showed that, by both criteria, the vortex that persists through the downstroke is due to translation. So the unsteady effect that makes flight possible must be the one that depends on translation; that is, delayed stall.

To give more lift than would be possible in steady motion, the vortices must be stronger than conventional aerodynamics would predict could persist. Ellington and colleagues suggest that the unexpected helical flow — out towards the wing tips — may help to stabilize the vortex, enabling it to retain its early strength for longer than would otherwise be possible. It remains to be discovered whether similar effects occur in the flapping flight of birds. In some cases, such as in slow or hovering flight, birds also generate more lift than conventional aerodynamics can explain. □

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OPTICAL STORAGE

The future is looking blue

Pauline Rigby

COMPACT disks in their existing form may soon be superseded. Current CD technology uses near-infrared laser diodes to read information, because they are long-lived and reliable. But blue would be much better than red. Because the size of a focused spot scales as the square of the wavelength, reducing the wavelength by a factor of two would increase the storage capacity by a factor of four. No wonder there is a concerted effort to produce a current-injected blue laser diode for continuous wave (c.w.) operation at room temperature. Last month in *Applied Physics Letters*, Nakamura *et al.* of Nichia Chemical Industries reported the first successful c.w. operation of a blue laser diode made from gallium-nitride-based materials[1].

Blue-chip research. Gallium-nitride-based blue laser diodes such as this may soon be in our CD players and multimedia machines. (Picture courtesy of Nichia Chemical Industries Ltd.)

A group of Japanese companies, headed by Toshiba and Matsushita, is working towards a common specification for the new 'digital video disk', which will have a data capacity of 4.7 gigabytes per side, 12 times as much as an ordinary CD. Only a 50 per cent increase in capacity is due to the reduction in wavelength (from the 780 nm used now to a red laser operating at 635 nm); the rest of the improvement is obtained by increasing the numerical aperture, which reduces the spot size of the focused laser beam, and by improving data compression algorithms. But with a blue laser, a digital video disk system could have a total capacity of 15 gigabytes.

Near-infrared lasers are based on gallium arsenide, which has a band-gap energy of 1.4 eV. Because wavelength is inversely related to band-gap energy, shorter wavelengths must come from materials with larger band gaps. The two candidates for providing shorter wavelengths are classes of material based on either gallium nitride (GaN) or zinc selenide (ZnSe). Work on ZnSe lasers has been in progress for longer, and working laser designs using this material are more sophisticated[2], but GaN may offer better prospects in the long term.

For a start, the band gaps available from GaN-based materials range from 1.9 eV up to 6.2 eV, whereas ZnSe has a gap of 2.67 eV, so GaN materials are potentially capable of providing much shorter wavelengths, extending into the ultraviolet. The shortest-ever semiconductor laser wavelength, 376 nm, was obtained from a GaN diode[3].

Nichia's new blue laser[4] uses four $Ga_{0.2}In_{0.8}N$ quantum wells for light emission at 411 nm. Quantum wells are layers of material only a few tens of atom layers thick, and they are more efficient at producing light than is bulk material because they attract electrons and holes (which recombine to produce photons).

Second, defects multiply easily in ZnSe lasers[2]. Defects act as nonradiative sites — places where the electric current is converted into lattice vibrations instead of photons — and these show up as dark spots on the device.

The best performance from a ZnSe laser so far was reported by Sony, who demonstrated a lifetime in excess of 100 hours for room-temperature c.w. operation of a 514.7-nm laser[5]. One hundred hours in the laboratory is a commendable duration, but still nowhere near good enough to put in a piece of equipment and sell. For that, lifetimes of the order of 10,000 hours are needed.

Increased lifetimes have been brought about by improving material quality — but even a perfect crystal of ZnSe will be susceptible to runaway defect generation, the process that kills lasing action. The quality of ZnSe being produced now is extremely high, so can much more performance be squeezed out of this material? In contrast, GaN is exceptionally stable at high temperature and under chemical attack, and so it should be resistant to the generation of defects.

Despite their immunity from the problem of defect multiplication, GaN lasers also fail in a very short time, because they get too hot. As the device heats up during c.w. operation, the difference in expansion between layers of different materials in the device causes it to break up under the strain. Some strain is already present before the device is switched on, because the layers have to be grown on a substrate material whose lattice does not match GaN, and this exacerbates the problem. Single-crystal bulk GaN would be the ideal choice of substrate material — then the crystal lattices would match exactly — but none is available at present.

Nichia's laser diode survived for less than one second when operated continuously at room temperature. By cooling it only a little to 243 K (–40 °C), however, its lifetime was increased to more than 30 minutes, long enough to allow spectral measurements. Spectra had been obtained before with pulsed current, which allows heat to dissipate between pulses. These spectra contained several sharp peaks, due to the temperature changes in the device during pulsed operation, but the c.w. results show a single sharp emission peak — proof of lasing action.

The design has already been improved — at the 1996 meeting of the IEEE Lasers and Electro-Optics Society, Nichia announced continuous operation at room temperature for 27 hours. It seems likely that they will meet their target for commercial production of blue laser diodes within two years. That's lucky, because systems are already being designed that will use the new blue laser technology. □

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