OPTICS

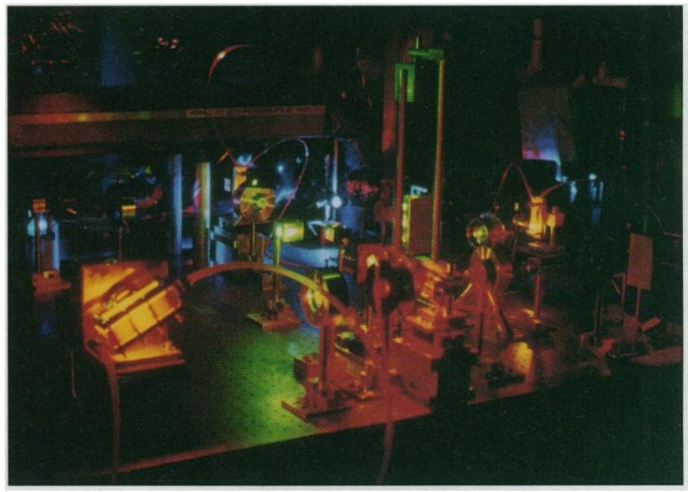
Researchers Build Novel Laser By Putting a Lock on Atoms

Look up "lasers" in any standard physics textbook, and you'll find one unvarying rule: Most of the atoms in the lasing medium must be in an excited, light-emitting state. The reason, explains Ed Fry of Texas A & M University, is that atoms that have not been boosted to an excited state "are like water on a fire." Unless they are thoroughly mopped up, "they'll put out [the laser], because they absorb photons." The requirement means that large amounts of energy have to be pumped into a laser before it can produce light, and it limits ultraviolet and x-ray lasers to operating only in extremely short pulses. But now, thanks to work by groups including Fry, the textbooks may have to be rewritten.

In one paper published in the 21 August *Physical Review Letters* and another paper submitted to the journal, the groups report the first demonstrations of lasers that work without a so-called population inversion—the state in which the number of excited atoms exceeds those in the ground state. Marlan Scully of Texas A & M and collaborators at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, were the first to achieve the feat, in infrared light. A separate collaboration including Scully, Fry, and collaborators at the Texas Laser Laboratory at the Houston Advanced Research Center (HARC) has now reproduced it with yellow visible light. In both cases, the researchers used quantum-mechanical sleight of hand to block atoms in the ground state from absorbing photons. In effect, the "water" in these lasers could no longer put out the fire.

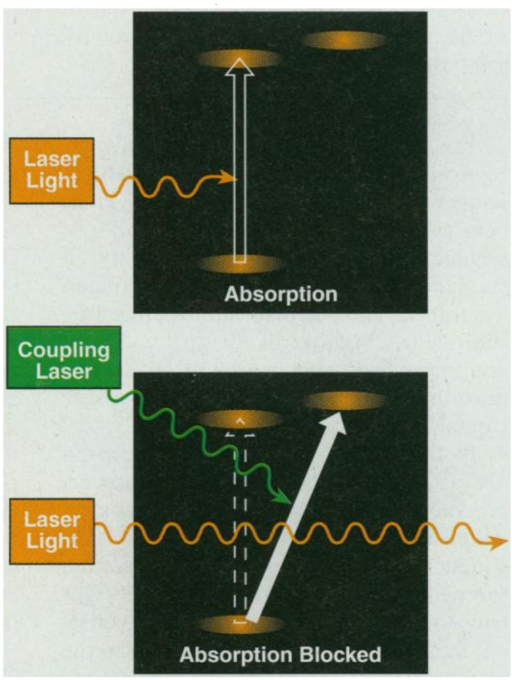
Although physicists have been moving toward lasing without inversion (LWI) for nearly a decade, says Lorenzo Narducci, a laser physicist at Drexel University in Philadelphia, the new results finally demonstrate a "truly highly coherent radiation source that does not need inversion." Agrees Herschel Pilloff, who manages the laser physics and quantum optics program at the Office of Naval Research, "The atomic beam experiments at HARC are ultradefinitive." If the effect can be harnessed to build ultraviolet and soft x-ray lasers, it could be a boon to semiconductor manufacturing. And the same strategy for manipulating the optical properties of a material could also open the way to a new generation of microscopes and even accelerators for particle physics, in which the particles would attain extraordinary energies by surfing on laser-induced electromagnetic waves (see box).

