Photonic crystals approach visible-light functionality

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A new photonic-crystal fabrication method creates high-aspect-ratio three-dimensional (3D) structures by removal of dielectric host material in an arbitrary fashion—a major step toward visible-light photonic crystals.

Evolution has sensitized the human eye to green light at wavelengths around 530 nm. Creation of structures and devices that can control and handle light propagation, detection, and emission at the visible spectral range will always be of the utmost importance due to their ability to directly interface with our sense of vision. Moreover, the forms of solar energy storage—whether hydrocarbon fuels, food generated via photosynthesis, or renewable energy resources such as wind and direct light—are all dependent on the spectral window through which Earth is receiving energy from the Sun. The major part of this energy reaches us in the visible spectral range and underpins our lives; essentially, light-matter interaction at visible wavelengths holds answers to our future food and energy needs.

Photonic crystals (PCs) are powerful light handlers and are used in numerous ways to control light on a sub-wavelength scale, including the ability to completely trap or localize light, to guide it in three-dimensional (3D) circuit paths on a microchip without scattering or diffraction loss, and to realize unprecedented forms of strong coupling between light and matter.[1, 2] However, due to fabrication challenges, the PC functionality window in the past has stopped short of entering the visible spectral range.

The largest technological challenge to fabrication of visible-light PCs is to structure materials in all three dimensions with spatial period smaller than typically half of the light's wavelength so that PCs will have a transmission block—an omnidirectional photonic bandgap (PBG). In the spectral range of the PBG no light propagates in the crystal in any direction due to complete destructive wave interference. If a defect is placed in the otherwise periodic dielectric microstructure of the PC, it acts as a trapping center to which light can be localized. The confinement volume of the trapped light can be much less than a cubic wavelength and lifetime of the captured light is limited only by intrinsic absorption in the underlying material.

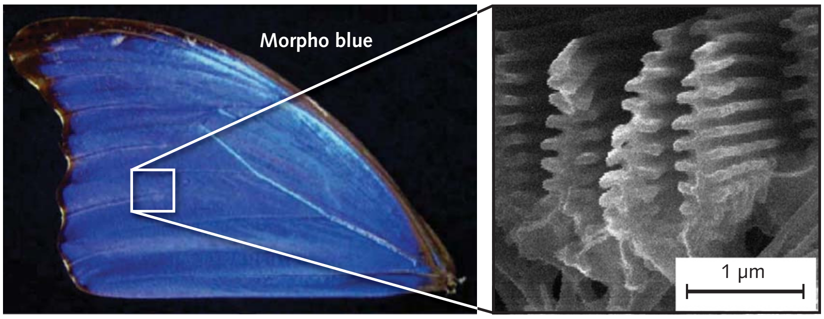


FIGURE 1. Nanotechnology can reproduce nature's highly reflective structures[3]; that is, the wing structure of a Morpho blue butterfly (*Morpho didius*) shows an omnidirectional color, unlike a reflection from a grating structure. (*Courtesy of Prof. A. Saito, Osaka University*)

Sub-100 nm structuring challenges

Nature's approach to nanostructuring is via self-organization and structural encoding of nanoscale architectures at the DNA level. The physical structure of a butterfly wing and the subtle balance between order and disorder in the structure is responsible for the structural color (see Fig. 1).[3] Interestingly, the color appearance is omnidirectional in a wide range of incidence angles due to the presence of disorder. However, naturally occurring materials and systems do not scatter light

