OPTICAL MASERS

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Optical Masers

These devices generate light in such a manner as to open up a whole new realm of applications for electromagnetic radiation. The salient feature of the light they produce is that its waves are all in step

by Arthur L. Schawlow

For at least half a century communications engineers have dreamed of having a device that would generate light waves as efficiently and precisely as radio waves can be generated. The contrast in purity between the electromagnetic waves emitted by an ordinary incandescent lamp and those emitted by a radio-wave generator could scarcely be greater. Radio waves from an electromagnetic oscillator are confined to a fairly narrow region of the electromagnetic spectrum and are so free from "noise" that they can be used for carrying signals. In contrast, all conventional light sources are essentially noise generators that are unsuited for anything more than the crudest signaling purposes. It is only within the last year, with the advent of the optical maser, that it has been possible to attain precise control of the generation of light waves.

Although optical masers are still very new, they have already provided enormously intense and sharply directed beams of light. These beams are much more monochromatic than those from other light sources; at their best optical masers rival the very finest electronic oscillators as a source of a single frequency. The development of optical masers is moving so rapidly that they should soon be ready for a wide variety of applications. These may range from space communications and radar to accelerating specific reactions in chemical technology.

To appreciate the limitations of light waves as they are ordinarily found, let us consider how they are produced. All light sources—incandescent lamps, arcs and so on—are essentially hot matter. In the familiar neon tube, it is true, the glass walls remain cool, but the electrons and gas atoms within the tube are accelerated to the high speeds normally associated with high temperatures. The atoms are continuously "pumped" to an excited state; then they fall back, losing energy and radiating visible light. They fall back, however, one atom at a time. The disorderly atomic motion we associate with a heated gas is paralleled by a disorderly outpouring of light quanta, or photons. Just which atoms radiate at any instant is purely a random affair. The excited electrons in the hot tungsten filament of an incandescent lamp also radiate randomly and independently.

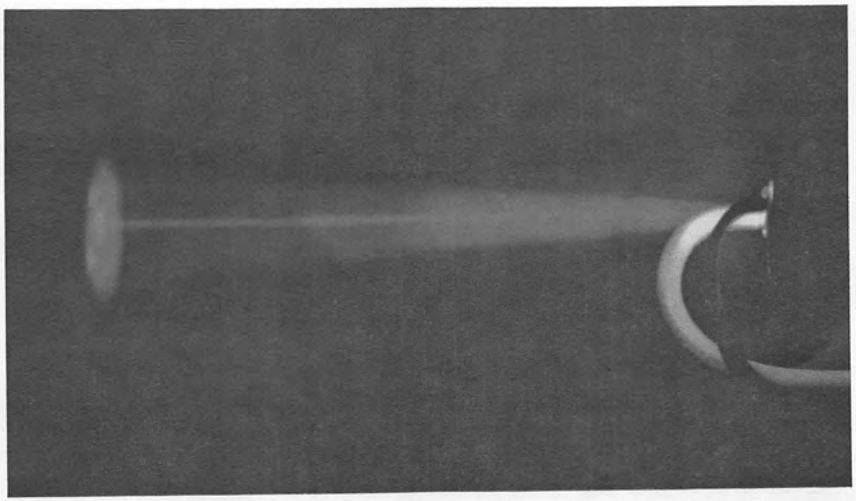
Thus the light that comes from any conventional light source is called spatially incoherent. This means that the light emerges in a jumble of tiny, separate waves that reinforce or cancel each other in random fashion; the wave front so produced varies from point to point and changes from instant to instant. The wave front resembles one that would be produced by throwing a handful of pebbles into a pool. If, on the other hand, only a single pebble were dropped into the pool, a coherent circular wave front would be produced. By the same token one can imagine a point source of light that could generate coherent waves whose fronts would form spherical surfaces. Alternatively, a suitable source might generate coherent light waves whose fronts were plane surfaces; at every point on the plane the strength of the electric field would be the same. As the wave fronts traveled past a given point in space, the field strength would be seen to rise and fall smoothly and rhythmically in phase, swinging from positive to negative in value.

If a conventional electronic oscillator that produces radio waves is connected to a small radiator of suitable design, the radiator will send out spherical coherent waves. If one wishes, the oscillator can be connected to feed a number of radiating antennas that will send out a directional wave, much like a plane wave.

