Photonic crystals boost light emission

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fusion alone can cool the spheres from a peak temperature of around 60 °C to room temperature in a matter of nanoseconds. Indeed, time-delayed pump–probe measurements confirm that the optical properties of the pop-up crystal fade within 3 ns, fast enough for a range of optical-switching applications.

The Pittsburgh group predict that the colloidal crystals could diffract as much as 97% of the incident light, but these first crystals have a diffractive efficiency of only 2%. Lattice defects – all too familiar to the makers of semiconductor devices – are implicated as the culprits, since colloidal crystals suffer from virtually all of the defects that affect conventional crystals. New techniques are needed to minimize these defects while maintaining the benefits of self-assembly.

Groups around the world are rising to the challenge. Alfons van Blaaderen at Utrecht University and Pierre Wiltzius at Bell Labs have demonstrated a particularly promising approach that is reminiscent of conventional crystal epitaxy. They use standard photolithography to deposit a polka-dot pattern of holes on a glass substrate, where the symmetry and periodicity of the pattern reflects the desired crystal structure. The small indentations provide a template for the first colloidal layer to align with, and subsequent layers are organized by the first layer to create a large single crystal.

This technique could be used to organize colloidal spheres with nonlinear optical properties into a single crystal, and the resulting structure could be preserved in a polymer gel. Such an approach could allow the large-scale fabrication of materials with optical properties that can be rapidly switched and continuously tuned, and promises a new generation of optical devices. □

Photonic crystals boost light emission

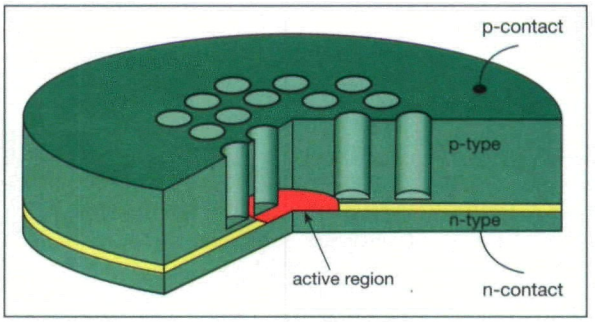
From **Misha Boroditsky** and **Eli Yablonovitch** in the Departments of Physics and Electrical Engineering, University of California, Los Angeles, US

FOR MANY years spontaneous emission of light was considered a natural and immutable property of radiating atoms. But we now know that spontaneous emission can be controlled by altering the environment of the atom: for example a metal mirror can be placed next to the atom, or it can be enclosed inside a metallic cavity or a photonic crystal. In this way, the vacuum fluctuations or zero-point electromagnetic fields in the atom's environment can be manipulated.

Photonic crystals are artificial structures that are periodic in one, two or three dimensions. These structures provide a band gap for electromagnetic waves, just as semiconductors have a band gap, or energy range, from which electron waves are forbidden. Photonic crystals can be used to suppress spontaneous emission in certain directions and enhance it in others. Shanhui Fan and colleagues from the Massachusetts Institute of Technology have now shown how photonic crystals could be used to create highly efficient light-emitting diodes (LEDs), those ubiquitous little lamps that turn up everywhere, from instrument panels to stadium-sized television displays (*Phys. Rev. Lett.* 1997 **78** 3294).

The sole purpose of LEDs is to emit spontaneous radiation. They consist of a p–n junction within a direct-gap semiconductor such as gallium arsenide, which converts electrons to photons with an internal efficiency approaching 90–100%. Surprisingly, one of main factors that limits the performance of LEDs is the difficulty of extracting light from materials that have a high refractive index, like gallium arsenide. Indeed, the escape cone of light from LEDs is so small that we normally see only 2% of the emitted light, while the rest bounces around inside the device and is lost. The traditional approach to overcoming this problem has been to redirect the photons that are emitted outside of the escape cone. But the MIT scientists suggest that the "wrong" directions can be inhibited altogether by making the LED from a two-dimensional photonic crystal.

The researchers calculated the characteristics of a thin slab of gallium arsenide containing a two-dimensional array of holes. A photonic band gap is created when the ratio of hole diameter to the spacing of the holes is chosen correctly.



In this cavity-enhanced LED, an electromagnetic mode is confined in three dimensions: the periodicity of the photonic crystal prevents light escaping horizontally while total internal reflection confines the light in the vertical direction. The active region is restricted to the volume at the centre of the device.

