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## Photonic Crystal Laser Generates Ultraviolet Output

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Photonic crystal lasers have potential as small and versatile sources in numerous applications. Such lasers with infrared output have been demonstrated in several laboratories around the world, but researchers at Northwestern University in Evanston, Ill., recently demonstrated the first ultraviolet photonic crystal laser.

A photonic crystal laser is a laser whose resonator is at least partially defined by the bandgap of a photonic crystal. The device's gain derives from a normal population inversion, which in this case was created by optically pumping a thin slab of ZnO semiconductor. Physically, the laser comprised a 200-nm-thick layer of ZnO deposited on a sapphire substrate, but the Northwestern researchers used a focused-ion-beam technique to etch a periodic array of cylindrical holes into the ZnO (Figure 1). The periodicity of the array created a photonic bandgap that forbade photons with frequencies within the ZnO gain spectrum.

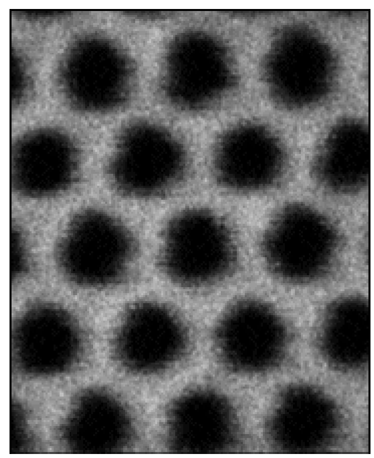
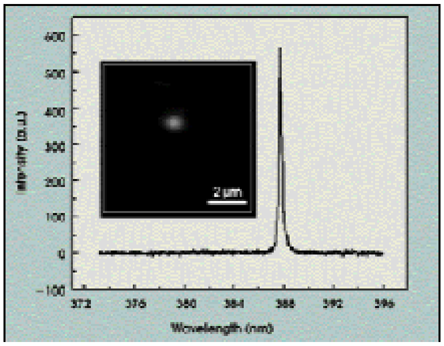


***Figure 1.*** *A scanning electron micrograph of the ZnO photonic crystal shows the periodic lattice of cylindrical airholes.*

Thus, photons were confined by index guiding in the vertical direction (because the effective refractive index of photonic layer made of ZnO is greater than that of the air above it and of the sapphire beneath it) and by Bragg scattering in the horizontal directions (because the photons were within the photonic crystal's bandgap). Efficient lasing in the structure as possible because of spatially localized defect modes, which formed near the edges of the photonic bandgap and allowed local propagation of photons for only short distances.

The ZnO laser slabs were about 8 μm$^2$, and each contained approximately 4000 air cylinders. The researchers focused the 355-nm pulses from a mode-locked Nd:YAG laser into an ~4-μm spot on the patterned part of the ZnO film. The picosecond mode-locked laser was not necessarily optimal for the experiment because the pulse duration was much shorter than the ZnO excited-state lifetime. Much lower peak powers would have been required from a nanosecond Q-switched laser, but such a laser was not readily available to the scientists at the time.

***Figure 2.*** *The light emerging from the ZnO surface had a bandwidth of 0.24 nm, a strong indication of*




*lasing action. The inset shows the ~1-µm$^2$ lasing mode.*

As they increased the energy of the pump pulses incident on the ZnO, they observed a sharp increase in the slope efficiency at about 2 nJ, indicative of laser threshold. Moreover, the spectral width above threshold was only 0.24 nm (Figure 2). They took these two observations as proof that lasing was occurring. The lasing mode was localized to an area of about 1 µm$^2$ on the ZnO surface (Figure 2, inset).

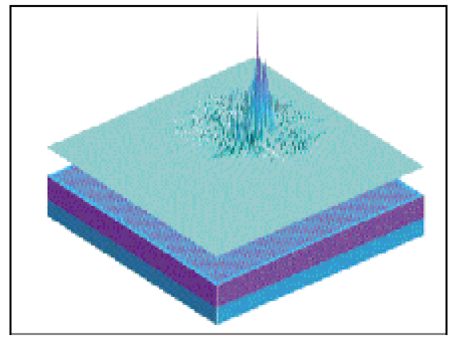


***Figure 3.*** *The calculated geometry of a confined mode is superimposed with a schematic of the weakly disordered photonic crystal slab made of ZnO on a sapphire substrate. The laser is about 8 µm on an edge, and some of the ~4000 airholes in the 200-nm-thick ZnO photonic crystal slab are visible.*

To understand their results, the experimenters performed a photonic band structure analysis of the situation and found that the calculated bandgap between 396 and 415 nm did not exactly match the gain spectrum of ZnO, which is centered at 385 nm with a width of about 12 nm. However, they believe that the existence of imperfections in the crystal structure -- visible as slight asymmetries of the lattice in Figure 1 -- would broaden the bandgap, so it would include the ZnO gain spectrum. A two-dimensional finite difference time-domain calculation shows a confined mode that exists in a weakly disordered photonic structure and that is similar to that in the experiment (Figure 3).

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