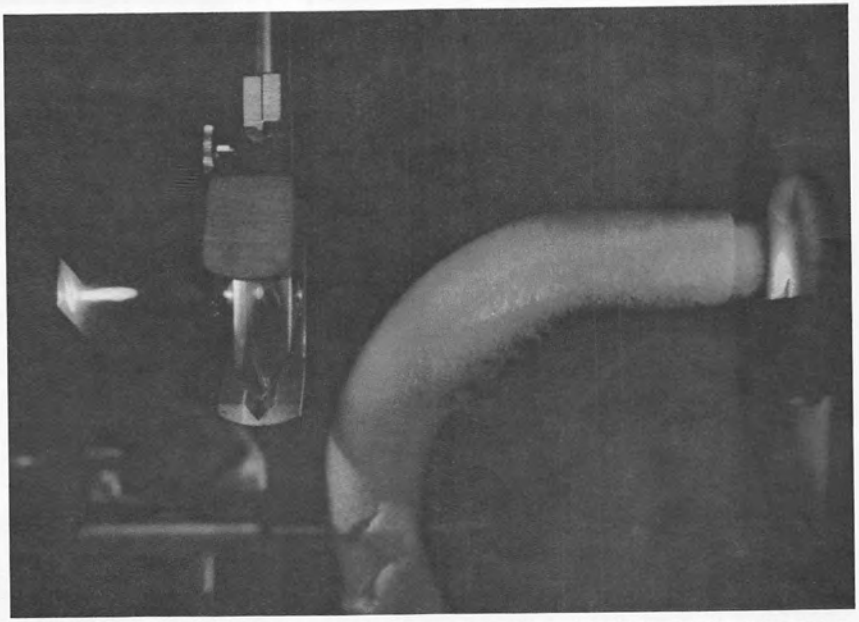
To obtain a directional wave from an incoherent light source one must start with a source of small dimensions. Then, by placing a screen with a hole in it some distance from the source, we can select the segment of the wave that happens to be going in the desired direction. Alternatively, the light emitted by a small source can be focused with a larger mirror or lens to yield a beam with sides that are roughly parallel. The sides of a beam produced by an arc lamp and a six-foot mirror diverge at an angle of about one degree. As we shall see, the output of an optical maser is both more directional and more coherent.

Perhaps the most important limitation of ordinary light sources is their inherent low brightness. No matter how high their temperature, they cannot emit more energy than a perfect radiator. The theoretical output of a perfect radiator, called a black body, is given by the famous black-body radiation curve first derived by Max Planck. The visible surface of the sun, for example, behaves much like a black body with a temperature of 6,000 degrees centigrade. The sun's total radiation, at all wavelengths, is seven kilowatts per square centimeter of its surface, and no matter how we collect and concentrate sunlight it is impossible to achieve any greater radiation density.

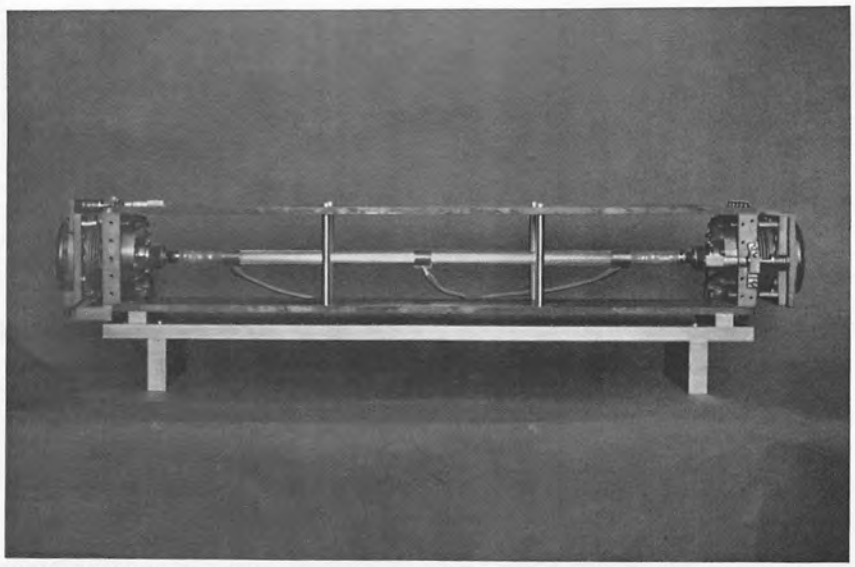
Although seven kilowatts may seem a substantial amount of energy, it is really not very much if one considers the tremendous width of the solar spectrum. To bring this point home let us compare the width of the visible portion of the electromagnetic spectrum with the width of a standard television channel, which is four megacycles. A little calculation



