

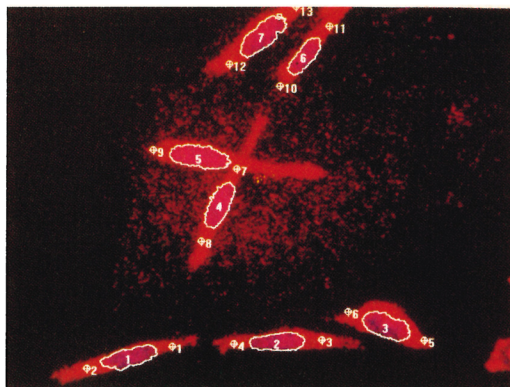
radiation are qualitatively different in that they largely involve the loss of chromosomal fragments. "The difference," says Hei, "is like day and night."

Crucially, cytoplasmic irradiation is far less likely to kill the cell than nuclear irradiation is. Even when a cell's cytoplasm is pummeled by 32 alphas, the cell still has a 70% chance of surviving and—with damaged DNA—multiplying. Comments Little, "The finding that cytoplasmic irradiation isn't cytotoxic is consistent with a great deal of earlier work. However, the observation that it is significantly mutagenic is new and unexpected."

DNA damage does not inevitably lead to cancer, nor is it the only factor involved. By one estimate, a cell's genome has to undergo as many as six independent mutational events before the cell's DNA-repairing defenses are overwhelmed and carcinogenesis is fully expressed. But, believes Hei, the noncytotoxicity of cytoplasmic irradiation could make it especially important in the induction of cancer.

How can you miss the goal and still score? Before they ran their experiments, Hei and his coworkers suspected that the damage caused by cytoplasmic irradiation was mediated by reactive oxygen species, which are thought to cause spontaneous mutations and which had already been shown to be present at elevated levels when the bystander effect takes place.⁴ To test this idea, they treated samples of target cells with two different reagents—namely, dimethyl sulfoxide (DMSO), which suppresses reactive oxygen species, and buthionine-S-R-sulfoxime (BSO), which promotes them. Compared with untreated cells, the DMSO-treated cells experienced 4–5 times fewer mutations, whereas BSO boosted the mutation rate—coincidentally—by the same factor. As a further test, irradiated cells were stained with an antibody that is especially good at recognizing oxidative DNA damage. The cytoplasmic targets took up the stain more intensely than did the nuclear targets.

If reactive oxygen species are the weapons, how is their destructive power delivered to the DNA in the nucleus? No one knows for sure. When an alpha enters a cell, it quickly sheds about 100 eV/ μm of energy in a tight region of ionization around the point of impact—so tight, in fact, that the direct products of ionization do not reach the nucleus when the point of impact is more than a few nanometers away. Somehow, a chain of reactive oxygen species must make its way to the nucleus.



HUMAN-HAMSTER hybrid cells, as seen by the image analysis system of the Columbia University microbeam. The rough ovals outline the cell nuclei, and the small circles, which are 8 μm away from the nuclei, indicate targets for alpha irradiation in the cells' cytoplasm. (Courtesy of Tom Hei.)

Innocent bystanders

In their most recent experiments, Hei's team investigated another aspect of the bystander effect. Instead of irradiating cytoplasm, they fired a lethal volley of 20 alphas at each of the nuclei in a randomly chosen subsample of cells. Dead cells don't replicate, so any increase in the overall mutation rate of the unirradiated cells must be due to the bystander effect. That's just what Hei's team found: In the unirradiated cells, the mutation rate tripled.

How genetic damage is transmitted from cell to cell, as opposed to within a cell, seems to depend on how the cells are arranged. When cells abut—as in the lining of our lungs and in Hei's experiments—they can exchange molecules through shared portals in their cell walls known as gap junctions. By treating the cells with a reagent called lindane, Hei closed the gap junctions and the bystander effect disappeared.

But the bystander effect has also

been seen in samples of nonabutting cells, leading some researchers, including Andrew Groszovsky (University of California, Riverside), to speculate that either of two mechanisms could be at work. In one mechanism, a signaling molecule makes its way through a gap junction from an irradiated cell to its unirradiated neighbor, which it dupes into behaving like a directly damaged cell. Alternatively, the signaling molecule, rather than being the sole agent of damage, triggers the production of reactive oxygen species, which attack the bystander cells without having to pass through a gap junction.

