Creating laser light

Quantum theory, metastable states, stimulated emission, and optical feedback are all part of the mysterious process of turning energized atoms into laser light.

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Clearly the physical mechanisms of light emission are subtle and complex. As last month's Back to Basics indicated, factors such as the chemical makeup of the light emitting material, its physical state (solid, gas, plasma), the manner of excitation, temperature, and even pressure can radically affect the kind of light created by incandescent lamps and gas discharges. But these effects merely hint at the underlying complexity and myriad forms of light emission.

Attempts to use classical theory to explain the radiation from a blackbody failed miserably, leading to Planck's famous radiation law and the dawn of quantum theory (see February's Back to Basics). Albert Einstein (1879-1955), who never fully accepted the philosophical implications of quantum theory, nevertheless conceived two of its most fundamental concepts: the photon (1905) and stimulated emission (1917). Both concepts were crucial to the invention of lasers.

Niels Bohr (1885-1962), perhaps quantum theory's most ardent champion, constructed the first quantum model of an atom in 1913, and with it he predicted the emission-line frequencies of atomic hydrogen with great precision. Soon afterwards, Arnold Sommerfeld (1868-1951), Wolfgang Pauli (1890-1958), and others made important refinements to the Bohr model that led to a more comprehensive explanation of line spectra and established a physical foundation for the periodic table of elements.

During the Roaring '20s, a burst of creative reasoning finally put Bohr's model on the firm theoretical footing it deserved. Help came in the form of Louis de Broglie's particle waves (1923), Werner Heisenberg's matrix mechanics (1925), Erwin Schrödinger's wave equation (1926), and Max Born's probability wave packets (1926). In just three decades, quantum theory blossomed into a radically new and successful explanation of matter and light. Today, quantum mechanics plays the leading role in our present understanding of the universe.

In the Bohr-Sommerfeld model of the atom, negatively charged electrons orbit a positively charged nucleus along specific paths called orbitals. The positions of these discrete orbitals depend upon a complex set of conditions, such as the number of electrons surrounding the nucleus, the number of protons in the nucleus, electron spin, the presence of nearby atoms, and the existence of electric and magnetic fields.

Each orbital defines a unique, stationary energy state within the atom. And when all of the electrons occupy orbitals that have the lowest potential energies, the atom is said to be in its ground state. At a temperature of absolute zero (0 K), all atoms are in their ground state. But electrons can be excited into high energy orbitals by absorbing energy in a variety of ways, such as through the vibrations of elevated temperatures, by collisions with other atoms or free electrons, via chemical reactions with other atoms, or through the absorption of photons.

Light emission involves a complicated set of physical processes. Even a single type of laser like a HeNe can radiate light at several wavelengths.

When electrons are excited into higher orbitals by the absorption of photons, for example, they will almost immediately decay back to the ground state. The process usually takes only about 10 ns and happens spontaneously. Spontaneous decay often leads to spontaneous emission of photons that have exactly the same frequency as the photons that excited the electrons in the first place. Light created in this way radiates from the atoms in random directions but at well-defined wavelengths called emission lines. These emission lines will intensify as more electrons are pumped into higher orbitals.

In atomic hydrogen, the set of absorption and emission lines that originate and terminate in the ground state $(n = 1)$ defines the Lyman series of energy transitions (see Fig. 1). Arrowheads pointing in both directions in the figure indicate that these energy transitions are two-way streets, resulting in either resonance absorption (upward energy transition) or resonance radiation (downward energy transition). But when electrons are excited to $n = 3$ or higher orbitals, more than one downward transition is possible. For example, from $n = 3$ the electron could drop straight back
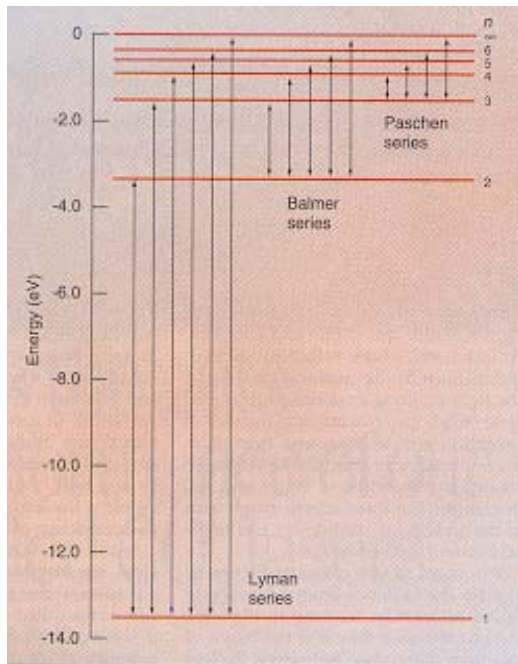