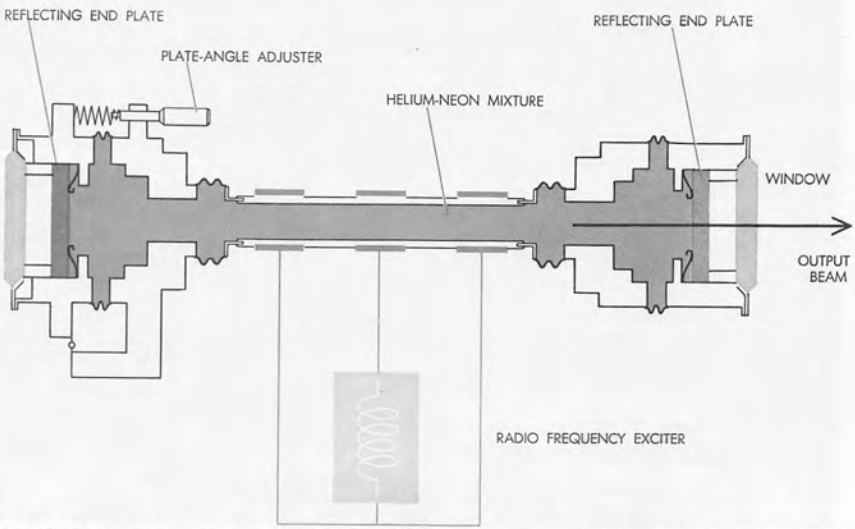
BEAM FROM RUBY OPTICAL MASER makes a thin streak of red light as it passes through smoke. Upper end of curved cooling tube at right is attached to front end of the maser housing, which here cannot be seen. The ruby crystal is mounted in the housing.



BRILLIANT BLUE-WHITE FLAME at left is incandescent carbon vapor produced by focusing a ruby-maser beam on a carbon target. The beam heated a spot on the target to about 8,000 degrees centigrade in .0005 second. The large curved object to the right is the same cooling tube seen in the photograph at top. The small lens used to focus the beam is mounted at the left of the tube.



GAS OPTICAL MASER employs a helium-neon mixture to produce an infrared beam. Reddish glow results from gas discharge of mixture. The gas maser, designed by Ali Javan, W. R. Bennett, Jr., and D. R. Herriott, was the first to operate continuously.



OPERATION OF GAS MASER depends on right mixture of helium and neon gases to provide an active medium. Radio frequency exciter puts energy into the medium. The output beam is built up by repeated passes back and forth between reflecting end plates.

shows that the visible region between the wavelengths of 4,000 and 7,000 angstrom units could contain 80 million television channels. In other words, each angstrom unit is about 100,000 megacycles wide. If one were able to filter out a narrow band of green light one megacycle wide from the region where the sun has its peak energy output (4,800 angstrom units), one would find that each square centimeter of solar surface produces only .00001 watt. To obtain as much as a single watt of green light one megacycle wide one would have to collect and filter the output from 10 square yards of solar surface. In contrast, man-made transmitters operating in the television region of the radio spectrum can easily generate 10,000 watts in a band much less than one megacycle wide.

Ordinary light sources are like the sun: they are broad-band noise generators that spread their output over a wide range of frequencies without supplying much power at any particular frequency. Even gas-discharge lamps, which emit light at a restricted number of narrow lines in the spectrum, do not approach the best electronic oscillators as sources of power at a single frequency.

There has been, of course, a great effort to extend electronic oscillators to shorter wavelengths. The length of the shortest waves that can be generated by electronic means is about one millimeter, or 10 million angstrom units. Any attempt to reach shorter wavelengths with conventional electronic designs meets with formidable difficulties. Foremost among these is the difficulty of fabricating the resonant structures that tune the oscillator. These structures can seldom be much larger than a wavelength in size. At millimeter wavelengths they are already so small that they are hard to make with uniform accuracy. To produce optical wavelengths, which are three orders of magnitude shorter, a radically different approach is needed.

