), proving that the light has an on-axis helical wavefront with $L = 1$ [19,20]. It was used as the pump source for laser ablation.

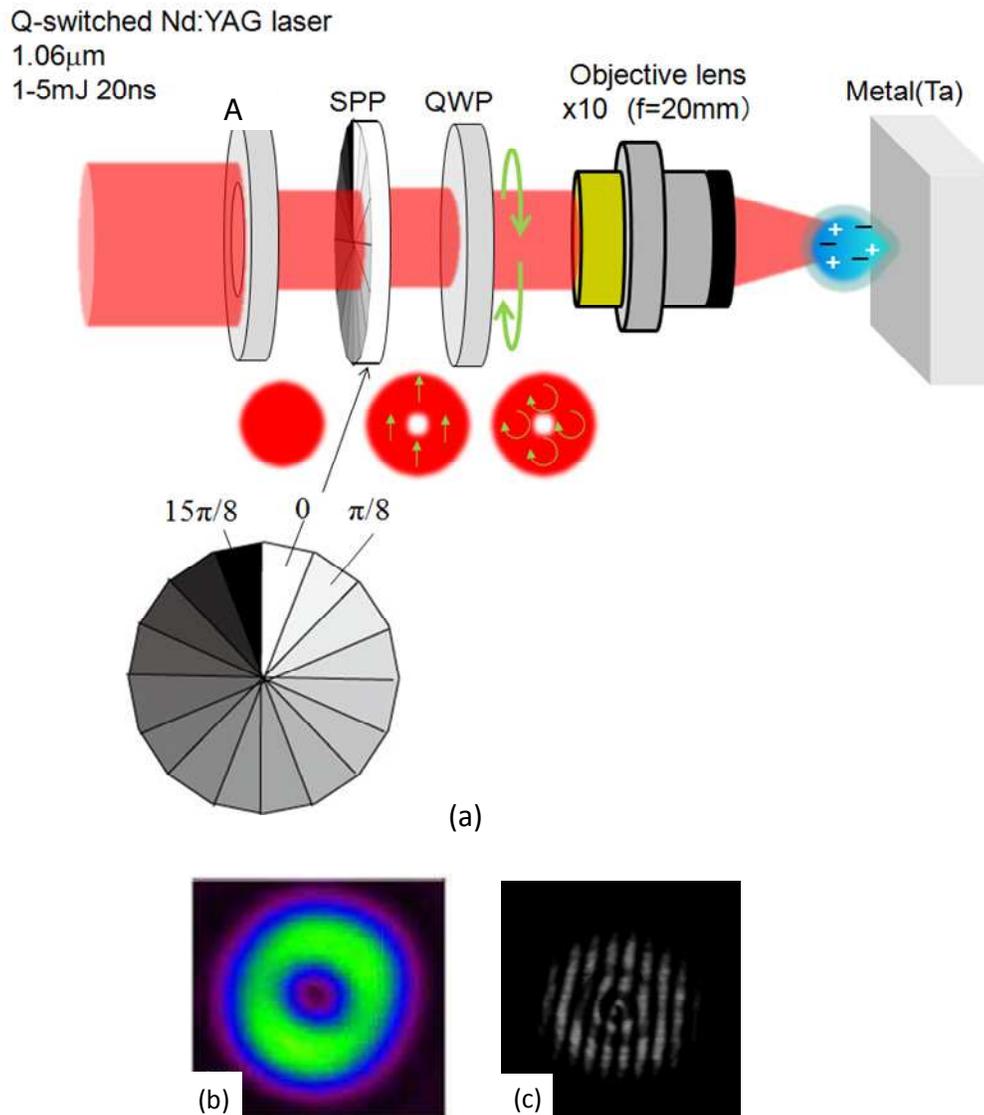


Fig. 2. (a) Experimental setup for metal microneedle fabrication system using twisted light with spin. A is an aperture, SPP is a phase plate, and QWP is a quarter-wave plate, respectively. (b) Intensity profile of the twisted light. (c) Interferogram formed by the twisted light and a plane reference wavefront. The folk-like fringes are seen at the center of the interferogram, proving that the light has an on-axis helical wavefront.

