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MASERS, LASERS, and ATOMIC RESONANCE

Remarkable new developments in the field of physical research have opened the way for greatly improved communications. Dramatic advances have been made in overcoming noise, and recent discoveries are making vast new areas of bandwidth available for communication—more bandwidth, in fact, than now used by all communications services put together. These accomplishments are made possible by radio-frequency and optical masers—the subjects of this article.

The real limits of good communication are set by *noise,* which interferes, and by the availability of *bandwidth* which can overcome noise and allow greater flow of information. The demands for more and better communication are so insistent that the radio spectrum is becoming increasingly jammed, even though it has multiplied more than 200 times in the last 20 years. The many new types of communication, and the growing complexity of human affairs are increasing this load at an ever-growing rate. For this reason, any new techniques which reduce noise or which make more bandwidth available are extremely important.

Such a technique is *MASER,* an acronym for *M*icrowave *A*mplification by *S*timulated *E*mission of *R*adiation. Maser amplifiers have the remarkable power of virtually eliminating thermal noise generated in the first stage of a radio receiver—the area which sets the limit of radio sensitivity. When masers are used, receiver sensitivity may be great enough to detect and measure the thermal noise radiated by distant objects. The maser principle has been extended to optical frequencies with outstanding success. The first man-made phase-coherent light has clearly demonstrated the possibility of efficiently using the tremendous bandwidth of light for communication.

An entirely new principle is employed in masers. Conventional amplifiers—electron tubes and transistors—amplify by using a weak input signal to control a much larger flow of current supplied locally. Since electrical current consists of countless electrons streaming through the circuit, a background of noise is built up by the random irregularities and collisions in the electron stream. The maser avoids this source of noise by amplifying not a flow of electrons, but an electromagnetic wave itself.

How Does It Work?

The maser's unique method of amplification is based on storing energy in the atoms or molecules of the maser material itself, then releasing it in a controlled fashion at the desired frequency. In effect, the maser behaves like a resonator which is able to store energy and release it in a new form on command.

All matter consists of atoms made up of a heavy nucleus surrounded by electrons. Under normal conditions, enough electrons surround the nucleus to neutralize its charge. (Although atomic electrons are believed to lie in concentric shells around the nucleus, like the layers of an onion, they are usually represented as occupying ring-like orbits.) It is important to note that the distance of each orbit from the nucleus represents the specific amount of energy possessed by the electrons. The closer the electron orbit to the nucleus, the lower the electron energy level.

An extremely important characteristic of matter is that the energy level of orbiting electrons can only assume certain specific values—like the rungs of a ladder. Any electron lying in a given orbit must possess a certain definite amount of energy—no more, no less. If enough energy is applied to the electron to raise it from one level to another, it will absorb exactly the amount of energy required for the jump, but no more. It is possible, of course, for an electron to absorb enough energy to jump several levels, rather than just one. Since nature always attempts to go "down hill," the excited electrons tend to return to their lowest energy level or "ground state." When an electron drops to a lower energy level, a *photon* of radiant energy is released, and the energy content of the photon is exactly equiva-

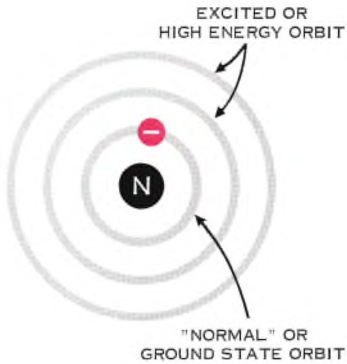


Figure 1. Atomic electrons normally occupy orbit around nucleus representing lowest energy level. When stimulated, electrons can only absorb the exact amount of energy representing a specific orbit. No intermediate values are possible.

lent to the energy previously absorbed by the electron as it jumped to the higher energy state.

Although the photon is a fundamental unit of radiation, different photons have different energy content, and this shows up as differences in wavelength. Thus, high-energy photons may appear as X-rays or ultraviolet radiation, while lower-energy photons might result in visible light of any color, radiant heat, or radio waves.