An attractive solution to the problem would be to stop trying to build these tiny resonators and to replace them by atomic or molecular resonators. Nature has provided us with a wide variety of such resonators through the entire infrared, visible and ultraviolet spectrum. Indeed, engineers are accustomed to using atomic oscillators in gas-discharge lamps. A single atom, however, radiates very little power, and that only intermittently. What is needed is some way to synchronize a large number of atoms so that they can work together to produce a powerful, coherent wave.

Such an approach has been made possible by the maser principle, discovered by Charles H. Townes at Columbia University [see "The Maser," by James P. Gordon; SCIENTIFIC AMERICAN, December, 1958]. Maser stands for "microwave amplification by stimulated emission of radiation." The original maser, completed in 1954 by James P. Gordon, H. J. Zeiger and Townes, used the vibrations of ammonia molecules to provide microwave oscillations of precisely determined frequency. Subsequently Nicolaas Bloembergen of Harvard University indicated a practical way to build the so-called three-level solid-state maser for use as a low-noise microwave amplifier. The first maser of this type was built at the Bell Telephone Laboratories by George Feher, H. E. D. Scovil and H. Seidel, and since then many others have been constructed. Radio astronomers have found them extremely valuable for amplifying very faint radio signals from space. Last year masers were also used to amplify the weak signals received on the bounce from the *Echo* satellite.

Stimulated emission, which is the basis of maser operation, is the reverse of the process in which electromagnetic waves, or photons, are absorbed by atomic systems. When a photon is absorbed by an atom, the energy of the photon is converted to internal energy of the atom. The atom is then raised to an "excited" quantum state. Later it may radiate this energy spontaneously, emitting a photon and reverting to the "ground" state or to some state in between. During the period in which the atom is still excited it can be stimulated to emit a photon if it is struck by an outside photon having precisely the energy of the one that would otherwise be emitted spontaneously. As a result the incoming photon, or wave, is augmented by the one given up by the excited atom. More important and more remarkable, the wave, upon release, falls precisely in phase with the wave that triggered its release. This phenomenon lies at the heart of the maser principle [*see illustration on following page*].

The problem in designing a maser is to prepare an "active medium" in which most of the atoms can be placed in an excited state, so that an electromagnetic wave of the right frequency passing through them will stimulate a cascade of photons. There must be an excess of excited atoms to enable stimulated emission to predominate over absorption. Atoms are raised to an excited state by injecting into the system electromagnetic energy at a wavelength different from the stimulating wavelength; the activating process is called "pumping."

Once an active medium has been prepared it can be enclosed in a reflecting box, or cavity resonator. Then a wave that starts out at one wall of the box will grow in amplitude until it reaches another wall, where it will be reflected back into the mass of excited atoms. Inevitably there are losses at the walls due to imperfect reflection. If the amplification by stimulated emission is great enough to make up for these reflection losses, a steady wave will build up in the box. At centimeter wavelengths it is not difficult to build a box having the dimensions of a wavelength and so designed that the wave will build up with only one mode of oscillation. A single mode of oscillation corresponds to a single frequency of output; extraneous modes create extra frequencies, or noise, and compete with the desired mode in extracting energy from the supply of excited atoms.

At optical wavelengths a single-wavelength resonator would have dimensions inconveniently small. To surmount this problem, Townes and the author proposed in 1958 that a maser for optical wavelengths could be built by making a special kind of resonator with dimensions thousands of times greater than the emission wavelength but which nevertheless would favor a particular mode of oscillation. In the optical maser the reflecting box is replaced by a device or structure with two small mirrors facing each other. A wave that starts out near one mirror and travels along the axis of the system will grow by stimulated emission until it reaches the other mirror. There it will be reflected back into the active medium so that growth can continue. If the gain on repeated passages is enough to make up for the losses at the mirrors, a steady wave will be built up. If one of the mirrors is semitransparent, a portion of the wave can escape through it, constituting the output of the maser.