Scully and company haven't tinkered with the essence of a laser: the simultaneous decay of a host of atoms from the excited state back to the ground state, releasing photons that all travel in step with one another. The light then bounces repeatedly back and forth between two mirrors that form a cavity. With each pass more photons are squeezed out of the lasing material, further amplifying and synchronizing the light.


SCULLY ET AL.

Light from light. An optics bench is bathed in yellow light from a laser like the one used to block absorption in a second laser.

As the textbooks point out, however, the process only works if a majority of the atoms in the material are in the excited state, so that the balance of photons emitted to photons absorbed is always positive. The catch is that once the atoms are in an excited state, says Narducci, they will easily decay back to the ground state. The shorter the wavelength emitted by the atoms, the faster they decay. Atoms that emit ultraviolet light or soft x-rays decay "in a jiffy," says Narducci. "Things get dramatically worse as you go to shorter and shorter wavelength. Here you are pumping like crazy, and the atoms decay faster than you can say 'boo.' "



Let it shine. Light tuned to the difference between an atom's ground and excited states is normally absorbed *(top)*. But a second laser can block the process by creating competing paths for absorption.

Atomic ratchet. The scheme for dodging this requirement was first proposed in the 1980s by Russian scientists—in particular Olga Kocharovskaya and Yakov Khain of the Institute of Applied Physics of the Russian Academy of Science and Yuri Heller and V. G. Arkhipkin at the Kirensky Institute of Physics in Siberia—and developed by Scully and collaborators and Stephen Harris of Stanford University (*Science*, 2 October 1992, p. 32). These theorists proposed a way to create a "quantum interference" between energy-absorbing transitions in the atoms of the lasing medium. In effect, the interference would put a lock on the atoms, allowing them to emit photons of the laser wavelength but not absorb them. "You have this atomic ratchet type of phenomenon," as Scully puts it, "in which you can quench absorption but maintain or keep emission." As a result, just a few atoms in the excited state would be enough to produce laser light.

Understanding how this quantum interference works, however, is something Narducci describes as "walking on the thin ice of difficult concepts." One scheme relies on atoms in which the ground state is coupled to two excited states, only one of which normally absorbs the laser photons. (The atoms in an alternative arrangement have a pair of ground states and a single excited state.) A strong "coupling" laser is tuned to the energy difference between the ground state and the second excited state, creating an alternative absorption path. As a result, an atom absorbing a photon could follow either of two paths from the ground state to the excited states. The paths compete with each other, however, setting up an interference, and the atom's probability of absorbing the photon drops to near zero. The few atoms that are needed for lasing can be excited by pumping them from states other than the ones that are blocked.

Scully had been interested in LWI since a 1989 hiking trip with Harris, who, says Scully, "explained [LWI] to me, and it struck a resonance." When Scully arrived at Texas A & M 3 years later, he set up two collaborations, one with Fry, who had been working on fundamental tests of quantum mechanics, and the other with Leo Hollberg at NIST in Boulder. As part of the deal with Hollberg, Scully also hired Alexander Zibrov from the Lebedev Institute of Physics in Moscow and sent him to Boulder. Says Hollberg: "He was the main person in the lab doing the experiment."

Fry and his colleagues at HARC went to work using a beam of atomic sodium, and what's called a Λ scheme, while Hollberg at NIST used rubidium gas and a V scheme. The notation is simple, says Fry: "If you have two excited levels and a common lower level, and you draw a line connecting those levels, it looks like a V. If you have one upper level and two lower levels, and draw lines connecting them, it looks like a capital lambda."

Now that they've managed to iron out the various kinks, Hollberg says the experiments are "not particularly difficult." What's required, he says, are two well-controlled semiconductor lasers, one to create the quantum interference and the other to trigger light emission, and a source of ordinary, incoherent light to pump the laser by bypassing the blocked levels. "Then you have to mainly understand the physics," he says, "and configure the system to take advantage of these coherences" by tailoring the density of the atoms in the gas and the intensities and colors of the lasers.

