Trapped photons lead to new class of lasers

The world's smallest laser cavities, each less than a single cubic wavelength, have led to the first continuous-wave UV and visible random lasers and could open the door to a host of other new devices, including brighter computer displays, improved fluorescent light bulbs, and batteries that store energy in photons.

Physicist Stephen Rand and materials scientist Richard Laine at the University of Michigan (Ann Arbor, MI) first developed a process for creating doped nanophosphor powders of almost any composition. When stimulated by a low-voltage (1 keV–10 keV) electron gun, alumina nanopowders doped with the rare-earth metal ions cerium ($\text{Ce}^{3+}$) and praseodymium ($\text{Pr}^{3+}$) at concentrations of $\pm 100$ ppm, emitted photons in the UV ($357$–$392$ nm), and red bands ($625$–$632$ nm), respectively.

One of the most remarkable results of the experiment is that it achieves continuous laser action by Anderson localization of electromagnetic radiation in the optical range for what is believed to be the first time. Because the nanophosphor particle sizes and inter-particle separations are less than a wavelength, the photons experience nearly total reflection without loss over distances of less than a single wavelength, oscillating in time but not in space. These points of light do not exhibit coherent properties commonly associated with laser light, although peers agree that the ‘random laser’ does indeed lase.

“Random lasers are counter-intuitive because people think that scattering is bad for lasing because it destroys coherence. But the scattering makes random lasers—it increases amplification and gain until you reach a threshold and start to generate light,” says Vladimir Shalaev of Purdue University (West Lafayette, IN), who also studies laser effects in scattering systems.

Although the powders, compressed into a 3-mm layer inside a vacuum chamber, do evidence clear lasing threshold, gain, and modest frequency narrowing on a 5d-4f electron transition of $\pm 100$ ppm, emitted photons in the UV ($357$–$392$ nm), and red bands ($625$–$632$ nm), respectively.

Figure 2 Autocorrelation of the pulse from the mode-locked VECSEL shows that the pulse is transform limited. The optical spectrum is shown in the upper right.

Cavity as a function of intensity, which mode locks the laser without any active control. The continuous-wave pump power is directly converted into pulsed power without control electronics or active elements in the cavity. Ultimately, the SESAM could be integrated into the gain structure, which would make the devices simpler to manufacture. This approach could produce single wafers of VECSEL/SESAM devices with no post-processing required.

The cavity length is inversely proportional to the pulse repetition rate, so making the cavity small results in high rep rates in the GHz regime. Pulses are virtually transform limited (see figure 2).

The current output wavelength of these lasers is 980 nm, but band-gap engineering can yield customized designs that operate at desired wavelengths, unlike traditional diode-pumped solid-state lasers (DPSS). “We could go to 1.5 $\mu$m with indium phosphide or InGaAsN-based materials,” says Keller, noting that 980 nm was a natural wavelength to start with because proven SESAMs were available. Next on the horizon is proving that the power and rep-rate scales and moving toward new wavelengths. — Michael Brownell
transition in Ce$^{3+}$ and a 4f-4f electron transition in Pr$^{3+}$, the light does not display speckle, or emerge in any particular direction, or show evidence of standard mode selectivity. The output is incoherent and omni-directional. These properties are due to the stationary nature of light generated as an evanescent field within the powders. Light only leaks out of the medium near the surface of the powder where the Anderson localization condition is compromised by the presence of the boundary.

**powder is the key**

A large part of the experiment’s success comes from Laine’s flame spray pyrolysis fabrication process. Metallo-organic precursors dissolved in ethanol produce powders by combustion in oxygen at about 2000°C. Sprayed into the combustion chamber at rates greater than 50g/h, charged particles with approximately 75 ions per 20-nm Ce particle and 800 ions per 40-nm Pr particle are collected electrostatically downstream from the flame.

“For our approach to work, the particles need to be quite a bit smaller than lambda for strong localization and packed more densely than one per cubic wavelength. That’s what’s different from previous work [on random lasers],” says Rand. In dense media with lossless reflection arising from multiple scattering, the threshold for laser action is greatly reduced.

“I’m very impressed with this work because it has huge potential in terms of applications,” says Purdue’s Shalaev. “Compared to quantum well and semiconductor lasers that are very expensive and hard to use, random lasers are cheap. You can have lasing paint, for example, and that could lead to incredible applications that could be sprayed on glass, walls, or any other object to produce light or displays.” Laine has already developed an ink-jet deposition process for the doped powder.

Rand has yet to make radiometric measurements on the random laser, “so we can’t answer efficiency questions or total output, but we expect the power [from the electron beam] is being very efficiently re-radiated.” —Winn Hardin

Researchers have created stationary light in dense ionized alumina powders inside an ultrahigh vacuum chamber.

**future memories**

Perceiving itself as being behind in the telecommunications and information industries, Japan has embarked on a catch-up program that aims at development of specific technologies according to broad timetables. Optical memory and data storage systems are among the critical technologies identified by Japan’s Optoelectronic Industry and Technology Development Association (OITDA) for focused development efforts aimed at IT-integrated societies of the 2030s.

Analysts see Japan’s population gradually declining from its peak at the turn of the century, and expect those over 65 will account for nearly 30% of the total population. Furthermore, say pundits, in Japan, the emphasis will no longer be on the basics of food, clothing, and shelter, but rather on the enjoyment of leisure time. The OITDA believes this is where information technology can play a significant role.

“The Ministry of Education, Science, Sports, and Culture (MEXT) has forecast a list of information technologies it expects to see commercialized in the next few decades, and they all show the need for a new generation of optical memory and data storage devices,” says Ryoichi Imanaka, general manager at AVC Company of Matsushita Electric Industries Co. (Osaka, Japan). Some of the technologies MEXT expects include telephones that automatically interpret other languages for their users, digital television, video on demand, electronic libraries, 256 Gb large-scale integrated circuits, cleaning and laundry robots, cell phones with global roaming, and optical memory devices that operate at molecular and elemental levels.

Imanaka predicts that people in 2030 will have access to various databases from their homes. “We’ll see most government services offered online—including voting,” Imanaka says. “And most healthcare services will be available from home as well. Doctors will be able to use remote devices to test and diagnose patients, and nurses will take care of bedridden elderly by controlling in-home service robots.” All of these technologies, says Imanaka, require massive data storage capacity.

By the 2030s, network speeds will probably