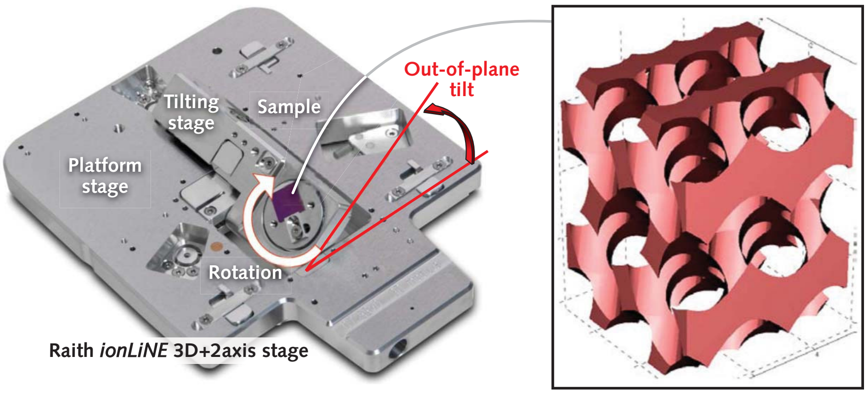


FIGURE 2. Free-space 3D positioning and photonic-crystal materials deposition/removal is realized on a specialized stage (left): 3D positioning of the platform stage on which a tilting stage is mounted. (*Courtesy of Raith GmbH*) The inset shows the geometry of a 3D structure that has a full photonic bandgap when made in titania (refractive index 2.7) and sub-wavelength 3D periodicity. (*Courtesy of Swinburne University*)

strongly enough to create a PBG or to trap light. This requires nanolithography using materials with a high refractive index greater than two. Modern top-down approaches of nanofabrication have only recently entered true nanoscale structuring where the feature sizes in all dimensions can be made at sub-100 nm levels. One promising example of such technology is the focused ion beam, which can create high-aspect-ratio 3D structures by removal of dielectric host material in arbitrary fashion by a direct-write approach.

Even though the fabrication of PCs with visible-light PBGs by 3D sculpturing using ion beams is challenging, our group used a 3D ion beam lithography (IBL) approach to fabricate a 3D PC slanted-pore (SP) structure with a wide and robust PBG by a simple two-step, direct-write processing of rutile crystalline titanium oxide (TiO_2). The geometry of the unit cell is chosen for the PBG at visible wavelengths around 633 nm. The fabrication technique, using a Raith GmbH (Dortmund, Germany) ionLINE setup, does not require time- and material-consuming steps of resist and mask coatings with subsequent wet or dry processing. Instead, a direct-patterning approach by gallium (Ga) ions is used to sculpture 3D structures out of the crystal with tens-of-nanometers resolution. The capability of direct write at arbitrary angles in 3D mode is a distinctive feature of 3D IBL.

Three-dimensional structuring is realized via a 3D positioning stage with an additional two-axes rotation (see Fig. 2). This direct-write sculpturing can create arbitrary 3D nanopatterns that have a full PBG when made in rutile. For the full PBG at the red wavelength of a helium-neon (HeNe) laser at 633 nm in TiO_2-rutile, the lateral period is $a = 260$ nm and the axial period $c = 1.4a$ or 363 nm. The radius of the pore $r = 0.31a$ or 80.6 nm for a PBG of approximately 11.5% relative to the gap center frequency.[4] This choice of parameters is robust in terms of slight deviations of the hole radius and volume fraction. But removal of up to 70% of the sample's volume is a challenging task as we recently discovered.[5]

The first fabrication attempt by IBL achieved pores with radius of 40–50 nm. The larger pores of $r = 80$ nm are required for the full PBG; however, a preferential milling of the edges at the larger diameters distorted the cell's geometry, limiting the achievable volume fraction of titania removal to 40–50% in this first experiment (see Fig. 3). Even with this geometry at smaller pore radii, the predicted stop gap is expected at 800 nm for