This band gap inhibits spontaneous emission within the plane of the slab – which is the wrong direction for light extraction – while the semiconductor continues to emit light normal to the slab and into free space. The MIT calculations are the first to use thin two-dimensional photonic crystals – previous studies only considered the infinitely thick case, which does not relate to practical devices.

But it would be even better if we could enhance the spontaneous emission. As early as 1946 Edward Purcell predicted that an atom in a cavity will radiate faster than an atom in free space. This implies that, in addition to preventing emission in the wrong directions, we can also enhance the emission in the "right" directions. One-dimensional cavity-enhanced LEDs – in which the cavity is made from a pair of parallel mirrors – were first proposed in 1992 by Fred Schubert, then at Lucent Technologies, and the most impressive of these devices were recently demonstrated by Hans de Neve and colleagues at the University of Ghent in Belgium.

If cavity enhancement could be extended to two and three dimensions, the total rate of radiative recombination would significantly increase, allowing faster communications signals and providing more effective competition against residual non-radiative recombination. Moreover, the output would resemble that from a laser: the light could be concentrated into a single mode, which could couple efficiently to optical fibres. Such LEDs could be useful for their raw output efficiency, as well as for high-speed, broad-band optoelectronic communications.

Three-dimensional cavity enhancement can provide a ten-fold increase in the spontaneous emission rate, which means that it would not be essential to suppress spontaneous emission in the wrong directions. Indeed, an open cavity that does not inhibit spontaneous emission can perform almost as well as a completely closed cavity that does inhibit spontaneous emission. This means that a full photonic band gap may not be necessary, although it might help in the cavity design.

The promise is great, but there are some practical problems. The layer of active material must be restricted to the small cavity volume where the enhancement takes place, which may require a difficult patterning and regrowth step in producing the semiconductor layer. In addition, most materials used in optoelectronics do not work well when they have a free surface near the region that generates light. These problems can be solved in part by using a two-dimensional structure in which the holes do not penetrate into the active layer at the bottom of the slab (see figure).

Other material systems may also ease these restrictions on device fabrication.

For example, Lionel Kimerling at MIT is developing silicon LEDs doped with erbium. These are more easily adapted to the concentration of active material within the cavity. Finally, the two new families of III–V materials – gallium nitride and indium gallium aluminium phosphide – could provide much better surface properties. All this work shows that photonic band-gap materials provide many possibilities for controlling spontaneous emission in semiconductors. More experimental tests are sure to follow, and these photonic crystals may soon be finding their way into practical devices. □

Superlattice lasers go to longer wavelengths

From **Manfred Helm** in the Institute for Semiconductor Physics, University of Linz, Austria

SEMICONDUCTOR lasers are one of the key devices in modern optoelectronics and optical communications. Most work at wavelengths from the visible to the near-infrared (0.5–2 μm), but semiconductor lasers operating in the mid-infrared (2–20 μm) are useful for gas-sensing applications such as pollution monitoring, or the control of industrial and chemical processes.

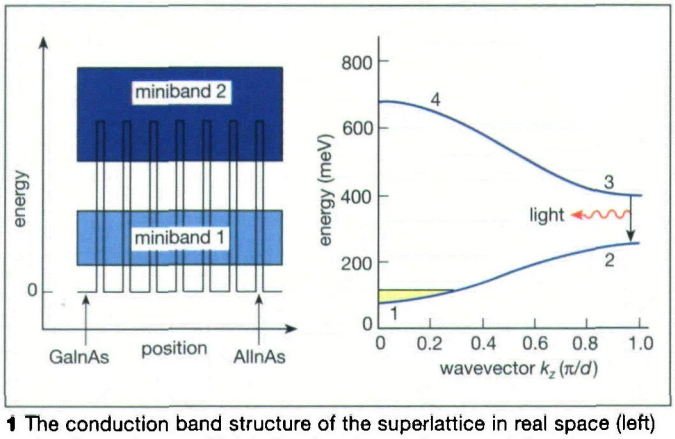
These longer wavelength lasers are mainly based on lead-salt semiconductors, but their use is limited due to high costs, problems with reliability, lack of compatibility with other optoelectronic materials and low operating temperatures. A new type of semiconductor laser has now been developed by a group at Bell Laboratories in New Jersey (G Scamarcio *et al.* 1997 *Science* **276** 773). It is based on a semiconductor superlattice and provides a high-power output in the mid-infrared.

Conventional semiconductor lasers essentially consist of a p–n diode. A negative voltage applied to the n-doped region extracts electrons from the n-type region and holes from the p-type region, injecting them towards the junction, where they recombine by emitting a photon. Thus the photon energy is determined by the energy gap between the conduction and valence bands of the semiconductor.