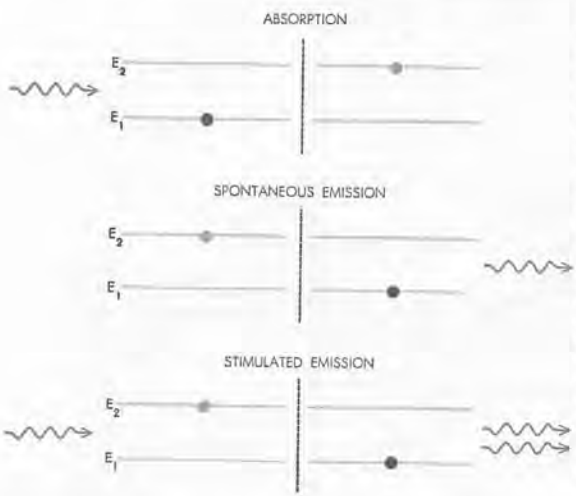
It is perhaps evident that a wave inclined at an angle to the axis will leave the system after only a few reflections, or perhaps without ever striking one of the mirrors. Such a wave will not have the same opportunity to build up as does a wave that travels straight along the axis of the system. Like other maser oscillators, the optical maser Townes and I described would be triggered off by the first photons to be emitted spontaneously after the system had been "pumped up" to the active state. (A maser designed to operate as an amplifier, on the

other hand, uses an input signal as a stimulating wave.)

We had every reason to expect that the output of an ideal optical maser constructed in this manner would be extremely directional, very powerful, essentially monochromatic and, above all, coherent. The output would be directional because the only waves emitted would have had to make repeated passages—perhaps thousands—without deviating very far from the axis of the maser. It would be very powerful because stimulated emission forces excited atoms to radiate much earlier than they would spontaneously. It would be very monochromatic because stimulated emission is a resonant process and takes place most strongly at the center of the band of frequencies that can be emitted in spontaneous radiation. These favored frequencies will in turn cause emission at the same frequency, so that the wave built up in the maser will contain only an extremely narrow range of frequencies or wavelengths.

Finally, the output of the optical maser, if it is a good approximation of a plane wave traveling in a single direction, will be spatially coherent because all the wave fronts are planes perpendicular to the direction of propagation. Since the maser output is nearly monochromatic, it also has time coherence. This means that there is a fixed phase relation between the portion of the wave emitted at one instant and the wave emitted after a fixed time interval. For a wave whose period is one second, crests follow each other at one-second intervals. On the other hand, if the frequency varies, the interval between crests is irregular. The more nearly the wave holds to a single, fixed frequency, the more nearly it exhibits time coherence.

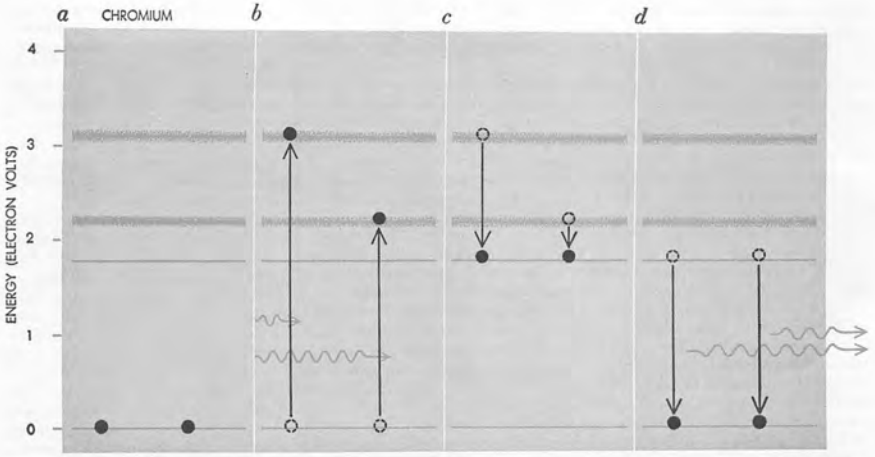
Testing these predictions required preparation of an active medium that would actually display maser action in the optical region of the spectrum. The first announcement of success was made last July by T. H. Maiman of the Hughes Aircraft Company, whose device used a ruby crystal. Between July and the end of 1960 four other substances were tested successfully by various investigators. These devices all embodied the concept of reflecting end walls, described above. At last count optical maser oscillations had been obtained at 11 different wavelengths. It seems likely that these wavelengths will soon be joined by many others.



