QUANTUM OPTICS

Coupled States Clear the Darkness and Quiet the Light

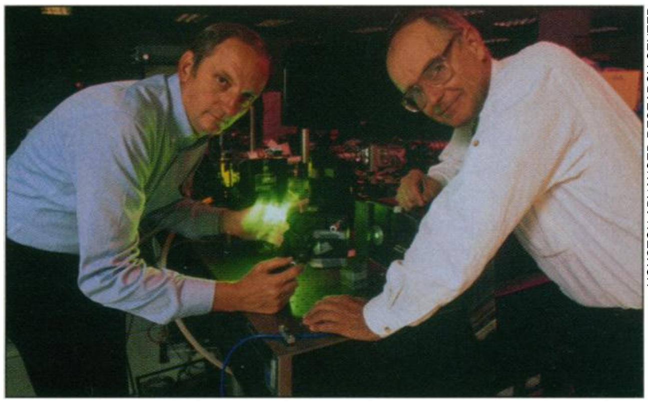
It may seem odd to think of a cloud of gas or a block of glass as a quagmire, but to a photon that's not a bad approximation. Once a light ray penetrates any material, it may be slowed, bent, or scattered as it struggles to get through. Worst of all, for optical devices, some photons may get bogged down entirely and be absorbed into the material. But in experiments reported over the past 2 years, researchers have found ways of using light itself, along with other forms of radiation, to clear a path through this morass. These results, which could have widespread practical applications, are so startling that they have already begun to open up a broad new field of research. Two weeks ago, for example, 70 researchers gathered in Crested Butte, Colorado, to discuss the topic at a meeting called "Atomic Coherence and Interference in Quantum Optics."

Perhaps the most dramatic demonstration of the new strategy came last year from Stephen Harris and his co-workers Atac Imamoglu and Klaus Boller at Stanford University, who used a laser of one wavelength to open a window for light of another wavelength through an ordinarily opaque material. Other researchers are using similar principles to boost the efficiency of lasers, beaming microwaves into the lasing medium in order to reduce the chances that a laser's photons will be reabsorbed before they shoot out in the laser beam. And while workers dream up still other ways to harness this ability to control absorption, others are turning the strategy on its head and using it to control the optical "static" that interferes with many precision measurements.

The heart of the strategy is to use a precisely tuned laser or microwave beam to link together different energy states occupied by electrons in an optical material. The results are so-called phase-controlled materials, which have optical properties so different from those of ordinary materials that theorist Marlan Scully of Texas A&M University and the Max Planck Institute for Quantum Optics calls them "in a very real sense, a new state of matter."

That seems a fair claim when you consider that Scully and his colleagues are tinkering with a basic feature of materials, their quantum-mechanical structure. One way to picture that structure is as a kind of energy ladder, each rung representing a permissible energy level for the material's electrons. When an electron falls from a higher rung to a lower one, it gives off a photon of light at a wavelength exactly matching the energy difference between the two rungs. When an incoming photon has just the right energy to boost an electron to a higher level, the opposite happens, and the photon is absorbed.

Ordinarily, an electron that has absorbed a photon has only one route to a higher energy state. As long ago as 1961, though, investigators realized that closely spaced rungs can compete for an electron from a lower level. And when that happens, Ugo Fano of the University of Chicago discovered, the electron may end up going nowhere. Fano studied a set of three energy levels in helium atoms: a resting, "ground state" and two narrowly spaced higher levels. You might expect that light at the right wavelength would be able to boost an electron to either of the higher levels. In fact, Fano discovered, the difference between the two energy levels is so small that the two possible transitions interfere with each other. In effect, the electron is paralyzed by the choice, and light at a wavelength that—by the normal rules of physics—should be absorbed by the helium passes straight on through. As Harris puts it, "Two paths to the same thing cancel."



Quantum opticians. Edward Fry *(left)* and Marlan Scully.

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Shining through. Such interferences are a rare thing in nature. But in the years since Fano discovered the phenomenon, lasers and other technical advances have opened the way to creating what Harris calls a "manmade Fano interference." That's what Harris and his colleagues did last year, building on work done in the 1970s by groups at the Universities of Pisa and Rochester. Strontium vapor, for example, ordinarily absorbs a particular wavelength of ultraviolet light from a probe laser, but when the Stanford workers beamed a green laser into the vapor, the transmission of the probe beam suddenly increased by 10 orders of magnitude.