Figure 1. Energy level diagram of atomic hydrogen, the simplest of all atoms, shows three series of energy transitions that terminate at levels designated by their principal quantum numbers, n = 1 (ground state), n = 2, and n = 3. Upward arrows specify absorption whereas downward arrows indicate emission. In more complex atomic systems, levels can split into many sublevels or even continuous bands of allowable energies.

to the ground state or go first to $n = 2$ and then to the ground state. Depending on which path is taken, three different photons could result. The more direct route to the ground state generates a single photon with an energy of 12.1 eV (resonance radiation), whereas the indirect route might produce two photons in succession: one with 1.88 eV of energy, and a second with 10.2 eV.

The two-step emission process describes a kind of fluorescence in which the energy absorbed by an atom is quickly reradiated at longer wavelengths. The 1.88-eV photon creates the red H_α emission line at 656.3 nm, which is well known to astronomers. This line is one of a group of transitions called the Balmer series. Of course, many other transitions are possible in hydrogen. And as the number of orbiting electrons grows through the ranks of the periodic table, so too does the intricacy of orbital transitions.

STIMULATING EMISSION OF LIGHT

In any atom, however, some transitions are likelier than others, and there are well-established selection rules in quantum mechanics that predict the probability of a given transition in various circumstances. This is important to know, because the likelihood of a transition ultimately determines the strength of an absorption or emission line. Moreover, an excited atom sometimes can find itself trapped in an energy state from which a downward transition is unlikely. The atom can linger in this so-called metastable state for microseconds or even milliseconds before decaying to a lower energy level.

The existence of metastable states can upset the thermodynamic equilibrium that normally prevails in atomic systems. If enough electrons get hung up in a metastable state, the population of atoms in this state could exceed the population of atoms in a lower energy state. If this happens, the atoms are said to be in a condition of population inversion, which is thermodynamically unstable (see Fig. 2).

In a sense, population inversion is an avalanche waiting to happen. When more energy is stored within the atoms at a higher state than at a lower one, the capacity for gain exists. In fact, lasers, which are light amplifiers, depend on population inversion for their gain. All that's needed is some kind of stimulus to set the downward transitions in motion.

Ironically, Einstein uncovered the stimulus for lasers some 40 years before Arthur Schawlow

and Charles Townes described how it could be put to use in the optical regime. Until 1917, stimulated absorption and spontaneous emission were the only modes known for energy transitions within an atom. But in that year, Einstein offered a powerful thermodynamic argument for a third kind of transition-stimulated emission.

Unlike spontaneous emission, in which an electron randomly decays to a lower energy level and gives off a photon in the process, stimulated emission is neither spontaneous nor random (see Fig. 3). With stimulated emission, an electron is induced to decay by a photon that has the same energy as the transition energy of the electron. When the electron encounters such a photon, it immediately decays and generates another photon with exactly the same energy as the photon that triggered the downward transition. As a result, not only do the two photons have the same energy, frequency, and wavelength, they are headed in the same direction and have the same polarization and phase.
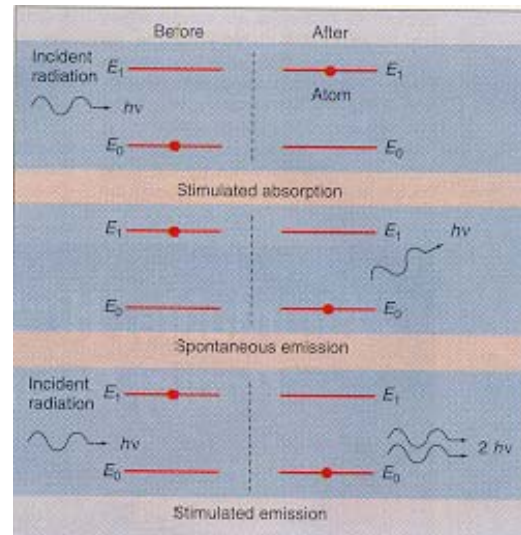

Figure 3. Stimulated absorption form a photon destroys the photon (top), spontaneous emission creates a random photon (middle), and stimulated emission creates a photon identical to the stimulating photon (bottom).

