Lasers Without Inversion

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Lasers do what they do because of stimulated emission, an event in which an excited atom or molecule is induced by a photon to release that photon's identical twin. Arrange to have many atoms producing photons by stimulated emission, and a chain reaction of light is the result, with all photons at the same wavelength traveling in phase. Normally, this requires a rearrangement of the populations, so that more atoms are in the excited energy level than in the ground state, which is called population inversion. Over the past few years, however, theorists have emphasized that it is in principle possible to have lasing without inversion (LWI), owing to subtle quantum interference effects in the lasing atoms (*1–4*). Indeed, recent experiments by several groups have demonstrated that LWI is feasible (*5–8*).

But who cares? After all, we have plenty of lasers that operate with inversion. One reason to care is that inversionless lasing puts us on the verge of a new field of research in laser physics and quantum optics. For example, as we seek the holy grail of a tabletop x-ray laser, we are frustrated by the rapid decay rate of highly energetic (x-ray emitting) states, and it is difficult to sustain a population inversion. We have, to date, been able to generate coherent soft x-rays with giant laser systems such as NOVA at Lawrence Livermore National Laboratory, which can dump large amounts of energy into a lasing medium in a short time. If we could just "ignore" the unexcited (lower level) atoms—that is, if we could obtain lasing without the need of an inverted medium—then maybe we could avoid the "sledgehammer" approach to the problem.

As the name implies, LWI allows us to extract energy from the lasing medium even if we have more atoms in the lower level than in the upper (that is, even if we have more atoms that could potentially absorb than atoms that could emit a photon). But what are these funny atoms that emit light but do not absorb it? Consider an atom in which the laser field is coupled to two levels rather than to just one lower level. Let us assume that this atom is prepared in a "coherent superposition" of the two lower levels $|b\rangle$ and $|c\rangle$. The complex probability amplitudes for absorption of light from levels $|b\rangle$ or $|c\rangle$ to the upper level $|a\rangle$ are given by A_{ab} and A_{ac}. To find the total probability of absorption from this coherent superposition, we must add the amplitudes before squaring because we are ending in a common state. This gives rise to interference terms, which under certain conditions cause the total probability to vanish. On the other hand, the probability of emission from an atom in the upper level invokes the sum of the squares $|A_{ab}|^2$ and $|A_{ac}|^2$.

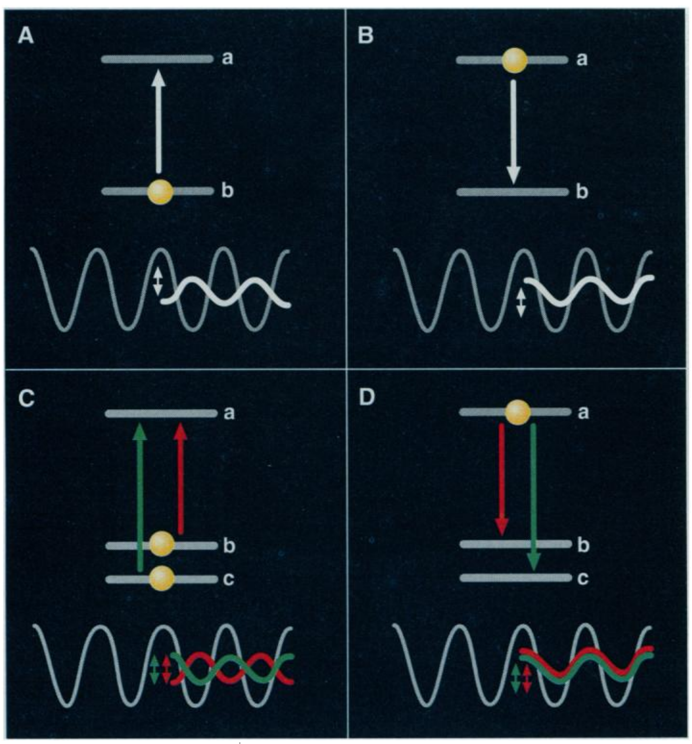

Fig. 1. (**A**) Absorption by a two-level atom: Induced dipole radiation interferes destructively with incident radiation. (**B**) Emission by a two-level atom: Induced dipole radiation interferes constructively with incident radiation. (**C**) Absorption cancellation by a three-level atom in a coherent superposition of lower levels: Induced dipole radiations of the two coherent emitters cancel each other and the incident single-mode radiation remains unaffected. (**D**) Emission by a three-level atom in the excited state: Induced dipole radiations of the two emitters are in phase with incident single-mode radiation and lead to amplification.

To understand this in a more physical way, let us ask how an atom manages to absorb, or emit, light. It essentially acts as a tiny oscillating electronic current (like the antenna on a radio transmitter but smaller) induced by the incident light field. Attenuation of an incident field is then the result of the radiation from this current interfering destructively with the incident light (Fig. 1, A and B).

Having seen how light is absorbed by the set of levels $|a\rangle$ and $|b\rangle$, we are in a position to understand why light is (potentially) not absorbed when we have two atomic transmitters, one associated with the $|a\rangle$ to $|b\rangle$ transition, and the other with the $|a\rangle$ to $|c\rangle$ transition. When an atom is in a coherent superposition of compound (doublet) lower levels, it is like having two tiny coherent oscillators within one atom: The contributions from these two emitters are out of phase by 180° and cancel each other (Fig. 1C).

The situation is different if the atom begins life in the excited state $|a\rangle$. Now, when we induce or stimulate the atom from $|a\rangle$ into $|b\rangle$ and $|c\rangle$, the phases of the oscillators are determined by the field so that emission by the atomic transmitters will not cancel but rather add (Fig. 1D).