The green laser had exactly the right energy to bridge the gap between an intermediate and an upper energy level among electrons in the strontium vapor. The ultraviolet light ordinarily boosts an electron from the lowest level directly to the highest, bypassing the intermediate state. But when the green "coupling" laser was turned on, the intermediate and upper levels were yoked together, creating two competing paths from the lower to the upper state. The resulting interference allowed ultraviolet photons that would normally have been absorbed by the vapor to sail through.

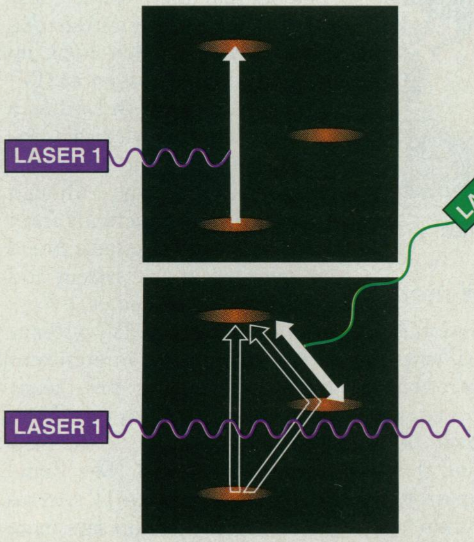
Harris hesitates to make any claims about the technological promise of this "induced transparency"—"so much of what we do ends up as a laboratory curiosity," he warns. But his demonstration has already inspired other workers who hope to boost the efficiency of lasers. Conventional lasers, after all, face a constant battle against absorption. The coherent light of a laser is generated as excited atoms in a lasing material decay into a ground state, releasing a cascade of photons. The trouble is that at the same time, other atoms still in the ground state absorb photons as fast as they are emitted. The only way to get anything out of the material has been to create a "population inversion"—pump in enough energy to produce more atoms in the excited state than in the ground state.

But that strategy takes a bite out of a laser's efficiency. Worse, creating a population inversion in x-ray and other very high frequency lasers is a Sisyphean task, because highly energized atoms slip quickly back into the ground state. To overcome these drawbacks, physicists have dreamed since the mid-1960s of creating a laser that could work without a population inversion. In 1989 Scully and Shi-Yao Zhu of the University of New Mexico suggested that coupled states might be the key. Scully, who credits earlier theoretical work by Harris with "pushing us in this direction," explains that he and Zhu envisioned a different system from Harris': Instead of coupling two excited states, they proposed to link two different ground states with a microwave field. The effect on absorption, they surmised, would be the same. Again, photons could be absorbed by two competing transitions—between the coupled ground levels and a higher state. The resulting interference would prevent absorption, giving photons free passage out of the lasing material. As a result, said Scully and Zhu, the laser could make do with a much smaller energy input than usual—far less than would be needed to create a population inversion.

The notion (proposed independently by

Russian physicist Olga Kocharovskaya of the Gorky Institute of Applied Physics) ran counter to laser orthodoxy, and it met some initial resistance, as mathematical physicist Brian DeFacio of the University of Missouri recalls. "My first thought was the idea was crazy. My second thought was to go through and find where it was wrong." Some months of part-time calculations later, he says, he became satisfied that the theory was "absolutely correct."

SOURCE: HARRIS *ET AL.*



Let it shine. Electrons jumping from a lower energy level to an upper one can absorb a laser beam *(top).* But when a second laser links an intermediate state to the upper one, the light-absorbing transition is blocked.

And now the first glimmerings of experimental confirmation are appearing. Last spring, Herbert Walther and Wolfgang Lange of the Max Planck Institute for Quantum Optics created an inversionless rubidium maser—a device that works on the same principle as a laser but generates microwaves instead of visible light. With absorption suppressed by a beam of low-energy microwaves, the maser generated a coherent microwave beam from a very sparse population of excited atoms. And in an experiment accepted for publication in *Optics Communications*, a research group directed by Jin-Yue Gao at Jilin University in Changchun, China, found that a sodium vapor in which the atoms were frozen in their ground state by an external laser field yielded laser activity without a population inversion.

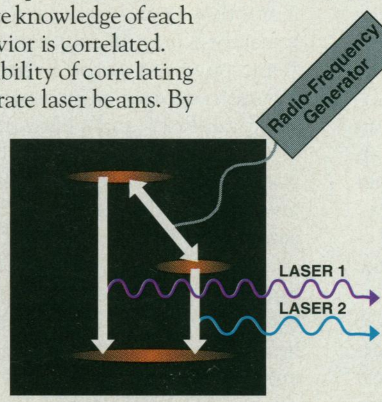
The still of the light. Absorption is only one of the vexing behaviors of optical materials. Another is "noise"—the random fluctuations in wavelength, intensity, and "phase," or timing, that taint even the purest source of light. But several laboratories have now found that here, too, the strategy of yoking together separate energy levels offers hope. Several recent experiments suggest that such linkages can marshal the photon-emitting transitions in lasers and other optical devices, sharply lowering the noise level.