The introduction of epitaxial techniques in the 1970s made it possible to grow ultrathin layers of different semiconductor materials. Depending on the material composition and the band gap of neighbouring layers, electrons can be confined in square potentials called quantum wells. The energies of the electrons in these wells are restricted to discrete energy states, as predicted by basic quantum mechanics.

It was soon realized that quantum-well structures could provide the basis for a semiconductor laser that uses only one type of carrier (e.g. electrons and no holes), provided that a population inversion could be achieved between some of the energy levels. The wavelength would be determined by the spacing of the energy levels, which in turn depends on the layer thickness. This type of device, now called a quantum cascade laser, was first demonstrated by the Bell Labs group in 1994 (see *Physics World* July 1994 p24). To date, this group has produced quantum cascade lasers that operate between 4 and 11 μm.

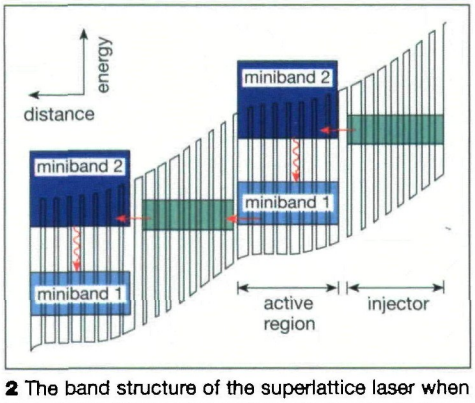
The group has used a slightly different concept in the new laser: the active elements are made from semiconductor superlattices rather than quantum wells. A superlattice is a periodic sequence of thin layers of two different materials. This creates a one-dimensional band structure within the conduction band, and represents the simplest realization of energy bands in a solid (figure 1). The one-dimensional bands are called "minibands" to distinguish them from the conduction and valence bands, and the gaps between them are called minigaps.



1 The conduction band structure of the superlattice in real space (left) and reciprocal space (right) showing the two lowest minibands. Electrons in the ground state (blue region) are excited to level 4 and then quickly relax to level 3. A photon is emitted when electrons relax into the lower miniband via a population inversion (levels 3 to 2) and the electrons then return to the ground state (level 1).

The superlattice laser exploits electron transitions between the two lowest minibands. This transition is located at $k_z = \pi/d$ in reciprocal space, where k_z is the wavevector perpendicular to the layers and d is the superlattice period. From the band structure, it is clear that a superlattice could work in a similar way to a conventional atomic four-level laser: electrons could be pumped from the ground state (level 1) into level 4, quickly relax to level 3, and build up a population inversion between levels 3 and 2. After a photon is emitted, electrons must be rapidly removed from level 2 into the ground state.

Fortunately, the relaxation times in a superlattice fulfil all the requirements for establishing a population inversion: the times taken to relax from levels 4 to 3 and 2 to 1 are much shorter than from 3 to 2 because the relaxation (via emission of optical phonons) within a miniband is faster than between two minibands. Moreover, in 1995 I showed that the transition at $k_z = \pi/d$ is up to five times stronger than transitions between quantum-well levels.



2 The band structure of the superlattice laser when under bias. Most of the voltage drops across the injector, which removes electrons from the lower miniband of one superlattice and injects them into the upper miniband of the next superlattice.

The laser structure is built up from layers of gallium indium arsenide ($Ga_{0.47}In_{0.53}As$) and aluminium indium arsenide ($Al_{0.48}In_{0.52}As$) grown by molecular beam epitaxy on an indium phosphide substrate. A crucial point is that the laser must be pumped by electrical injection: this implies that there must be a voltage drop across the superlattice, which could modify or even destroy the band structure (figure 2). To avoid this problem, the Bell Labs team has not made the laser structure from a single superlattice, but from 25 repetitions of an eight-period superlattice with a period of 5.3 nm.

The superlattices are separated by an "injector" that helps to remove electrons from the first miniband and inject them into the second miniband of the next superlattice. This is achieved by using a "graded-gap" superlattice in which the ratio of barrier thickness (AlInAs) to well thickness (GaInAs) increases along the injecting path. The result is that a quasi-miniband forms in the injector when a voltage is applied (figure 2), while the injector exhibits high electrical resistance when there is no voltage. This behaviour guarantees that most of the voltage drop is across the injector and that the band structure in the superlattice remains fairly flat, as required for the operation of the