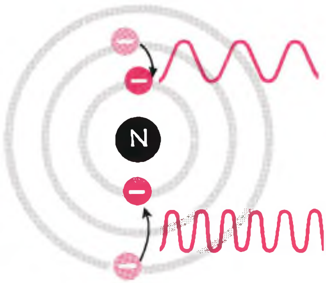


Figure 2. Excited atoms tend to return to lower energy level, but may require external stimulation to do so. Stored energy is released as a single photon or energy packet having characteristic frequency.

The exact amount of energy absorbed or emitted by an electron in jumping from one energy level to another is different in each material and for each combination of electron rings. Thus, an electron will emit radiation of one wavelength in going from the second to the first ring in a substance, and a second wavelength when dropping from the third to the second ring. In addition, a third wavelength will be produced if the electron drops from the third to the first ring.

It is interesting to note that the light from the familiar "neon" signs occurs in this way. Molecules of gas are excited to upper energy states by the high voltage. As the excited and ionized gas molecules drop back to their ground state, they emit light of characteristic color. By using various gases, different colors are produced. The yellow-orange light of sodium vapor lamps, and the bluish-green from mercury vapor lamps is also produced in this fashion. Although light from such sources is much more nearly monochromatic than incandescent light, it usually consists of two or more colors or spectral lines because of the many different energy state transitions which contribute to the light output.

Atomic Amplification

The basic principles of atomic behavior described above also apply to molecules. Like atoms, molecules are capable of assuming a number of specific energy levels, and this fact was used to obtain the first maser-type amplification in 1954. The ammonia molecule exhibits two distinct energy states, the lower of which is normally more heavily "populated" than the upper. That is, more molecules will normally be found in the lower energy state than in the higher. In ammonia, the two states can be separated electrostatically, thus providing a way of discarding low-energy molecules and concentrating the high-energy molecules in a resonator. When a weak 24,000-mc signal was used to irradiate the high-energy ammonia vapor, the molecules "flipped" to their low energy state, releasing photons of additional 24-kmc energy which reinforced and amplified the input signal. By feeding some of the 24-kmc output back into the system, continuous oscillations of unprecedented stability were obtained. In fact, the ammonia maser was found to be such a stable oscillator that a clock regulated by its output frequency would vary less than a single second in several centuries!

The ammonia maser is not suitable as a communications carrier, however. The inherent bandwidth of the device is only about that of a single voice channel, and it cannot be tuned or varied in frequency conveniently.

In answer to these shortcomings, a different type of maser was developed, using solid-state materials. These masers are broadband, tunable, and can be designed for almost any UHF or microwave band. In order to tune the atomic resonance, a crystalline substance is used in which small amounts of impurity ("doping") substances replace some of the host atoms of the crystal lattice. A doping material is chosen which has unpaired electrons in one or more of the inner rings. This refers to the fact that orbital electrons behave like spinning magnets, and normally occur in pairs in which the two members have opposite spin directions. Because the paired electrons oppose each other, they will not respond to a magnetic field. When the doping material has unpaired electrons, however, these can be "lined up" in a magnetic field. These electrons can then achieve higher energy states by overcoming the magnetic field and "reversing direction." When "triggered" by suitable stimulation, the electron snaps back to its low-energy alignment and emits a photon of its characteristic wavelength. Under these conditions, the amount of energy required to make a transition from one energy state to another can be varied continuously by changing the strength of the magnetic field. The greater the magnetic field, the higher the output frequency. This is analogous to the tone produced by a stringed instrument. The greater the tension on the string, the higher the

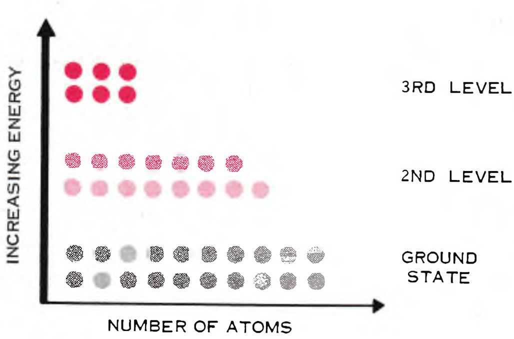


Figure 3. Normally, all energy levels are "populated" by thermal agitation, which causes downward as well as upward jumps. Cooling reduces such activity. When low-energy population predominates, material ab-absorbs rather than amplifies.