The rewards for doing so would be especially high in interferometry, a technique for fine-scale measurement that relies on the relative phases of two laser beams. When the beams are sent along separate paths, then brought together again, the "interference pattern" or "beat frequency" that results is exquisitely sensitive to changes in the length of one of the paths. The trouble is that quantum fluctuations in the relative phases of the two beams—a form of noise—limit the sensitivity of the measurements. But in 1985, Scully argued that if two laser beams are generated in the same material and the upper levels of the light-emitting atoms are linked with a third electromagnetic field, the problem can be at least partly circumvented.

This solution, recently demonstrated by Michael P. Winters and John L. Hall of the Joint Institute for Laboratory Astrophysics (JILA) in Boulder and Peter Toschek of the University of Hamburg, relies on a quantum-mechanical twist: Linking two energy levels has opposite effects on absorption and emission. For electrons trying to climb into or out of a pair of linked states, the coupling sets up a destructive interference that blocks the transition—and hence prevents absorption. From the point of view of electrons decaying out of linked states into a lower state, though, the interference is constructive; whenever the electrons spontaneously decay, emitting random photons, they do so in synchrony. As theoretical physicist Lorenzo Narducci of Drexel University puts it: "The [coupling] field forces the two formerly independent states to talk to each other—to have knowledge of each other," so that their behavior is correlated.

That opened the possibility of correlating the noise in the two separate laser beams. By coupling the upper levels responsible for two frequencies of light in a helium-neon laser, Winters, Hall, and Toschek ensured that when the phases of the two beams fluctuated because of spontaneous emissions, they did so in step with each other. In this "correlated emission laser," says Narducci, "the two beams may still be messy, but they are messy in the same way." In an interferometer, this mirror-image noise would cancel out, boosting the instrument's sensitivity. One endeavor that might benefit from this little trick, Hall and his colleagues venture, is the detection of gravitational waves, subtle wrinkles in spacetime that might reveal themselves as minute displacements along one arm of an interferometer.

SOURCE: SCULLY



Photons in lockstep. By linking two upper energy states, an electromagnetic field correlates the noise in two laser beams.

As induced transparency, lasers without inversion, correlated-emission lasers, and other phenomena move from the realm of theory into the laboratory, Scully has been encouraged to envision new uses for materials with coupled states. "Nothing is so practical as a good theory," he exults. One future he envisions for these materials, which he refers to as phaseonium, is in optical devices that rely on high refractive indexes.

Phaseonium. Materials with a high refractive index are "sticky," from light's point of view; light slows when it enters the medium, and it is sharply bent—refracted—as well. Both properties have technological appeal. Higher-refraction lenses could boost the resolving power of optical microscopes. And a high-refractive index gas that could slow light might open the way to a new generation of electron accelerators in which lasers would provide the impetus. Such accelerators are a long way from being realized, in part because light waves travel much too fast for electrons to surf along their crests. Notes Narducci, "Light outraces the electrons it is intended to accelerate." One solution would be to beam the laser into a tenuous but highly refractive medium, which would put the brakes on the light without scattering the electrons.

That solution raises a new problem, however: Materials with a very high index of refraction normally absorb a lot of light—and absorption is anathema to both microscopes and lasers. But by coupling two ground states or upper levels in a gas, Scully proposed last October in Brussels at a Solvay conference on quantum optics, absorption can be ruled out, while the desirable high refraction remains. The resulting phaseonium could serve as a microscope "lens" or a light-retarding medium in a laser accelerator.

Scully says he is currently carrying on research in this latter area with Texas A&M's Edward Fry at the Houston Advanced Research Center.

It may be a while before Bausch and Lomb starts making phaseonium lenses, but for Scully, phase-controlled materials have already had a very practical impact. At one time, he combined theoretical work in quantum optics with ranching and agricultural research in New Mexico. Now, he says, "the energy I used to put into cattle, I'm now putting into quantum optical experiments. We're working like crazy on phaseonium."

–**Neal Singer**

Neal Singer is the science editor at the University of Illinois at Urbana-Champaign.