Armed with the concept of stimulated emission, we can sketch a simple picture of how a laser functions at the quantum level. First we must somehow attain a population inversion in the atoms of our laser medium. This requires enough energy to pump more atoms into the metastable state than there are in the lower energy state. How much energy this takes depends on the medium. Once we achieve population inversion, however, the spontaneous decay of electrons from the metastable level will create photons with just the right energy to cause an avalanche of stimulated emission.

Left to its own devices, the medium becomes a super-radiant mixture of spontaneous and stimulated emissions, but it is not a laser in the customary sense of the word because the light radiates in all directions. Nevertheless, the medium will have a small gain while the population inversion persists, and the radiation will have laser-like qualifies. But if the radiation can be partly contained with optics, then stimulated emission will be extracted from the medium much more efficiently. One of the most effective ways to contain the radiation is to place the laser medium inside a Fabry-Perot interferometer (see Fig. 4).

The Fabry-Perot consists of two parallel mirrors placed some distance apart. Some of the light trapped inside this optical cavity will experience multiple reflections as it bounces back and forth between the two mirror surfaces. In fact, monochromatic light traveling perpendicu-
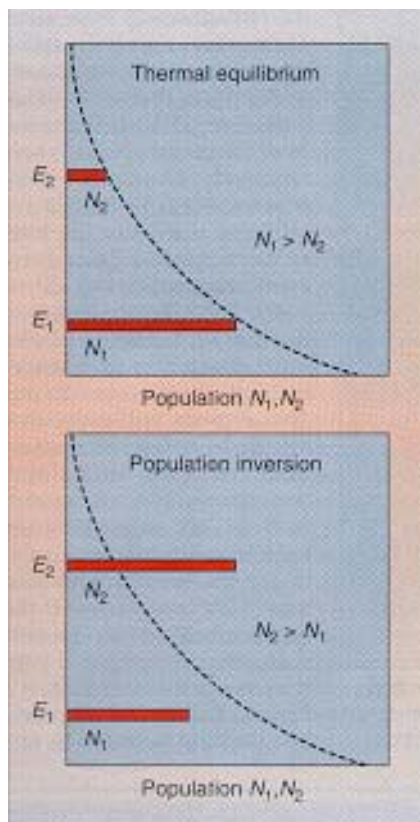

Figure 2. At thermal equilibrium, Boltzmann statistics predict that the population of atoms in a lower-energy state (E_1) will exceed the population in a higher-energy state $(E_2,$ top); population inversion turns this relation on its head (bottom).

lar to the mirror surfaces will form a standing wave if the distance between the mirrors is an integral number of half-wavelengths (see March's Back to Basics). In this condition the light is said to be resonant with the cavity.

The resonant condition transforms the interferometer into a highly selective filter-how selective depends on the reflectivities of the mirrors. At resonant wavelengths, the reflectivity inside the cavity can be very high, creating an excellent feedback environment for the laser gain medium. Because a portion of the spontaneous and stimulated light inside the cavity passes back and forth through the medium, the medium is effectively stretched to many times its actual length. And with each pass, more photons are stimulated into existence.

If the population inversion is high enough to overcome all of the energy loss inside the cavity, the so-called threshold condition will be met and lasing will begin. To couple light out of the laser cavity, one mirror is usually made partially reflective; a small hole in an otherwise totally reflective mirror also will suffice. Because laser light consists mostly of the stimulated emission generated with each pass through the gain medium, it is coherent and highly directional.

Unlike the light from conventional sources, such as incandescent lamps or gas discharges, laser light is exceptionally monochromatic. A HeNe laser, for example, is about 10 million times more monochromatic than the 589.6-nm emission line of a sodium-vapor discharge lamp. And because lasers are amplified light sources, their intensities can reach levels many orders of magnitude greater than the sun.

The light from most lasers also diverges very slowly as it propagates through space, a result of its monochromaticity and the multipass cavity design. But what really sets laser light apart from other radiation (and what contributes to some of the qualities just mentioned) is the high degree of
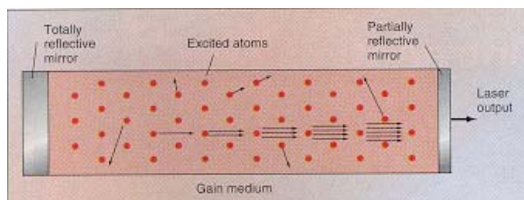

Figure 4. Placing a laser medium in an optical cavity formed by two parallel mirrors (Fabry-Perot) effectively stretches the medium to many times its actual length and creates a feedback environment for efficient amplification of the stimulated emission.

phase correlation across the wavefront and in time, defined as spatial coherence and temporal coherence, respectively. This means the crests and troughs of the individual wave trains stay in step with each other across the beam and for an extended interval of time.