3. Experimental results and discussion

Laser-scanning microscope images of processed surfaces pumped by twisted light with (a) $J = 2$ and (b) $J = 0$ angular momentum are shown in Fig. 3. After the single-shot deposition of twisted light with $J = 2$, a protuberance appears at the center of the processed surface. The vertical length (the length between a top and a bottom ends of the protuberance) and thickness (FWHM) of the protuberance were approximately 4.4 ± 0.23 and 9.2 ± 1.7 μm , respectively. The aspect ratio, defined as the ratio of the length of the protuberance to its thickness, was relatively small (on the order of 0.5). By overlaying light pulses, it is possible to shape the central protuberance. After three $J = 2$ pulses, the protuberance becomes a needle with a height (from the target surface) of ~ 10 μm . The microneedle can be narrowed by deposition of

a few more twisted light pulses, resulting in a tip diameter of less than $0.3\ \mu\text{m}$. (The tip diameter is measured 5% below the end of the needle.) The aspect ratio of the microneedle is estimated to be 4.5.

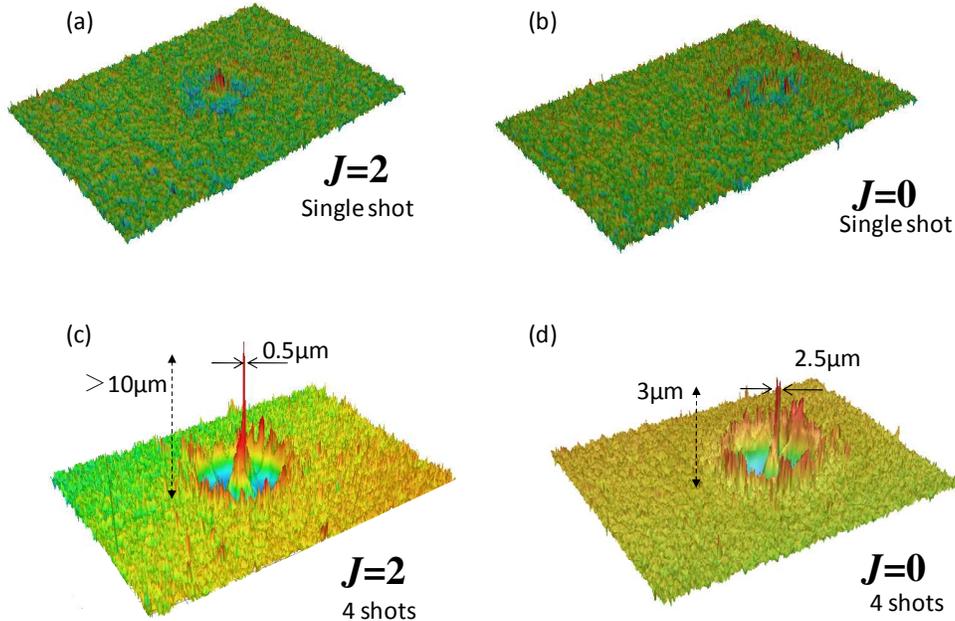


Fig. 3. Surfaces processed by a single twisted light pulse with total angular momentum of (a) $J = 2$ and (b) $J = 0$. Surfaces processed by deposition of four twisted light pulses having angular momentum of (c) $J = 2$ and (d) $J = 0$.

When $J = 0$, the processed surface has no central protuberance and a lot of debris collects along the azimuthal direction around the outer circumference. Even by overlaying several twisted light pulses onto the surface, only a fat protuberance can be structured, with an aspect ratio of less than 3. Figure 4 summarizes the experimental data obtained for a total angular momentum of 2.

To understand these experiments, the following model is adopted. Figure 5 shows the basic concept of the model for microneedle fabrication using twisted-light laser ablation. The focused light pulse provides orbital angular momentum to the laser-induced plasma, thereby yielding azimuthally-rotated motion of the plasma along the annular intensity profile of the twisted light. In the case of $J = 2$, the orbital and spin angular momenta of the light couple together constructively. The spin gives the laser-induced plasma an orbital motion so that it revolves on its axis. As a result, the plasma is directed efficiently toward an on-axis hole originating from the phase singularity and is confined in the hole by photon pressure. After that, the plasma, confined in the hole by the repulsive photon pressure, recombines and accumulates at the center of the processed surface, resulting in a structured microneedle.