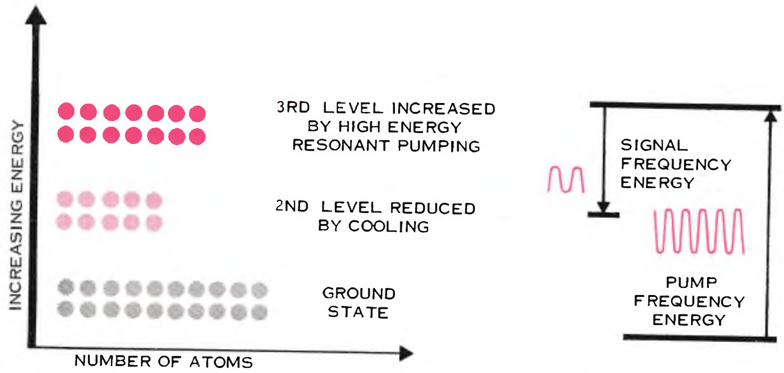


Figure 4. In 3-level maser, atoms are continuously pumped to third level, skipping second level because of atom's resonant response to high pump frequency. Second level is further reduced by cooling, thus creating greater population in third level than in second. Signals of a frequency equivalent to energy difference between the two levels will trigger downward shifts, thus amplifying signals.

note produced. Although the string is resonant at one specific frequency, and can be stimulated most readily by that frequency, other frequencies can also cause it to produce its own characteristic tone.

For much the same reason, masers usually must be operated at very low temperatures. At normal temperatures, the thermal agitation in the maser material stimulates downward transitions randomly, thus reducing the number of high-energy electrons available for amplifying the input signal. If there are more electrons in the ground state than in the high-energy states, the maser will actually attenuate the signal rather than amplify. For this reason, present-day radio-frequency masers require the chill of liquid helium or liquid nitrogen for operation. At these temperatures the material is so still that few downward transitions occur except when stimulated by the desired signal.

In order for a maser to operate continuously, it is necessary to find some way of pumping electrons from the ground state up to the higher energy levels without interfering with the microwave amplification. This can be achieved as diagrammed in Figure 4. Some material is selected that has at least three energy levels. Since more energy is required to pump electrons up two levels than one, the maser material is irradiated with high frequency microwaves corresponding to the energy jump from the ground state to the *third* level. Since the electrons are sensitive to the energy level of wavelength of the excitation, most will go directly to the third level; very few of the electrons will be pumped to the second level, thus leaving it relatively empty. As a result, there will be more electrons at the third level than at the second, and amplification of the microwave frequency represented by the energy difference of the two states is possible. When a signal corresponding to the energy difference between levels two and three is received, it triggers downward jumps, and the released energy reinforces the input signal.

Communicating with Light

The maser's recent accomplishments are not limited to the reduction of radio noise, but also include the first significant breakthrough in making the optical spectrum available for efficient communications. The bandwidth available in the visible or white-light portion of the spectrum alone is tremendous — 250 *million* megacycles! This bandwidth has been wasted for communications purposes heretofore because there has been no way to use it efficiently. Even the very best optical filters have passbands equal to hundreds of thousands of megacycles. Any attempt to restrict the bandwidth of an optical signal by filtering reduces the power of the signal tremendously, since most light sources distribute their output over an extremely broad spectrum, but have very little power in any narrow portion of the spectrum.

By contrast, optical masers concentrate their entire power output into extremely *narrow* portions of the spectrum. An optical maser recently demonstrated by Bell Laboratories is said to produce light having a spectral width of less than one kilocycle at a carrier frequency of 100,000 megacycles. The intensity of light from such a maser may be millions of times greater than that from the sun itself, for a comparable bandwidth.