LWI and related effects may look good on paper, but can they be observed? In fact, these ideas have been verified experimentally (*9*). At the "Lasers '92" conference (*5*) and in recent articles (*6–8*), three groups have independently reported amplification in a noninverted atomic vapor as a result of induced coherences in a ground-state manifold (Fig. 2). The three experiments were not designed to generate intense high-frequency light or x-rays, but are to be viewed as proofs of principle.

Perhaps the most simple experiment, from a conceptual point of view, is that of the Texas group (*5, 7*). Two strong continuous wave–laser fields forced the sodium atoms into a coherent superposition of two lower levels with a fixed phase by means of a Raman-type process. After a small amount of population was pumped into the upper level by a short pulse, a weak probe was amplified without inversion because of the coherence between the doublet. In the Münster experiment (*6*) with samarium atoms, a short Raman pulse was used to initiate a ground-state coherence. An applied magnetic field shifted the energies of the ground levels relative to each other, and the coherence

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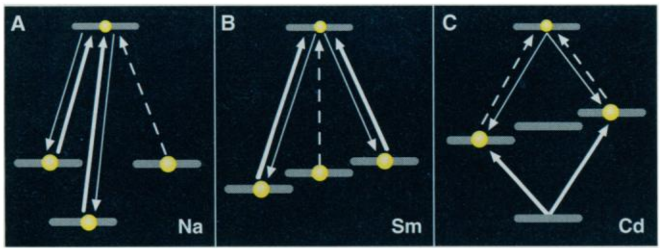

Fig. 2. (**A**) Texas, (**B**) Münster, and (**C**) Amsterdam experiments on LWI. The heavy lines are the coherence-generating fields, the dashed lines indicate pumping into the upper lasing level, and the thin lines are the probe transitions.

started to oscillate with a period determined by the level splitting. Inversionless amplification or absorption of a probe pulse was observed depending on the phase of the oscillating coherence. In the Amsterdam experiment (*8*) on cadmium, a pulse was again used to lift the atoms from the ground state into a coherent superposition of two intermediate magnetic sublevels, and noninversion amplification of a probe pulse was observed.

As is very often the case with new concepts, the study of coherent atomic systems revealed other interesting properties and possibilities. Electromagnetically induced transparency, as predicted by Harris and coworkers (*10*), is a case in point. They proved that when a strong field is present on one transition, such as $b \rightarrow a$ of Fig. 1C, a weak probe will not be absorbed on the $c \rightarrow a$ transition. In this way, they can render an opaque medium transparent. Furthermore, the medium will be highly dispersive, and thus, this effect may be used to slow down the group velocity of short light pulses (*11*) or to make a high-precision magnetometer (*12*) based on the Zeeman level shifts induced by tiny magnetic fields.

It is also possible to use atomic coherence to generate a large index of refraction (*13*), to produce large nonlinear optical coefficients (*14*), and even to quench quantum noise (*15*). In fact, it may be noted that such a phase-coherent atomic ensemble is in a real sense a new state of matter, which has come to be known as "phaseonium."

The physics behind LWI and related effects as explained here is based on atomic coherence and interference. To some extent, it is possible and profitable to recast this picture in terms of so-called "dressed states," such that one state (called the antisymmetric state) does not engage in absorption (or emission), while another (symmetric state) does. If the lower laser-level population is put into the nonabsorbing antisymmetric state, any small amount of population placed in the excited state could be said to lead to lasing with inversion to the empty symmetric state. In this sense, LWI would be lasing with hidden inversion in a dressed basis. However, there is more to the story.

In the original work of Harris (*2*), LWI was based on quantum Fano-interference, for which there is no dressed state description. Likewise, the so-called Raman coherence scheme, as studied experimentally by the Texas group, has no simple dressed state or hidden inversion description. In all cases, however, atomic coherence and interference explains the physics, and we emphasize the utility and generality of this approach. The interplay between atomic coherence effects and quantum optics is a rich field of fundamental and applied research and will be an exciting area of scientific activity for some time.

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Polyketide Biosynthesis: Molecular Recognition or Genetic Programming?

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Polyketides are a large and diverse family of natural products, most of which are produced by Actinomycete bacteria and by fungi. Two classes of polyketides have been extensively studied—the polycyclic aromatic polyketides, typified by the antitumor antibiotic tetracenomycin C (1) and the blue-pigmented octaketide actinorhodin (2), and the partially reduced, branched-chain fatty acid lactones, known more generally as macrolides and represented by the broad spectrum antibiotic erythromycin A (3) (Fig. 1). Complex polyketides are synthesized by a mechanism analogous to the chain-elongation steps of fatty acid biosynthesis, with acetate, propionate, and butyrate forming the fundamental building blocks (*1–3*). The oxidation level and stereochemistry of the growing polyketide chains are adjusted after each condensation step in the chain-elongation process (*1–3*).

The application of molecular genetics to polyketide biosynthesis has yielded dramatic insights into the organization and function of these biosynthetic systems and has allowed the isolation of polyketide synthase proteins. Two landmark developments stand out. Malpartida and Hopwood have reported the cloning of the entire set of actinorhodin biosynthetic genes from *Streptomyces coelicolor*—a 26-kilobase gene cluster (*4*). The polyketide synthase (PKS) genes, identified both by complementation of known mutations as well as by targeted gene disruptions, showed sequence similarities to conserved domains of the genes for fatty acid biosynthesis. More recently, Katz, at Abbott Laboratories (*5*), and Leadlay, at the University of Cambridge (*6*), each cloned and sequenced the genes from *Saccharopolyspora erythraea* responsible for synthesis of the parent macrolide for erythromycin, 6-deoxyerythronolide B (*4*). The *ery*A gene is organized into three large (10-kilobase) open reading frames containing a series of domains, each responsible for one of the individual steps of reduced polyke-

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