So far the two LWI demonstrations constitute little more than a proof of principle. One of the obvious next steps is to see if the scheme opens the way to more practical ultraviolet or soft x-ray lasers. Such short-wavelength lasers would have immediate applications throughout technology. "Most atomic absorptions are in the blue and ultraviolet," says Hollberg, which would suit these lasers to detecting trace substances in pollution monitoring and medical diagnosis. And because short wavelengths of light can be focused more tightly, such lasers would be a boon to microlithography—the precision etching technique used to carve ever smaller integrated circuits.

But that's for the future. As Fry puts it, "Right now, it doesn't give you anything for practical applications, but you have to start somewhere."

–Gary Taubes

Slowing a Light Wave—in Order to Catch It

One kind of particle accelerator—the now-defunct Superconducting Super Collider (SSC)—helped bring physicist Marlan Scully to Texas A & M University in 1992. Now he has turned his attention to a very different kind of accelerator. Scully says he came to Texas because he believed that his field, laser and atomic physics, could contribute to the high-energy physics work at the SSC, to be built elsewhere in Texas. But when the project was canceled 2 years ago, Scully devoted his full attention to a scheme for adjusting a material's optical properties that may lead to practical short-wavelength lasers (see main text)—and a new generation of compact accelerators that could more than make up for the loss of the SSC.

Scully and his collaborators are betting that both technologies will profit from their ability to put a lock on certain atomic energy transitions that normally absorb light. They have already used the technique to elicit laser light from a gas with a smaller input of energy than is required for traditional lasers. Now they are exploring its use in accelerators in which atomic particles would surf on a laser-driven electromagnetic wave.

Laser-driven particle accelerators have attracted intense interest in recent years because they promise higher particle energies than conventional accelerators, from a much smaller and cheaper package. The particles—most likely electrons—would gain energy from two laser beams that cross at a slight angle, so that the electric fields generated by the beams interfere and create a wave that propagates along with the light. "This [wave] is what the electrons ride on and what they extract energy from," says Scully.

But to keep the wave and the electrons in step, the light has to be slowed. Otherwise, says Ed Fry, who collaborates with Scully at Texas A & M, "you get acceleration on the forward edge of the electromagnetic wave, but then the electric field changes sign and slows the electron back down again." And while the speed of light in a vacuum is unvarying, light can be slowed by passing it through a material with a high refractive index. Then, says Fry, "you [can] have a particle moving right along with the light wave, which just keeps pushing it, and accelerating faster and faster."

Ordinary highly refractive materials are relatively dense and would scatter the beam of particles, defeating the purpose of the accelerator. An alternative is to operate in a tenuous material, but at a wavelength very close to one that the material normally absorbs. As Scully explains, "All known atoms can get a huge index of refraction by operating near a resonance, when the atom wants to absorb light. ... When that happens the index of refraction goes through the roof. It gets millions of times larger. That's the good news. The bad news is that all the photons get gobbled up because the atoms desperately want to absorb them." But by blocking the normal absorption of light, says Scully, "we can get an index of refraction many orders of magnitude larger per atom than anyone has ever seen," even in a rarefied medium.

Since August, says Scully, a collaboration between his group at Texas A & M and Leo Hollberg and his colleagues at the National Institute of Standards and Technology in Boulder, Colorado, has done just that. By quantum-mechanically blocking absorption in a tenuous gas and then probing it with light at a wavelength normally absorbed by the gas, they observed a manyfold jump in its index of refraction. (Hollberg says he's not yet sure of the exact increase.) According to Scully, the group will soon submit a paper describing the results to *Physical Review Letters*.

One place he envisions putting the effect to work is in microscopes, where resolution is limited by the wavelength of the light. The wavelengths of visible light are fixed, but increasing the index of refraction of the medium surrounding the object will slow the light—and because the light's frequency stays constant, its effective wavelength drops. Boosting the index of refraction by a factor of 10 would result in a 10-fold increase in resolution, Scully says.

But it's the implications of the work for accelerators that have Scully most excited. "We're now very optimistic that we have the wherewithal to make a better laser accelerator," he says.

–G.T.