According to Groszovsky, the health implications of this kind of research, though unestablished, could be important and could

lead to serious reconsideration of the underlying physics of developing risk models for low-level radiation carcinogenesis. Despite a recent coup of turning healthy human cells into tumors in lab dishes,⁵ it remains a challenge to deduce an *in vivo* effect from an *in vitro* study.

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Lasing Demonstrated in Tiny Cavities Made with Photonic Crystals

We have been so successful in engineering semiconductors to manipulate electrons that we are naturally interested in similar ways of controlling photons. One promising means is to create structures with periodic variations in the index of refraction—such as a hexagonal array of air holes penetrating a thin gallium arsenide film. As lightwaves scatter within the periodic dielectric structure, destructive interference cancels out light of certain wavelengths, thereby forming a photonic bandgap similar to the bandgap for electron waves in semicon-

Researchers are moving closer to the goal of using photonic bandgap structures to make new, flexible, optical devices.

ductors. Photons whose energies lie within the bandgap cannot propagate through the structure. This exclusionary property can be used to advantage to create a low-loss cavity: Simply put a defect into a periodic structure and you have a region within which the otherwise forbidden wavelengths can be locally trapped. In a similar fashion,

a line of defects can serve as a waveguide. Researchers have been studying such bandgap structures, also called photonic crystals, in the hopes of harnessing their potential to control photons.

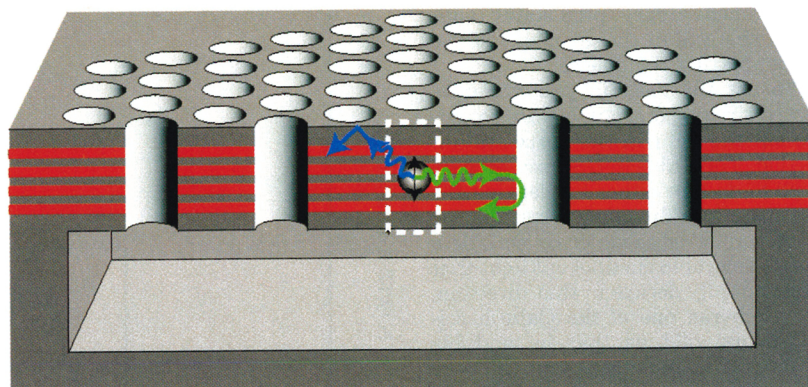
The effort is starting to pay off. One step in that direction is the two-dimensional bandgap laser recently demonstrated by experimenters from Caltech and the University of Southern California.¹ The cavity consisted of one filled hole (a defect) in an otherwise periodic array of holes penetrating a light-emitting, semiconducting film. The dimensions of this photonic-defect cavity were less than the wavelength of infrared light, making it the short-wavelength equivalent of the microwave cavity that comprises a maser. The interest in such micrometer-sized cavities was stimulated in part by Edward Purcell's 1946 assertion that the smaller the cavity, the greater the enhancement of spontaneous emission.

Oskar Painter of the Caltech group feels that one of his group's big accomplishments is the demonstration that photonic crystals can be fabricated with high enough quality to strongly localize photons to form an optical cavity. "This work opens the door for highly dense, integrated, nano-optic structures," he says. So far, the laser has too high a threshold pump power to be of technological importance, but its designers are working to improve its characteristics.

Other research groups have also recently reported two-dimensional photonic bandgap lasers, but their designs do not feature such tight confinement of the light.^{2,3} In their lasers, the bandgap regions have no defects; instead, the photonic crystals underlie or partially penetrate into the active region: Only light with wavevectors matching those of the photonic crystal are given positive feedback. By contrast with the photonic defect laser developed by the Caltech-USC group, these other lasers confine light over a considerably larger spatial region, on the order of $100\text{ }\mu\text{m}$. That's because the index of refraction modulation is nearly a hundred times smaller than in the defect laser. An important new aspect of these two-dimensional lasers is their ability to couple light efficiently into a narrow beam propagating vertically out of the planar structure.