Two types of optical maser have been demonstrated to date. One type consists of a pink ruby cylinder, the ends of which are ground parallel and polished optically flat. Each of the polished ends is silvered, one completely and the other only partially, so as to reflect about 98% of the light striking it. (Pink ruby-crystalline aluminum oxide doped with a small amount of chromium—is one of the substances that have proved so successful in radio masers.)

When the ruby is subjected to a very intense flash of light, unpaired electrons in the chromium ions are pumped up to higher energy levels. After a brief period, they drop to a relatively stable energy state, but still above the ground state. When stimulated by photons of the right frequency, the electrons drop to the ground state and emit photons which reinforce the stimulating light.

In the first instant of this process, the light within the maser travels in all directions. Light which happens to be traveling at some angle with respect to the axis of the maser is rapidly lost through the sides of the ruby cylinder, either immediately or after a very few reflections.

Those light rays, however, which travel exactly parallel to the axis of the cylinder are reflected back and forth between the two reflective ends of the cylinder. With each trip down the length of the maser they become progressively stronger as more and more high-energy electrons are stimulated to give up a photon of light at their own frequency.

From the end of the cylinder, which is slightly transparent, an intense beam

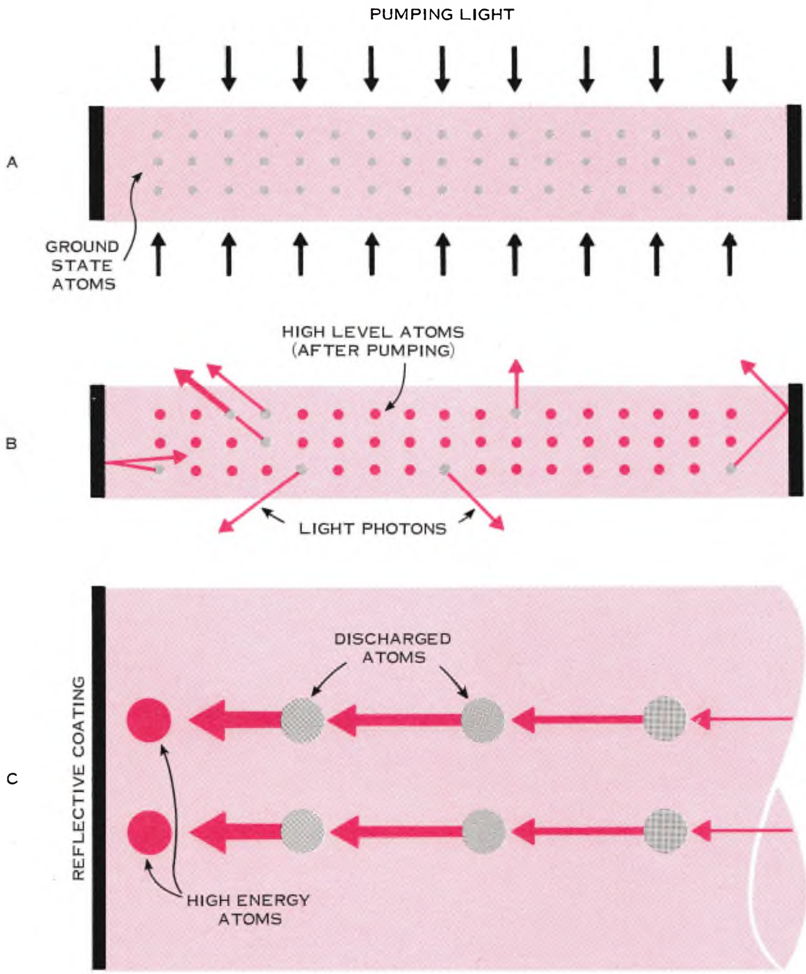
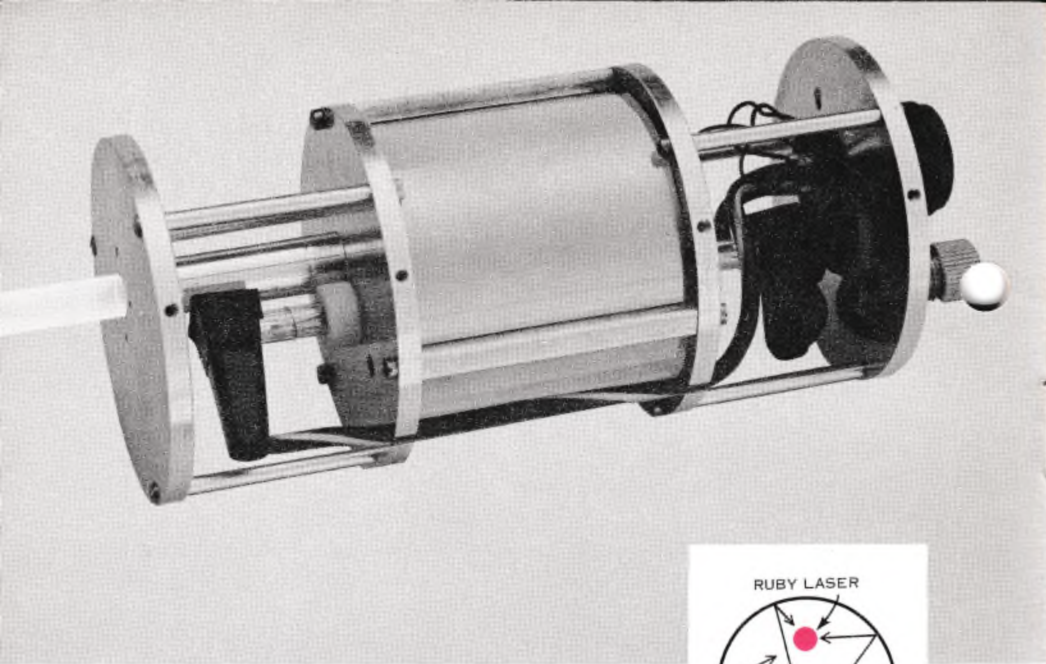