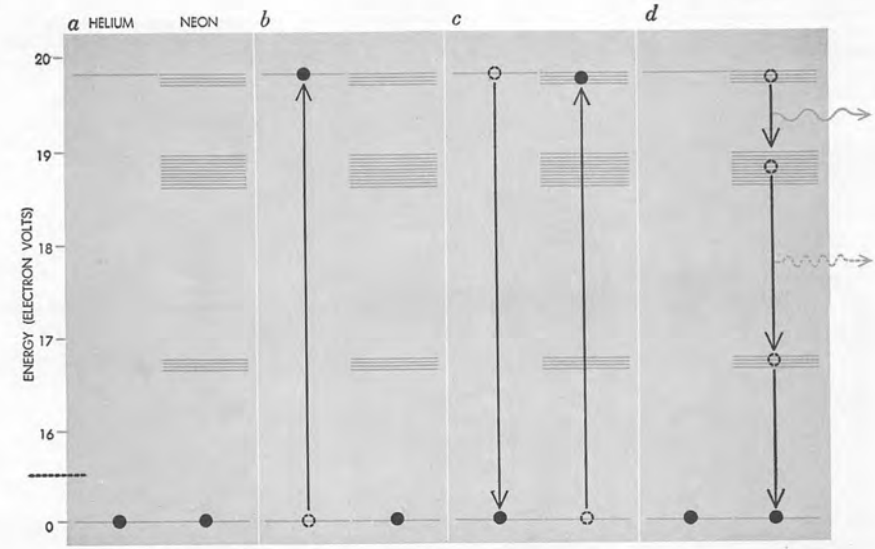
STIMULATED EMISSION of photons (*bottom*), the basis of maser operation, is contrasted with absorption (*top*) and spontaneous emission (*middle*). When an atom in the "ground" state (*black dot at top left*) absorbs a photon (*wavy colored arrow*), it is excited, or raised to a higher energy state (*gray dot at top right*). The excited atom (*middle left*) may then radiate energy spontaneously, emitting a photon and reverting to the ground state (*middle right*). An excited atom (*bottom left*) can also be stimulated to emit a photon when it is struck by an outside photon. Thus in addition to the stimulating photon there is now a second photon of the same wavelength (*bottom right*) and the atom reverts to the ground state.

Maiman's ruby maser is typical of those using crystals. Ruby is aluminum oxide in which a few of the aluminum atoms have been replaced by chromium atoms; the more chromium, the deeper the color. Maiman used a pale pink ruby containing about .05 per cent chromium. The color results from the fact that the chromium atoms in the crystal absorb a broad band of green and yellow light, along with ultraviolet light, and let only the red and blue pass through. Moreover, the light that is absorbed raises the chromium atoms to an excited state from which two steps are required to carry them back to the ground state. In the first step they give up some of their energy to the crystal lattice and land temporarily in what is called a metastable state. If they are not subjected to stimulation, their stay at this level lasts a few milliseconds while they drop at random to the ground state. Photons emitted during this final drop have a wavelength (at room temperature) of 6,943 angstrom units, which accounts for the characteristic red fluorescence of ruby crystals. In an optical maser, however, the first few photons released at this wavelength stimulate the still excited chromium atoms to give up photons and tumble to the ground state much sooner than they would normally; the result is a cascade of photons all at the 6,943-angstrom wavelength.

For use in an optical maser the pink ruby is machined into a rod about four centimeters long and half a centimeter across. Its ends are polished optically flat and parallel and are partially silvered. The rod is placed near an electronic flash tube that provides broadband pumping light. What Maiman discovered before anyone else is that the most powerful of these lamps, when connected to a large power supply, is capable of raising most of the chromium atoms to the excited state. Up to a certain critical flash intensity, all that happens is that the ruby emits a burst of its typical red fluorescence spread over the usual decay period for the excited atoms. But above a critical level maser action takes over, and an intense red beam, lasting for about half a thousandth of a second, flashes out from the partially silvered ends of the rod. This shows that a



CHROMIUM ATOMS (*black dots*) in a ruby maser crystal are "pumped" to higher energy levels and then stimulated to emit photons, producing a maser beam. Atoms in the ground state (*a*) absorb photons (*wavy colored arrows*), which pump them to one of two energy "bands" (*b*). The atoms give up some of their energy to the crystal lattice and fall to a metastable energy level (*c*). When stimulated by photons from other chromium atoms, they emit photons of a characteristic wavelength and fall to ground state (*d*).