On the other hand, in the case of $J = 0$, the orbital and spin angular momenta of the twisted light work against each other to produce insufficient confinement of the plasma in the on-axis hole.

Zhao et al. have demonstrated that the spin-orbital coupling in a highly focused system such as optical tweezers can influence the movements of the orbiting gold particles [21]. Our experiments shows that spin and orbit angular momenta can also couple together in materials processing with a relatively loose focusing, though a complete characterization would require further experiments such as direct observation of the plasma dynamics using a fast-gated CCD camera.

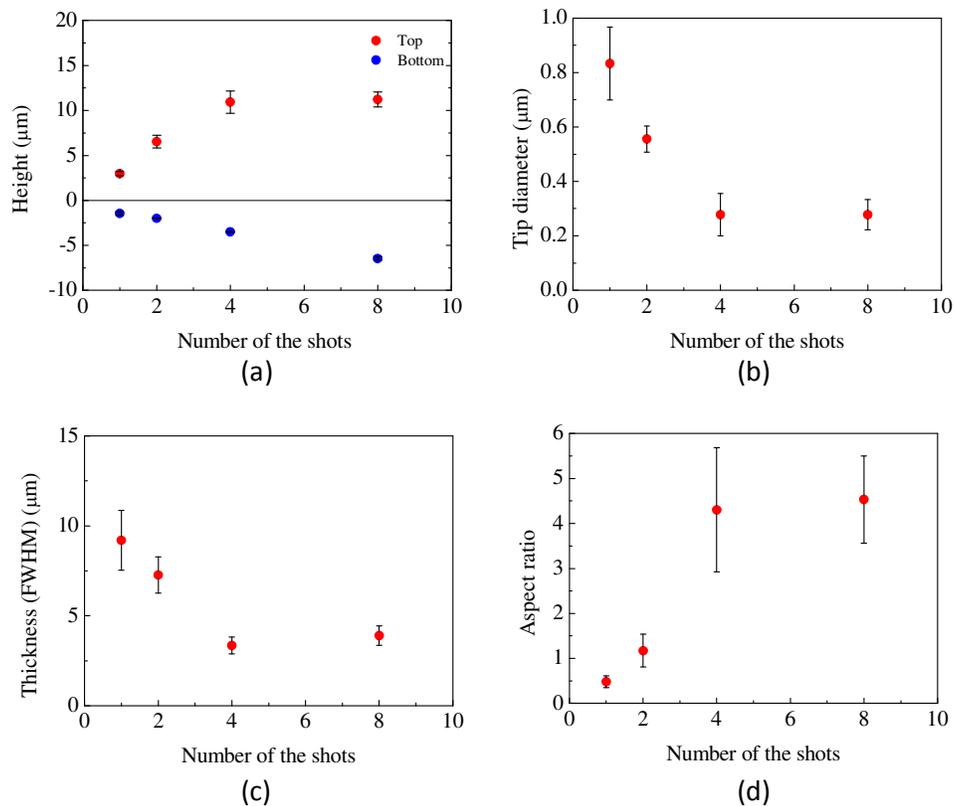


Fig. 4. Experimental measurements of the (a) height, (b) tip diameter, (c) thickness and (d) aspect ratio of the structured protuberances. Error bars show the standard deviations of the measured values.

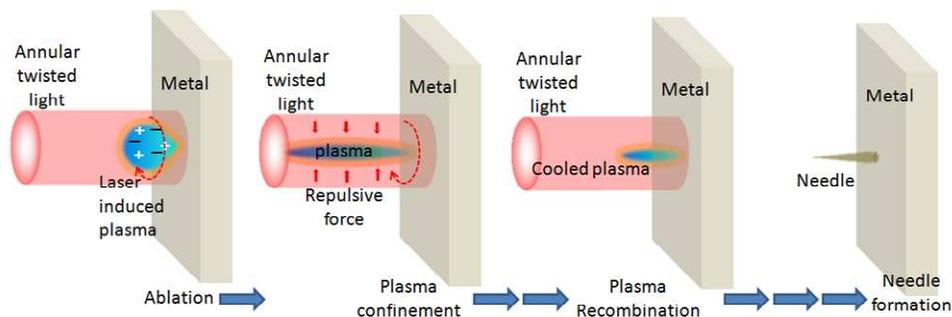


Fig. 5. Model for a microneedle fabrication by 'twisted-light with spin' laser ablation

