gold through the triangular spaces formed in between. Four spheres in contact formed a mask for a bow tie[3]. The space between the tips of the triangles and the shape of the triangles control the resonant frequency of the antennas.

Their next step was to make a tunable antenna to experimentally investigate how the resonant wavelength varies with gap size and compare the results to theory. Normally, chrome is used as an intermediate layer to stick to the gold and the glass. Instead, the researchers left out the chrome layer so that the gold layer only feebly stuck to the glass. This allowed them to move one of the gold triangles using the force from an atomic force microscope probe tip and thus tune the nanoantenna resonance. In this way, they were able to investigate the optical response of the same antenna with 32-nm-thick triangles as a function of the spacing. This investigation would not have been possible by making a set of antennas with different gap sizes, as fabrication constraints rule out the possibility of producing identical triangles.

The team measured optical scattering from the antenna using dark-field excitation, and predicted the behaviour with different gaps, although it was not clear from their paper how they took the curvature of the tips into account. Unlike some of the earlier work carried out with electron-beam lithography[2], they observed more than one resonance develop as the spacing decreased. One reason is that by using spheres as shadow masks, the triangles formed had widths that tapered from top to bottom. This meant that the region near the top of the tip produced a different resonant wavelength from the region further along the taper. One resonance tends to be associated with plasmon wave propagation along the top surface and the other by propagation along the surface in contact with the silica. In the earlier experiment the films were thinner so that the walls at the gap were more vertical than in the antennas used in the more recent work[1,2]. Merlein *et al.* used the discrete dipole approximation[4] to calculate the resonances and were able to predict the behaviour of complicated three-dimensional structures, and to follow through with both theory and experiment for different gap sizes to the point where the triangles touched, without changing the shape of the triangles. They could even experimentally measure the effect of overlapping one tip above the other.

Their paper demonstrates a practical way to make a tunable nanoantenna. However, to make useful antennas with predictable characteristics, it would probably be simplest to deposit less gold and make thinner samples or use ion etching or electron-beam lithography. The important advantage of using colloidal masks is that multiple samples with predictable characteristics can be made fairly easily, and can be inexpensively reproduced.

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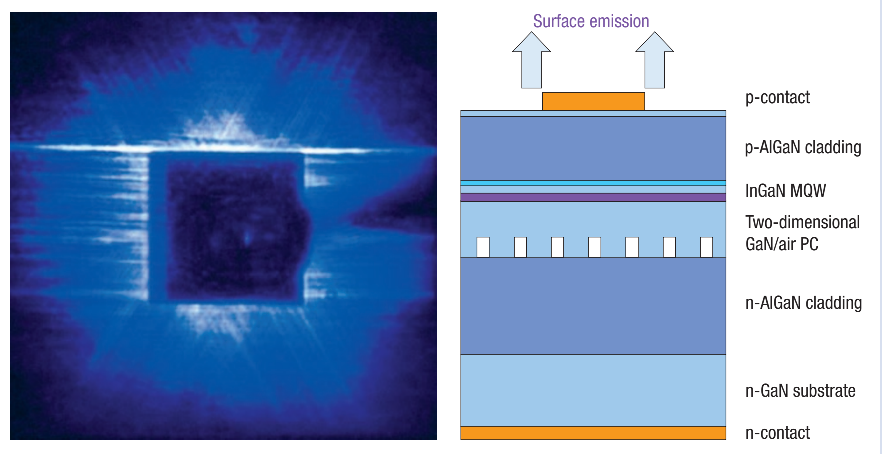
PHOTONIC-CRYSTAL LASERS

Designer blue beams

The demonstration of a photonic-crystal surface-emitting laser (PC-SEL) that operates in the blue, at the shortest wavelength reported so far, could be good news for the development of large-area visible lasers with custom-designed beam shapes (*Science* **319,** 445–447; 2008).

Photonic-crystal surface-emitting lasers combine a light-generating active semiconductor region with a two-dimensional photonic-crystal structure to create a laser cavity with unique properties. For example, the periodicity and size of the photonic crystal determines the laser's beam shape, enabling the creation of so-called doughnut beams and other patterns. Another virtue of the design is that the laser emits light from its top surface, so that large emitting areas are possible while retaining a single longitudinal and lateral mode. However, until now operation of PC-SELs has been limited to the infrared and wavelengths longer than 980 nm.

Now, Susumu Noda and co-workers from Kyoto in Japan have made a GaN PC-SEL and report lasing in the blue at a wavelength of 406 nm. The electrically driven laser operates at room temperature under pulsed conditions, and emits around 0.7 mW of blue light when a drive current of about 9 A is applied.



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The laser consists of a layer of InGaN multiple quantum wells (MQW), which are grown over the top of a GaN/air two-dimensional photonic-crystal structure and surrounded by cladding layers and electrodes.

Although the laser's threshold current of 6.7 A and its submilliwatt output powers are not ideal, Noda told *Nature Photonics* that the performance can be substantially improved by optimizing the MQW region and photonic-crystal-structure geometry, and by using a transparent or ring-shaped top electrode.

Noda envisages potential applications ranging from information storage and biology to materials processing. "These PC-SELs can be utilized as super-resolution light sources that could be focused to a spot much smaller than blue-violet wavelengths by using doughnut beams. This could be applied to next-generation DVDs," commented Noda. "In addition, by using the merit of large-area coherent oscillation, very-high-power blue-violet laser sources can be achieved while keeping a single longitudinal and lateral mode."

Oliver Graydon