HELIUM AND NEON ATOMS (*black dots*) constitute the active medium of the gas maser. At the start both are in the ground state (*a*). Electron bombardment pumps helium to a higher energy level (*b*). When helium and neon atoms collide, the helium loses its energy to the neon, which is raised to one of four distinct energy levels (*c*). When stimulated by an outside photon, the neon contributes a photon (*wavy colored arrow at top in "d"*) to the maser beam and falls to one of 10 energy levels. The neon then reverts to the ground state in steps; the photon emitted in the first step (*wavy broken arrow*) does not contribute to the maser beam.

sufficient excess of atoms has been pumped up to the excited state to make up for the losses at the ends.

In 1959 the author had predicted that it should be possible to build an optical maser using a dark red ruby that contains about 10 times as much chromium as the pink ruby. It was predicted that at this higher concentration maser action would take place simultaneously at two different wavelengths—7,009 and 7,041 angstroms [*see illustration on opposite page*]. This mode of operation was recently demonstrated in a maser built by G. E. Devlin and the author, and in another built by I. Wieder and L. R. Sarles of Varian Associates. Still other solid optical masers, using samarium or uranium ions in a calcium fluoride crystal, have been constructed by P. P. Sorokin and M. J. Stevenson of the International Business Machines Research Laboratory. These masers oscillate at wavelengths of 7,080 and 25,000 angstroms respectively.

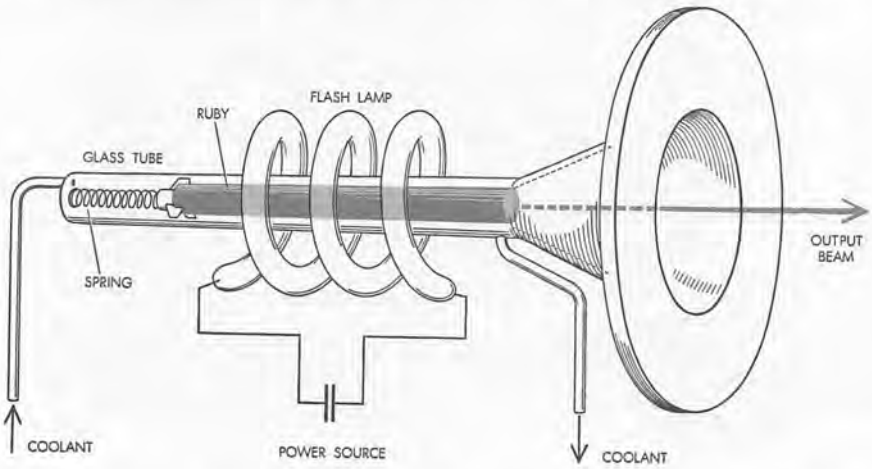
All these masers were first operated in short bursts, but they seem potentially capable of continuous operation. The active medium used by Maiman, however, is less well suited than the others in which the stimulated emission comes in a transition to an intermediate energy level that is some distance above the ground state. It is not necessary, therefore, to expend a lot of energy pumping half the atoms out of the ground state so that emission can predominate over absorption. In the newer materials the intermediate state—where the atoms land after emitting photons of the desired frequency—can be emptied simply by cooling. Hence the active medium contains very few atoms "tuned" to absorb the photons produced by maser action. Only enough pumping is needed for this action to begin.

A totally different way to obtain excited atoms for an optical maser employs gas atoms in an electric glow-discharge under very special conditions. In a mixture of helium and neon gas it is possible to secure maser oscillation at several wavelengths in the infrared region around 10,000 angstroms. This system was proposed in 1959 by Ali Javan of the Bell Telephone Laboratories. A successful prototype, constructed by him in collaboration with W. R. Bennett, Jr., and D. R. Herriott, was demonstrated early this year. The principal feature of this maser is its ability to operate continuously and with a very low energy input—about 50 watts in the first model.

In Javan's maser the stimulated emission occurs when a neon atom falls between two intermediate levels, the lower of which is well above the ground state. Only a modest input of energy is required to produce a gas discharge—essentially like that in an ordinary neon sign—and this in turn provides a continuous supply of neon atoms at the proper level of excitation needed to produce a continuous maser beam [*see illustrations on page 4*]. As in the ruby masers, the beam is built up and made coherent by bouncing back and forth between reflecting end plates.