We also demonstrated the fabrication of a two-dimensional 5×6 microneedle array by twisted-light laser ablation. Two twisted light pulses are overlaid on a target, and after that, the target was translated. As shown in Fig. 6, the resulting needles are uniformly well shaped with an average length and tip diameter of 11 and 0.5 μm , respectively. The standard deviations in the length and tip diameter are estimated to be 1.9 and 0.15 μm , respectively. Therefore, microneedle fabrication using twisted-light laser ablation exhibits excellent reproducibility.

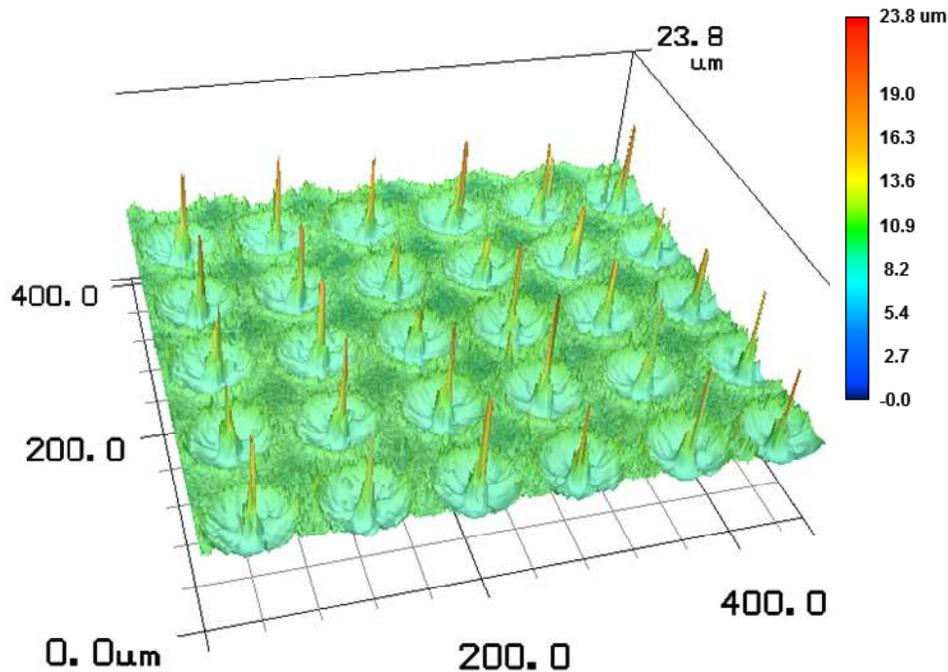


Fig. 6. Two-dimensional 5x6 microneedle array fabricated by using twisted light with spin. Two twisted light pulses were overlaid on a target for a needle fabrication, and after that, the target was translated.

4. Conclusion

In conclusion, we have presented the first demonstration of microneedle fabrication using laser ablation by nanosecond twisted light with spin. The total angular momentum of the twisted light determines the structure of the microneedle on the processed surface. When several twisted light pulses with $J = 2$ are overlaid on a target, a microneedle with a vertical height exceeding $10 \mu\text{m}$ and tip diameter of $0.3 \mu\text{m}$ results.

We have also fabricated two-dimensional microneedle arrays. The number of needles was 30, all of which were of uniformly good quality. Laser ablation based on twisted light with spin enables direct control of the motion of the laser-induced plasma, resulting in a two-dimensional microneedle array with excellent cost efficiency. This method could open up new applications including high-speed nano-imaging, energy-saving displays, bio-medical nano electro-mechanical systems, plasma physics [22], laser acceleration [23], and extreme-ultraviolet generation [24].