Defect-mode laser

The bandgap defect laser built by the Caltech-USC group is shown schematically in the figure above. The basic structure is a thin semiconductor slab made of indium, gallium, arsenic, and phosphorus. Within this slab, the semiconductor is layered into four quantum



PHOTONIC CRYSTAL MICROCAVITY is formed by a defect in a hexagonal array of holes (dotted region). The cavity volume is less than a half-wavelength cubed. Any photon moving in the horizontal plane will reflect off the array of holes and back into the cavity region (green arrow). A photon trying to escape vertically will be confined by total internal reflection (blue arrow). The four red layers indicate the semiconductor quantum wells that emit $1.55\text{ }\mu\text{m}$ light when stimulated optically. (Adapted from ref. 1.)

wells which, when exposed to pulses of radiation, emit light with a wavelength of $1.5\text{ }\mu\text{m}$ (a wavelength used for optical communications). The index of refraction of the semiconductor is about 3.5 and is surrounded by air (with an index of refraction of 1.0), so that this thin slab—only half a wavelength thick—acts as a very narrow waveguide, trapping light weakly in the vertical direction by total internal reflection.

Into this horizontal waveguide, the Caltech-USC researchers etched a hexagonal lattice of vertical air holes, or voids, with radii of 180 nm and interhole spacings of 515 nm. This lattice has a complete bandgap in two dimensions—that is, the bandgap exists in every direction in the horizontal plane. One hole has been left out of the center of the lattice, becoming the defect that serves as the cavity: Bragg reflections from the surrounding lattice of holes confine the light horizontally within this cavity. The Caltech-USC researchers adjusted somewhat the size and positions of holes immediately adjacent to the defect to tune the defect-mode resonance wavelength within the photonic bandgap and to split a mode degeneracy, resulting in a single cavity mode—one that is polarized predominantly in the horizontal direction.

The Caltech-USC laser cavity has a volume of 2.5 cubic half-wavelengths, close to the minimum of 2.0 predicted recently by a group from the University of California at Los Angeles.⁴ To accomplish lasing in this small volume, the researchers needed a cavity with a sufficiently high quality factor Q (a measure of the cavity's ability to trap photons). The laser operated by the

Caltech-USC group had a Q of only 300. With recent improvements in Q , Painter tells us, he and his colleagues have operated the laser at room temperature.

In a laser with dimensions on the order of microns, one works hard to confine the light effectively within the cavity, but to measure the light, one needs to let it leak out somewhere. Even though the defect mode in the Caltech-USC laser largely propagates in the horizontal plane, the losses from that mode occur primarily in the vertical direction. Hence, the researchers have been able to study the laser emission by the light that gets coupled out of the top surface. Above threshold, the emission spectrum peaks sharply around 1504 nm, close to the theoretically predicted value. (See the figure on page 22.)

The Caltech-USC laser has a high threshold pump power (on the order of mW), in part because the pump beam is so much larger than the defect mode. The pump power is also high because the thin film does not currently have a thermal heat sink, so that the radiative efficiency is low. The experimenters have been working to reduce the threshold power as well as to further characterize the dependence of the lasing on the lattice parameter, the size of the holes next to the cavity, and so forth.

All the data indicate that the lasing results from the photonic defect cavity, but it would be nice to prove that directly by imaging the lasing mode with a near-infrared camera in the near- and far field—that is, near and far from the source, relative to a light wavelength. So far, the strongest evidence that the lasing comes from the defect mode is the finding that the

lasing modes vary predictably with small changes in the geometry of the holes abutting the defect.

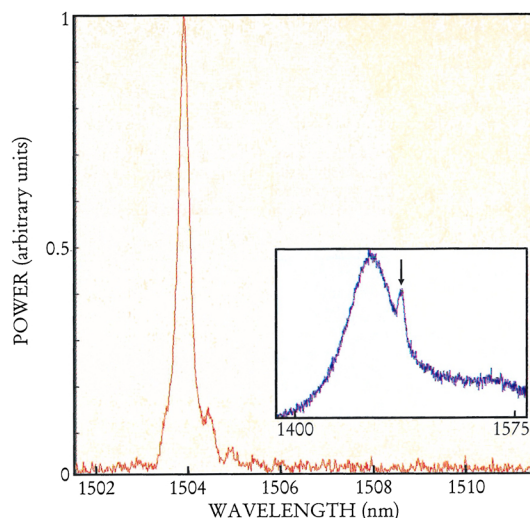
To use the laser in photonic integrated circuits, one might want to couple out the light in the horizontal direction. The Caltech-USC researchers hope to do that either by cleaving the structure in a direction perpendicular to the preferred mode or by making a line of defects to channel out light that exponentially decays in that direction. Axel Scherer, one of the Caltech collaborators, told us that he and his coworkers are hoping to pump the laser electrically and continuously. They are not yet certain whether they can do that with the same basic design.