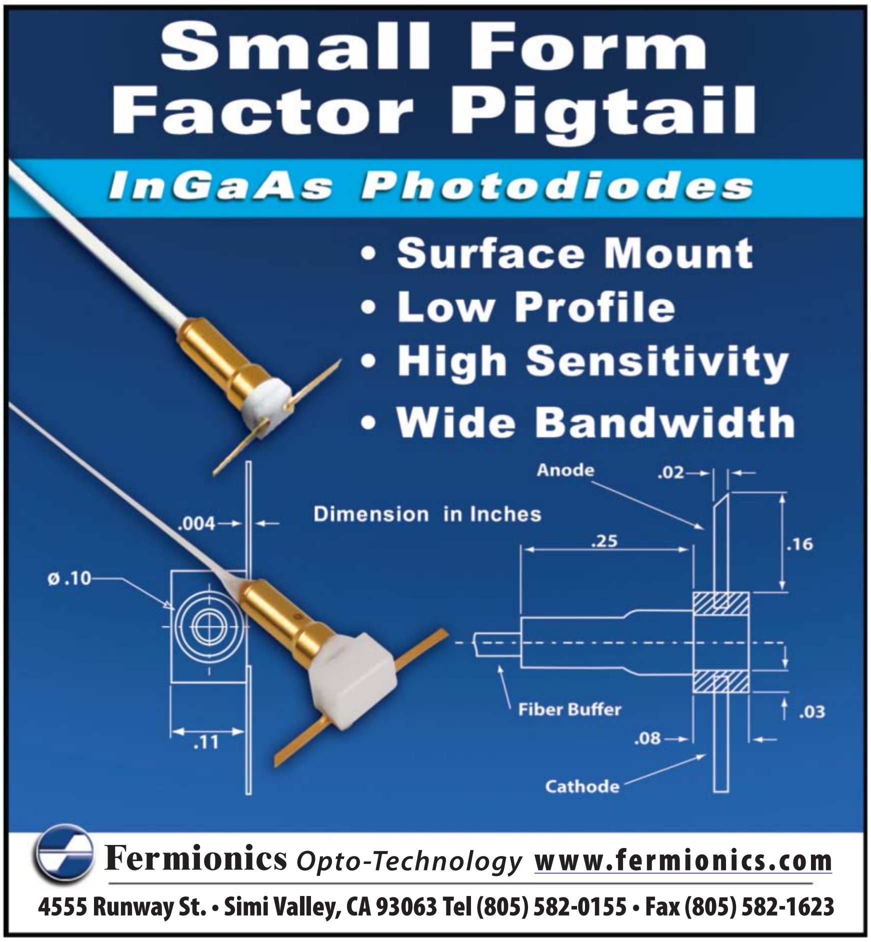
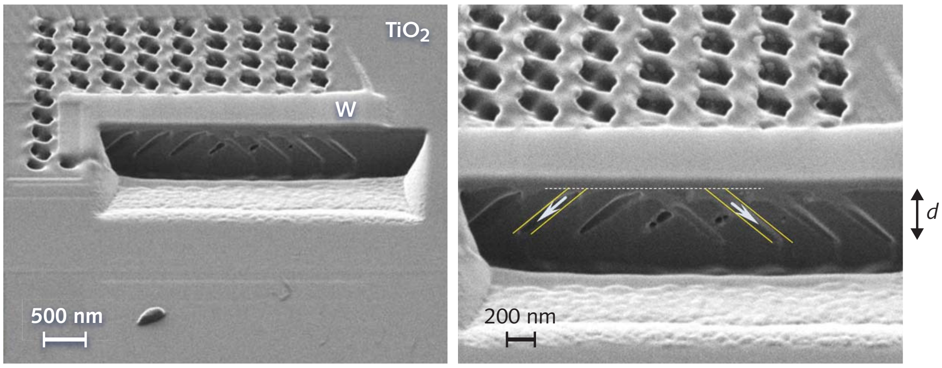


FIGURE 3. Scanning-ion microscopy images of the ion-beam sculptured photonic crystal structure in rutile-titania single crystal are shown at different magnifications; *d* is the depth of the structure at a $\pi/4$ tilt. Tungsten coating was used for sectioning of the fabricated structure. (*Courtesy of Swinburne University*)