Figure 5. Stimulating light is absorbed in ruby laser (optical maser), thus exciting ions in crystal lattice to higher energy state (indicated by red). As some of these drop to lower energy state, they radiate characteristic infrared "light" which stimulates other ions, thus amplifying light. All such radiation escapes through side of laser except that which happens to be exactly parallel to axis of rod. These rays are "trapped" by reflective coatings at ends, and are greatly amplified by repeated trips through rod.

of light flashes. One might assume that the low transparency of the end coating would introduce considerable loss. This isn't so, however. The light that doesn't escape is reflected back through the maser material, gaining strength as it goes. Even though the light within the maser may make hundreds of thousands of



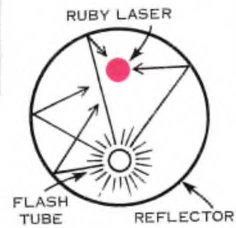


Figure 6. Practical laboratory laser encloses ruby rod and flash tube in highly reflective cylinder to concentrate light flash on ruby. Although cooling is not necessary to achieve laser action, it reduces amount of light required. Coherent infrared beam emerges from opening on left.

trips back and forth along its length, there is little loss, for the beam continues to be amplified as long as the input flash persists and keeps the electrons excited to a high-energy state.

Two factors in this process endow the radiation from an optical maser with unique properties; when the wavefront of light stimulates an electron to emit its photon, the photon *reinforces* the wavefront with no delay at all. As a result, the light traveling parallel to the axis of the cylinder becomes *phase coherent* because every atom that contributes to the wavefront is synchronized by the wavefront itself. In effect, a standing wave is set up within the maser by the light waves as they travel back and forth gathering intensity.

Another notable property of the light from the maser is that its beam is remarkably parallel. This results from the fact that the light is coherent, but also because only those rays which are exactly parallel to the axis of the cylinder can remain within it long enough to be amplified significantly. This is exactly what is achieved by using extremely large paraboloidal antennas in radio.

