Toward 3D photon trapping and propagation control

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Prism-assisted one-step exposure UV lithography and holographic lithography enable easier fabrication of micro- and nanoscale 3D and 2D photonic crystals.

Micro- and nanostructures are important for micro-electromechanical systems, photonic crystals, photonic integrated circuits, micro-optics, microfluidic devices, and plasmonic optoelectronic devices. They are used in a wide range of practical applications including optical displays, memory, sensors, high-speed computing interconnections, photonic planar lightwave circuits, as well as medical fluidic filtering and drug delivery devices.

Current fabrication techniques have different strengths and weaknesses when it comes to these structures. Traditional methods such as photolithography, laser direct-write maskless lithography, and gray-scale lithography are suitable for microstructural patterning. E-beam lithography, extreme ultraviolet, and x-ray lithography—which employ shorter wavelength beams—can help improve pattern resolution for finer-scale nanostructural patterning. Contact lithography (including soft lithography and nano-imprint lithography) can make higher-resolution nanostructures, but most of these existing lithography tools are limited to 2D micro- and nanostructures.

Ideally, we would like to use 3D micro- and nanostructures, which have natural advantages. For example, a 3D micro- and nano-structure can be used to confine photons and to control light propagation in 3D, which is almost impossible for a 2D structure. However, the complexity of 3D micro- and nanostructures makes them very difficult to fabricate with traditional methods. Multilayer 2D patterning using photo- and e-beam lithography tools can yield 3D-layered structures, but their resolution is limited to a few microns. We have achieved high-aspect-ratio 3D patterning by photocuring with UV light.

We used ‘SU-8’ photoresist (commercially available from MicroChem) and a prefabricated photomask as a template. We made complex 3D surface patterns on our chosen substrate (see Figure 1) by exposing the photoresist at an angle (‘inclined lithography exposure’) and rotating the photomask. Our patterns have different widths at different depths. For example, microgears, pyramid structures, microlens arrays, and tapered conical polymer microneedles can be fabricated in this way.

We can simplify the process further by refracting the beams through prisms. This removes the need for rotation and enables us to use a single exposure. By using refracted beams from multiple prism surfaces, we can build up very fine quality, complex 3D microstructures.

We could produce the same microstructures by rotating the sample and using inclined UV lithography. However, refraction by the photoresist limits the incident angle for traditional inclined UV lithography. Specifically, the angle between the side surface to be fabricated and the substrate surface normal must be less than 36.5°. This restriction can be overcome by immersing the sample in a liquid with a suitable refractive index, but the prism-assisted method is simpler.

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We can also use the same method to make more complex 3D photonic crystal structures. With a periodic arrangement of holes in the fixed photomask, a combination of different exposure beams refracted at a variety of angles from different surfaces of the prism produce a set of slanted exposure beam columns that yield the 3D micro-structures in a single exposure (see Figure 2). The transverse resolution we can achieve is several microns and greater, depending on the depth requirement.

Even finer resolution 3D nanostructures can be made by holography lithography, which uses multiple interference laser beams at suitable incident angles to the photoresist-coated sample surface. The beams interfere, and so 3D geometric interference patterns (like a crystal lattice) can be formed. The laser wavelength determines the lattice constant for a specific structure. By carefully selecting multi-beam incident angles, through mirror reflections or multi-surface prism refractions with a common coherence laser source, the feature size and period of the resulting 3D structure can be as small as sub-wavelength (e.g., 200 nm) or as large as several microns.

We have fabricated a 3D nanostructure using seven-beam interference (see Figure 3). We used a green coherence laser and a green-sensitive SU-8 photoresist. The basic principle for obtaining this kind of complicated structure is that we use a 2D hexagonal structure with a bigger lattice constant to modulate a 3D face-centered cubic crystal structure in the [111] direction.

In summary, prism-assisted one-step exposure makes it possible to produce nanostructures means that we can design photonic crystals for visible light, which are otherwise difficult to achieve. Together, prism-assisted UV lithography and holography lithography allow us to fabricate 3D micro- and nanostructures to support various practical applications. In the future, we may consider different 2D and 3D micro- and nanostructures and examine their properties and applications.

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**References**