Researchers Report Evidence for Lasing Without Inversion

We have come to think that lasing requires an inversion of population between atoms in an excited state and those in a lower state: Normally the probability of absorption from the lower state equals the probability of emission from the higher state, so that the only way to have more photons coming out than going in is to start with more atoms in the upper state. It would be useful to decouple the probabilities of emission and absorption, so that one could lower the loss associated with absorption without reducing the emission.

In some atomic systems the symmetry between emission and absorption can be broken if there is destructive interference between two quantum paths leading to absorption but no such interference in the emission paths.[1] In their quest for lasing without population inversion, many groups have been applying strong driving lasers to couple coherently two of the atomic levels and bring about the desired interference.[2]

Success may now be at hand. In an experiment performed at the National Institute of Standards and Technology, in Boulder, Colorado, a team of researchers from the US, Germany and Russia recently demonstrated continuous-wave laser oscillations in an atomic system that should have no population inversion.[3] The researchers offer detailed calculations and indirect experimental evidence to support their assertion that the lasing is not dependent on the relative populations in the atomic levels.

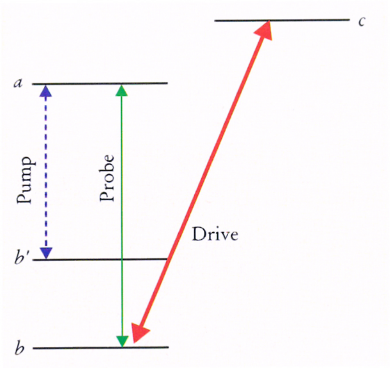
Participants in the experiment at NIST were Alexander S. Zibrov, Mikhail D. Lukin, Dmitri E. Nikonov and Marlan Scully, all of whom hold joint appointments with Texas A&M University, the Texas Laser Lab and the Max Planck Institute for Quantum Optics, in Garching, Germany; Leo W. Hollberg and Hugh G. Robinson of NIST; and Vladimir L. Velichansky of the Lebedev Institute of Physics, in Moscow.

The goal of lasing without inversion has attracted many researchers, who are intrigued by the possibility of making lasers in a new way. One hope is to produce devices that lase at frequencies in the ultraviolet and beyond. To get such high frequencies requires a large separation between energy levels, but if a system could lase into the ground state without population inversion one wouldn't have to pump so many atoms into

> A recent experiment may have achieved what many others have sought: a new way of lasing that avoids the need to pump many more atoms to a higher state than remain in the ground level.

the high-lying atomic states.

The experiment at NIST builds on numerous theoretical studies of various atomic configurations and growing numbers of experimental efforts, all aimed at achieving lasing without inversion. In the last few years, several groups have demonstrated inversionless amplification—but not inversionless laser oscillation.[4] Thomas Mossberg of the University of Oregon contends that there has been lasing without population inversion in some two-level systems,[5] as opposed to the three levels effectively involved in the experiment at NIST. He realizes, however, that others might debate the issue with him: The debate would hinge on how each side defined "lasing" as opposed to a "parametric process." (In a parametric process the atom acts more as an intermediary in the interaction among light fields, returning to its initial state.) In any case, systems with more than two levels have the distinct advantage of lasing at a wavelength that is different from that of the drive laser.



FOUR-LEVEL MODEL of an atom illustrates one scheme for lasing without inversion. Lasing occurs between levels a and b. A coherent drive field (red) couples b and c, causing destructive interference in the path for absorption from b to a. An incoherent pump laser (purple) takes atoms from b' to a. A weak probe laser (green) is then amplified by the stimulated emission. (Adapted from ref. 3.)

Some atomic systems have no inversion in the population of the energy eigenstates, but if one considers the so-called dressed states of the atom plus the drive field, the upper states may be more heavily occupied than the lower ones. Scully and his colleagues assert that they have shown lasing in a system that has no population inversion in either of these bases.

Coherent coupling

Scully and his colleagues achieved lasing in a system of rubidium-87 atoms. Although the atom has 32 atomic levels, including the hyperfine and Zeeman sublevels, that must be included in detailed calculations, the essential physics is contained in three levels—shown as a, b and c in the figure on this page (the fourth level, b', plays a smaller role). Shown in the figure are two ground levels, b and b', which are narrowly separated by the 6.8-GHz ground-state hyperfine splitting (the level spacings are not drawn in proportion to the energy separations), and two upper levels, a and c. Transitions are allowed between either of the upper states and either of the lower states.

Inversionless lasing occurs between levels a and b. To make it happen, the researchers need to prevent atoms in level b from absorbing energy and being excited to level a. In addition they must populate level a, albeit with fewer atoms than remain in level b. To cancel the absorption, Scully and his colleagues applied a strong coherent drive field that couples levels b and c. Because of the coupling, an atom can be excited to level a with a weak probe laser either by jumping directly from b to a or by going first from b to c and back and then on to a. The amplitudes for these quantum paths add and can interfere destructively, greatly reducing the probability of absorption from b to a. At the same time, the probability of emission from a to b remains unchanged.