In conventional microwave practice, a paraboloidal antenna is used to gather the radio energy into a tight beam which can be directed at the distant receiving antenna. The narrower the beam, the more energy reaches the receiver, and the lower the loss in transmission. The shorter the wavelength of the radiated energy, for a given size antenna, the narrower the beam since

$$\textit{Beamwidth (radians)} = \frac{\textit{wavelength}}{\textit{aperture}}.$$

It is this relationship that permits low-power microwaves to be used for high-density radio communication. The optical maser betters this many thousands of times, however. For instance, microwave signals of 5900 mc have a wavelength of just about two inches. If these are concentrated by a reflector having a diameter of 100 feet, the resulting beamwidth will be 0.00166 radian or 0.96°. At the distance of the moon, this beam will spread out to a diameter of about 3700 miles. By contrast, the beamwidth already achieved by an optical maser was so narrow that its light would spread only about 50 miles at the distance of the moon! Thus, a tremendous potential for space and satellite communications is suggested.

The ruby *laser* (as the optical maser is more frequently called—*L*ight *A*mplification by . . .) is essentially a "one-shot" device which is currently most useful as a research tool. The intensity of light required to excite a sufficient number of chromium ions to higher energy levels is difficult to achieve on a continuous basis. In addition, cooling in liquid nitrogen is required for best operation. Nevertheless, during the short period of the pumping flash, the laser output achieves extremely high levels, and has been used for taking ultra-high-speed photographs at tremendous magnifications. The device has been used to demonstrate the possibilities for communication over a 25-mile cross-country path and through a two-mile waveguide. In addition, the laser has been teamed with a telescope to form an "optical radar" having much higher resolution than conventional radar.

Gas Lasers

Early this year, a continuously-operating laser was demonstrated which had at least 60 times the spectral line narrowing as the ruby laser. It is this ability to reduce the "spread" of frequencies of the unmodulated light beam that makes the laser of such great potential value to communications. The ideal oscillator, for instance, produces a pure sine wave which may be modulated with information. Ordinary incandescent light is inherently "noisy" since it originates in every atom or molecule of the source, each of which has its own frequency of emission. The solid-state laser improves on this tremendously, but still has a fairly diffused output, due to the interaction of the excited ions and the crystal lattice that suports them, and because of the violence of the energy pulse required to achieve laser action.

The gas laser operates in a somewhat different fashion than the ruby version. Instead of a solid crystal, rarified neon gas is used. Neon has several groups of energy levels, one of which is suitable for laser action. The problem is essentially one of pumping electrons to this upper level without also filling the steps below it at the same time, as would be the case if an ordinary low-frequency discharge were used, as in ordinary neon display signs.

A solution was achieved by mixing helium with the neon. Helium has an energy state approximately the same as the energy level in the neon that it was desired to fill, as shown in Figure 8. Furthermore, it was possible to excite the helium selectively—that is, without exciting the neon—by using a radio frequency of 28 mc. The excited helium atoms transfer their energy to the neon atoms at the desired level, leaving the neon suitably excited and ready for optical stimulation.

In dropping from the *2s* to the *2p* levels, the neon atoms give off photons in the infrared region around 12,000 Angstroms. After reaching the *2p* levels, the electrons rapidly decay to the *1s* level, giving off photons of the familiar reddish neon glow and leaving the *2p* level relatively empty. Thus, it is possible to keep the *2s* level more "populated" at all times than the *2p* level, thus permitting light amplification. As in the ruby laser, plates at each end of the container reflect the infrared radiation back and forth, allowing it to build up and become more coherent.

Applications

The output from the gas laser has provided the narrowest spectral lines so far achieved, and points the way toward opening up the optical spectrum for communication. So far, the only modulation that has been possible is to modulate its intensity with an external Kerr cell, thus providing the equivalent of amplitude modulation. As more materials are discovered in which laser action can be obtained, it may be possible to "beat" various optical frequencies together to obtain transmission at any desired operating frequency.

