Vortex-laser microprocessing

Takashige Omatsu

A microneedle with a height of >10μm and a diameter of <0.3μm is formed by deposition of only a few laser pulses onto a metal.

Vortex lasers, previously used in optical tweezers and superresolution microscopes, exhibit unique features—such as an annular intensity profile and orbital angular momentum—caused by a phase singularity. We propose a new approach to next-generation materials processing by employing vortex lasers. We have demonstrated metal-microneedle fabrication based on top-down laser ablation using circularly polarized vortex lasers.

Metal microneedles are formed by deposition of only a few laser pulses onto a metal target. They have a height of at least 10μm above the target surface and a tip diameter of less than 0.3μm. We also fabricated a 5×6 2D microneedle array that can be used as electrodes for a variety of nanoscopic imagers, energy-saving field-emission displays, plasmonic probes, and biomedical nano-electromechanical systems. Most previous fabrication methods of metal microneedles required several chemical processes, resulting in limited time and cost efficiencies. Our microneedle-array fabrication technique, based on vortex-laser ablation, should reduce the time and cost of fabricating 2D metal-microneedle arrays.

A circularly polarized vortex laser is composed of a conventional Q (quality)-switched neodymium-doped yttrium aluminum garnet laser—characterized by a wavelength of 1064nm, a pulse duration of 30ns, and pulse energy of ~2mJ—combined with a quarter-wave plate and a spiral phase plate that is azimuthally divided into 16 parts using an nπ/8 phase shifter (where n is an integer between 0 and 15). Such a laser exhibits a total angular momentum (J) that is equal to the vector sum of the orbital (L) and spin angular momenta (see Figure 1). Thus, when the direction of the vortex with L = 1 is the same as (or opposite to) that of the circular polarization, the laser’s total angular momentum is J = 2 (or 0). We focused the laser using an objective lens (Mitutoyo’s M Plan Apo NIR, magnification factor: 10, numerical aperture: 0.26) to a 130μm-diameter spot on a target polished tantalum plate with a thickness of ~1mm.

We observed the processed surface of the target sample with a confocal laser-scanning microscope (Keyence VK-9700/VK9710-GS, spatial resolution: 0.02μm).

The vortex laser with J = 2 produces a protuberance at the center of the processed surface. By overlaying a few J = 2 vortex-laser pulses onto the processed surface, the central protuberance is shaped into a needle with a height (from the target surface) of ~10μm and a tip diameter of less than 0.3μm. (The tip diameter is measured at 5% below the end of the needle.) On the other hand, when J = 0, much debris is seen in the azimuthal direction around the outer circumference, without a central protuberance. Even by overlaying several J = 0 vortex pulses onto the surface, only a broad protuberance is obtained (see Figure 2).

Continued on next page
The vortex laser transfers its orbital angular momentum to the laser-induced plasma, yielding azimuthally rotated plasma motion along the laser’s annular intensity profile. When \( J = 2 \), the spin angular momentum of the vortex laser provides axial motion to the laser-induced plasma. It assists in directing the plasma efficiently toward an on-axis hole caused by the phase singularity and confining the plasma in the hole by repulsive photon pressure. Subsequently, the plasma is piled up at the center of the processed surface and forms a microneedle. In contrast, for \( J = 0 \), the spin angular momentum of the vortex laser works against the orbital angular momentum to prevent plasma confinement in the on-axis hole.

We also fabricated \( 5 \times 6 \) 2D microneedle arrays with uniformly good quality (see Figure 3). This new approach to materials processing will invite new applications, such as in high-speed nano-imaging, energy-saving displays, and biomedical nano-electromechanical systems. We will next focus on these aspects. Our experiments also show evidence that spin-orbit coupling, which is well known in quantum mechanics, can influence light through materials processing. This provides new quantum-mechanical scope for optics, which could lead to a novel field in photonics.

**Figure 3.** \( 5 \times 6 \) 2D microneedle arrays fabricated using a vortex laser.

Author Information

Takashige Omatsu
Chiba University
Chiba, Japan

Takashige Omatsu received his PhD in applied physics from the University of Tokyo (Japan) in 1992. In 2007, he was appointed professor at Chiba University. He is a member of the Optical Society of America and an associate editor of *Optics Express*.

References