The drive field also serves to accumulate atoms in level b', because level c can decay into either of the lower levels. An incoherent, broad bandwidth field applied between levels a and b' can then pump a small number of atoms up to a. If the rate of decay from level c is slower than the spontaneous emission rate from a to b, the population of level a can remain smaller than that of b. When the weak probe field is applied between a and b, the emission rate should dominate and amplification should occur.

This particular atomic system, called the V configuration, is only one of many configurations that have been explored in the quest for lasing without inversion. It serves more generally to illustrate the quantum interference one can get by applying coherent coupling.

Experimental evidence

Scully and his collaborators performed several tests on their system to look for gain, laser oscillation and the absence of inversion. First they measured the transmittance as a function of probe frequency, with and without the incoherent pump laser. With the pump the transmittance develops a narrow peak at resonance and exceeds the value one would get if no absorption were present. The gain from a 6-cm-long vapor cell was about 10 percent. The transmittance curves were very similar to those based on calculations.

Next, to demonstrate laser oscillations, the experimenters at NIST placed the rubidium cell inside a ring cavity resonant with the 794-nm transition between a and b and turned off the probe laser. The system then oscillated on the 794-nm transition line with an output power of about 30 μW. The figure at the right shows the power as a function of the drive frequency. The three spikes correspond to different longitudinal modes of the laser cavity.

Scully and his coworkers performed two tests to check for population inversion. First they found that the gain depended on the spectral width of the probe and drive lasers. The probe laser cannot affect the population distribution because it is too weak, so this change in gain with linewidth must be a coherence effect. This test alone does not tell the group what the population of the levels is, only that population inversion is not involved in the production of gain. Second the researchers noted that the frequency of lasing on the transition from a to b tunes with the drive frequency, which takes the atom from state b to state c. If population inversion were involved, the system would not depend on a one-to-one correspondence with the drive frequency.

The efforts to produce lasing without inversion are part of a broader and very active field involving coherent control of atomic systems. Many studies involve a phenomenon known as "electromagnetically induced transparency," in which a laser applied to an atom at one wavelength prevents absorption by light at another. (See PHYSICS TODAY, May 1992, page 17.) The phenomenon has potential applications in nonlinear optics because canceling the absorption may allow a system to operate very close to resonance, where the nonlinear effects are largest, without being killed by absorption losses.

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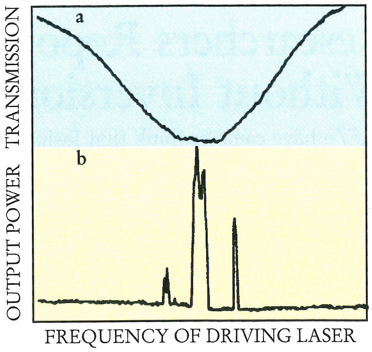

EVIDENCE FOR LASING. **a:** Transmission through a reference cell shows a broad absorption as a function of the laser drive field. **b:** Output power of the ring cavity has spikes at values of the drive frequency corresponding to the three longitudinal modes of the cavity. The lasing should not depend on the drive frequency if it results strictly from a population inversion. (Adapted from ref. 3.)

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How Low Can the Violin Go?

Accomplished violinists can generate anomalous low frequencies on their instruments. These unusual tones can be understood in terms of multiple reflections of a single wave at the bow. In effect the reflections prolong the sound-producing cycle first analyzed by Helmholtz.

Almost all beginning violinists generate the sound of a small woodshop when practicing low notes. Almost no professional musicians cultivate that scratchy rumble to produce definite tones of lower frequency than the violin is normally capable of. Yet such tones can be generated, and several investigators are trying to make sense of them.

In 1989, at the University of Northern Iowa, in Cedar Falls, music professor Frederick Halgedahl discovered such tones and physicist Roger Hanson began to analyze them. By exerting larger-than-normal force with the bow on the lowest string (G at 196 Hz) and employing careful bow control, Halgedahl was able to isolate individual, stable tones ranging from 155 Hz (about a musical third lower than the open string) down to 47.4 Hz (slightly more than two octaves lower). These frequencies are not subharmonics; they have no simple relation to the fundamental frequency of the free string. From the sound spectra, Hanson discovered that the fundamentals for these anomalous low tones were either weak or missing, but because the subsequent harmonics in the sound were strong, the ear "heard" the true harmonic sequence, and the listener "perceived" the true low tone nevertheless. Hanson, with Andrew Schneider and Benjamin Ross, also observed the string with optoelectronic detectors and found very complicated waveforms, as shown in the figure on page 21.

The researchers anticipated that the low notes would have little musical importance. They were therefore surprised to read in the *New York Times* (21 April 1994) of a performance by concert violinist Mari Kimura in which she used these very tones, discovered independently, to musical advantage.

Knut Guettler, at the Norwegian