Already it has been proposed that lasers operating in the blue-green region might provide a superior means of detecting underseas objects, because of the ability of an intense laser beam of this color to penetrate water. In surface or space communication, the great power of a laser beam at a select fre-

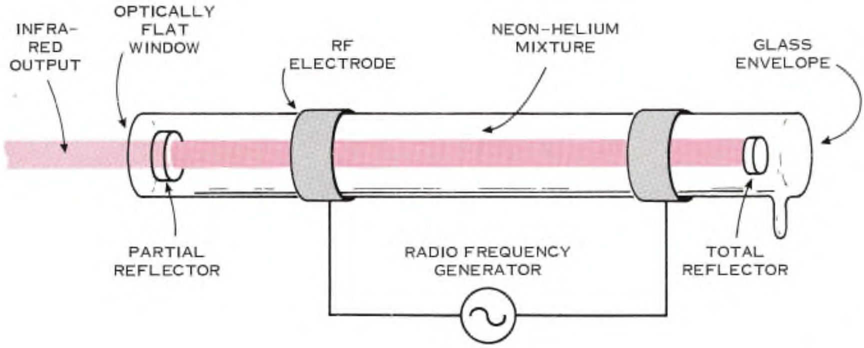
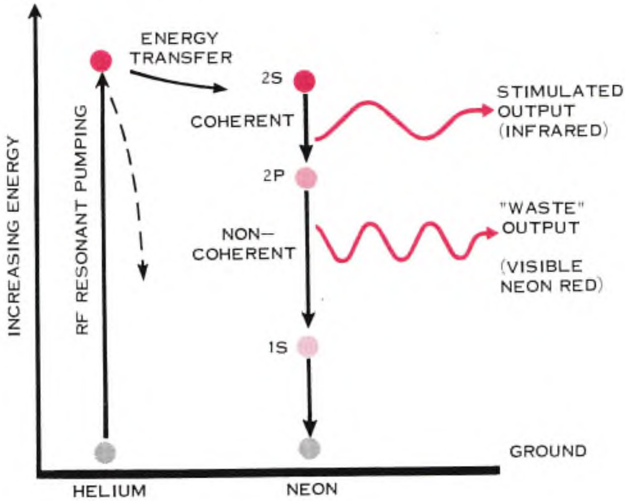


Figure 7. First continuous-action laser uses helium-neon mixture, radio excitation instead of light. As in ruby laser, reflective coatings at each end trap light, build it up. Output is sixty times more coherent than that obtained from solid lasers.

Figure 8. Helium atoms are excited to upper level by 28-mc radio frequency which has little effect on neon atoms due to atomic resonance. Energy is transferred to neon by random collisions. Atoms drop from 1s and 2p levels spontaneously.



quency indicates that there would be no problem of masking even by the brightest sunlight, since the maser's output is thousands of times brighter than the sun's surface for the same bandwidth. It would only be necessary to filter the detector so that power at other frequencies would not overload it.

This ability to concentrate large amounts of energy in narrow portions of the spectrum suggests many more uses outside the field of communications. Because of the extreme coherence of the beam, it is possible to focus it to a spot having a tremendous concentration of power. Power concentrations in excess of a million watts per square centimeter have already been demonstrated (in a small spot), and temperatures far in excess of any previously achieved outside of an atomic reaction appear easy to attain. Such temperatures should prove to be a powerful research tool, and might even permit nuclear reactions now limited to large and expensive facilities. ●

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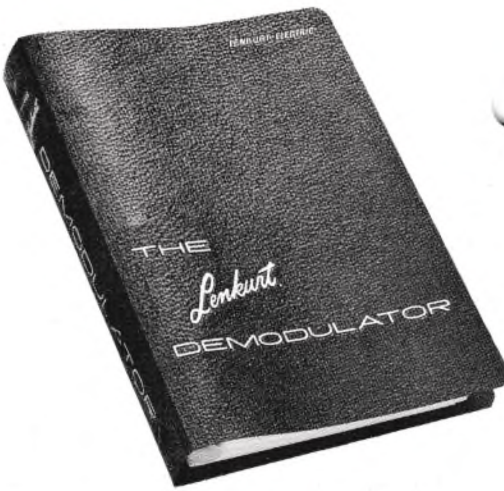

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