Distributed feedback lasers

Last December, researchers from Bell Laboratories, Lucent Technologies, and MIT reported a laser that was also based on a photonic crystal,² but its features are quite different from those of the defect laser operated by the Caltech-USC group. The gain medium in the Bell Labs-MIT device is a solid-state organic material, which emits light when stimulated optically. It is deposited on top of a silicon dioxide layer within which a triangular lattice of voids has been etched. The organic film fills the 50 nm deep holes and extends 200 nm above the silicon dioxide film to form a two-dimensional planar waveguide. The periodic modulation of the dielectric constant introduced by the holes imposes symmetry conditions on the light propagating within the lasing medium; standing waves develop only for those electromagnetic modes propagating along the six symmetry directions of the triangular lattice. (Unlike the defect laser, this photonic crystal does not have a complete bandgap.) The design of this laser is similar to the one-dimensional distributed feedback lasers, in which a periodic grating gives positive feedback to the desired modes.

After stimulating the organic gain material with 337 nm light, the Bell Labs-MIT team collected light emitted in the vertical direction and found two lasing peaks, at 580 nm and 596 nm, corresponding to the transverse modes expected to be propagating within the laser.

At the time of their December paper, the Bell Labs-MIT experimenters had no direct indication that the coherent oscillation they observed could be attributed to the two-dimensional photonic crystal. In a recent paper, however, they report such evidence. Specifically, they show that the laser light coupled vertically out from the planar guide and collimated into an array of spots in the far field allows a direct



LASER SPECTRUM for an optically pumped photonic-crystal-defect cavity. The power peaks sharply above the threshold for lasing. Below threshold (inset), the emission from the defect region (vertical arrow) sits atop the broad emission from unprocessed material surrounding the defect.

interpretation of the two-dimensional character of the lasing action.⁵ The researchers can control the angular distribution and number of spots by tailoring the dimensions and symmetry of the two-dimensional dielectric lattice. Dick Slusher of Bell Labs, a member of the team that developed this laser, explained to us that vertical coupling into well-collimated spots requires the spatially extended lasing regions afforded by distributed feedback from small index modulations in the planar guide. As one special case, the experimenters can get a single output beam at 90° to the surface. Slusher feels that this coupling mechanism may be important in a number of applications that require optically efficient coupling to fibers and other optical structures.

A collaboration of scientists from Kyoto University and from Sumitomo Electric Industries, Ltd in Yokohama, Japan, has now reported an electrically pumped, room-temperature laser based on a two-dimensional photonic bandgap structure.³ (They described this device at the Workshop on Electromagnetic Crystal Structure in Laguna Beach, California, in January.) Like the Bell Labs-MIT device, the Japanese laser results from distributed feedback, but, by contrast, it features semiconductors as the gain medium. In the Kyoto-Sumitomo device, the layer containing the indium-gallium-arsenide-phosphide multiple quantum wells sits atop a layer of indium phosphide with a triangular array of shallow air holes. The active layer is not penetrated by the photonic crystal but feels its influence nevertheless. The group's leader, Susumu Noda, and his colleagues measured both the near- and far-field radiation in the vertical direction to be sure that it had the characteristics of

coherent emission from the photonic crystal. When the researchers measure the output in the horizontal plane, they see spots in each of the six symmetry directions, similar to the six spots seen by the Bell Labs-MIT collaboration. But the diffraction in the vertical direction is first order. As a result, the Kyoto-Sumitomo collaborators see a single coherent beam emitted from the top of the laser (rather than the six they would get with second order diffraction).

Noda told us that he and his colleagues will be announcing in November that they have fabricated a three-dimensional bandgap structure with a wavelength as short as 1.1 μm and with a bandgap attenuation of 18 dB. Researchers had previously reported photonic crystals with bandgaps around 1.55 μm and with attenuations of about 10 dB (see PHYSICS TODAY, January, page 17).

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