These unique properties make the laser an indispensable tool for research, medicine, industry, and communications. Since Theodore Maiman's first successful laser in 1960, laser action has been observed in virtually every form of matter: liquids, gases, solids, and even gelatin, such as Schawlow's whimsical "edible" laser. It's been said that even a telephone pole will lase if you pump it hard enough.

Some of the most successful laser designs to evolve from all this research include gas lasers such as He-Ne, CO_2, argon-ion, and HeCd; solid-state lasers such as ruby, Nd:YAG, and Nd:YLF; tunable solid-state lasers such as Ti:sapphire and Alexandrite; semiconductor lasers such as AlGaAs, InAlGaAs, DFBs, VCSELs, and quantum-wells; and liquid dye lasers. All of these laser types incorporate an astounding mix of science and technology. A peek at the internal workings of the HeNe laser reveals just how diverse and intricate the physics of light emission can be.

PARADIGM LASER

The HeNe gas laser has a surprisingly complicated set of circumstances responsible for its stimulated emission (see photo on p.127). Basically, the laser medium consists of a narrow discharge tube filled with a helium-neon gas mixture. The typical concentration ratio is 10 atoms of helium for every atom of neon. As with the neon tubes used for advertising, an electrical discharge excites the gases, but the similarity ends there.

Much of the energy of the free electrons created by the discharge is absorbed by collisions with the more numerous helium atoms (see Fig. 5). These collisions, called resonance collisions, pump the helium atoms into a metastable energy state *(1s2s)*. The energy of this state happens to be nearly identical to a metastable state of neon *($2p^55s$)*. Through resonance collisions between the excited helium atoms and ground state neon atoms, the helium gives up its energy to the neon, raising it to its metastable state. From this long-lived ($\approx$100 ns) energy state, stimulated transitions to a short-lived ($\approx$10 ns) lower-energy state *(2p53p)* will generate laser light at 632.8 nm

once sufficient population inversion is achieved between two states.

Neon atoms in the lower energy state, called the terminal laser level, quickly decay to an even lower energy state ($2p^53s$), from which they promptly decay back to the ground state, from which the process can start all over again.
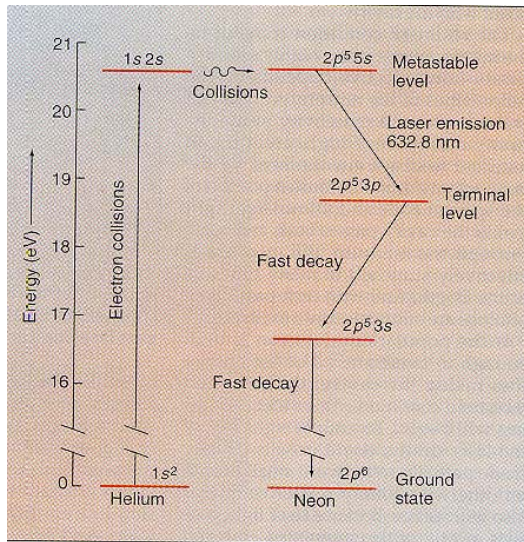

Figure 5. Simplified energy-level diagram of a HeNe laser operating at 632.8 nm shows how neon atoms (right) reach metastable level through a complicated series of resonance collisions involving helium atoms (left). The stimulated downward transition from the metastable level to the terminal level in neon generates the laser light. The notation indicates which orbitals take part in the process. The $2p^53p$ and $2p^53s$ orbitals have fast decay times, which facilitates population inversion in the longer-lived metastable orbital.

The HeNe laser neatly illustrates one way of creating laser light. There are dozens of other methods. But whatever the approach, the basic prerequisites for laser light are the presence of a metastable state, some mechanism for pumping atoms into the metastable state, a population inversion of atoms in the metastable state, stimulated emission, and some kind of optical feedback to enhance the stimulated emission and control its output. Without all five of these conditions, a laser would be just another flashlight and electro-optics would be just another branch of optics.

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