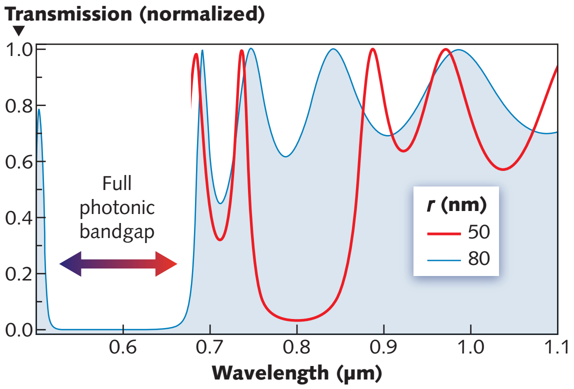
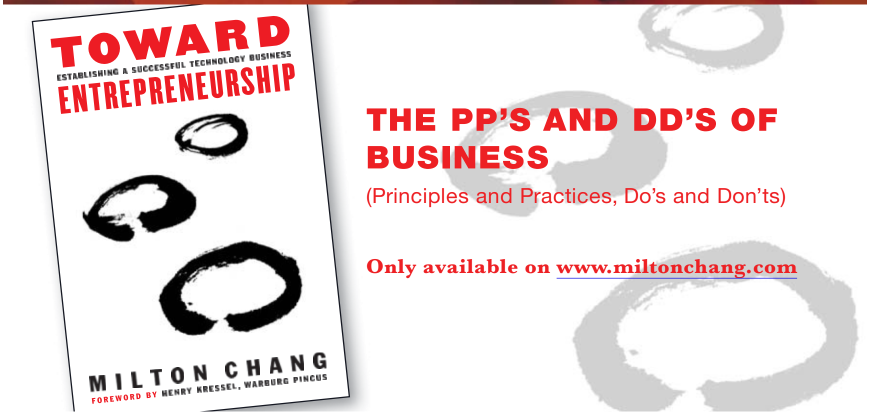


FIGURE 4. A finite difference time domain (FDTD) simulated transmission spectra is shown at normal incident for photonic crystals with different pore radii, r, of the slanted pore (SP) photonic crystal with pore length $l = 1.5$ μm. (*Courtesy of Swinburne University*)

1.5-μm-deep pores (see Fig. 4). This shows that even comparatively shallow pores can provide strong modulation of the transmission (and reflection) and can find applications for light transmission control when the full PBG is not required. By using control of light dispersion at the wavelengths corresponding to the edge regions of the stop band, it is possible to control direction of propagation at different angles of incidence. This opens an engineering potential in applications of light focusing, collimation, and redirection in micro-optics and optofluidics applications. It can also be used for light trapping in thin solar cells where impinging light at certain angles of incidence is redirected and propagates almost parallel to the solar cell surface and increases the probability of absorption.[6] The same principle of light redirection is applicable for the inverse problem: for the light extraction from high-refractive-index materials used in LEDs where trapped light has to be extracted.

Despite challenges, further improvements in 3D IBL sculpturing are in reach. Optimization of milling can produce larger pores and patterning larger areas will enable detailed optical characterization. Namely, by introducing trepanning and concentric outward scanning of strongly focused ion beams during milling, together with optimization of the chemical doses and other enhancements, PCs functional at visible wavelengths can be fabricated. It is noteworthy that the other popular methods used in materials structuring at the sub-micrometer range such as direct laser writing in photopolymers (a serial and



PHOTONIC CRYSTALS

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parallel methods) and dry plasma etching (parallel) cannot easily be adopted for sub-100 nm nanofabrication.[7, 8] The 3D IBL approach is promising for practical applications especially because it is a maskless and direct-write process.

Photonic crystals have important practical applications in confining light on an optical microchip for all-optical information processing, in trapping and absorbing light in thin films for efficient solar energy harvesting, as novel light emitters, as optical sensors, and for photocatalysis, to mention only a few.[9, 10] ◂

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