The helium-neon maser exemplifies the increasing subtlety of maser designs. The energy needed to raise the neon atom to an excited state is not supplied directly by an incoming photon; it is supplied by collision with an excited helium atom. Many other possibilities remain to be explored. Energy levels suitable for masers may be found in many different kinds of system. For example, in the infrared region spectral lines are produced by vibrations of gas molecules, by vibrations of crystals and by electronic excitations of certain atoms in crystals. Which of these may be usable in a maser can be discovered only by a detailed study of a system's spectrum.

Now that optical masers have been built, how closely do they match expectations in power, directionality, coherence and the narrowness of the band of wavelengths produced? We know



RUBY MASER is powered by a flash lamp, which provides pumping energy. Output beam is emitted through partially silvered end of ruby crystal; other end is completely silvered. Beam builds up by repeated reflection between the ends. Liquid nitrogen is used to cool the ruby, though it can also be operated at room temperature. Only the front end of the maser housing (*right*) is shown.

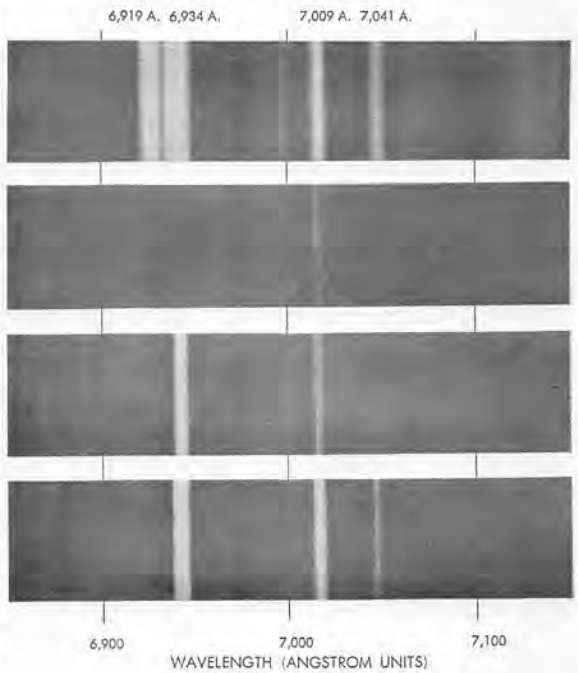
most about the pink ruby. In short bursts its power output reaches 10,000 watts for a beam measuring less than a square centimeter in cross section. The sides of the beam are parallel to within less than half a degree; at lower power the divergence drops to about a twentieth of a degree. The latter divergence corresponds to a spread of only five feet per mile, and it could be reduced by running the beam through a telescope backward. With telescopic demagnification it should not be difficult to project on the moon a spot of light only two miles in diameter.

If desired, the maser's power can be focused to produce intense heating. For instance, a lens with a focal length of one centimeter will focus the beam to a spot only a hundredth of a centimeter in diameter, corresponding to an area of one ten-thousandth of a square centimeter. In this spot the maser beam will deliver power at a density of 100 million watts per square centimeter. Brief though the flash is, its power is thousands of times greater than could be obtained by focusing sunlight and is enough to melt or vaporize a spot on the surface of even the most refractory material. This was first demonstrated by my colleague W. S. Boyle [*see bottom illustration on page 3*].

It is not surprising that the ruby maser falls short of ideal performance in some respects, particularly in the narrowness of the band of wavelengths it produces. Because it is violently pulsed, the ruby rod heats appreciably. Nevertheless, when the maser threshold level is reached, the band of wavelengths narrows to about .02 angstrom, or about 1,000 megacycles. This is as narrow as the sharpest spectral line from any nonmaser light source.

The ruby is far surpassed in the narrowness of its output of wavelengths by the gas maser of Javan, Bennett and Herriott. This maser produces spectral lines less than one kilocycle wide at a carrier frequency of 100,000 megacycles. The gas maser's power output per kilocycle of band-width is about 100 million times that of a square centimeter of the sun's surface. It is possible that the frequency of a maser's output will drift slightly over a period of time, but over a short period it is remarkably stable; in the radio range this stability is equaled only by the finest frequency standards and by atomic clocks.

Of all the properties of the optical maser, none is more striking than the spatial coherence of its light. This is readily demonstrated by using the maser

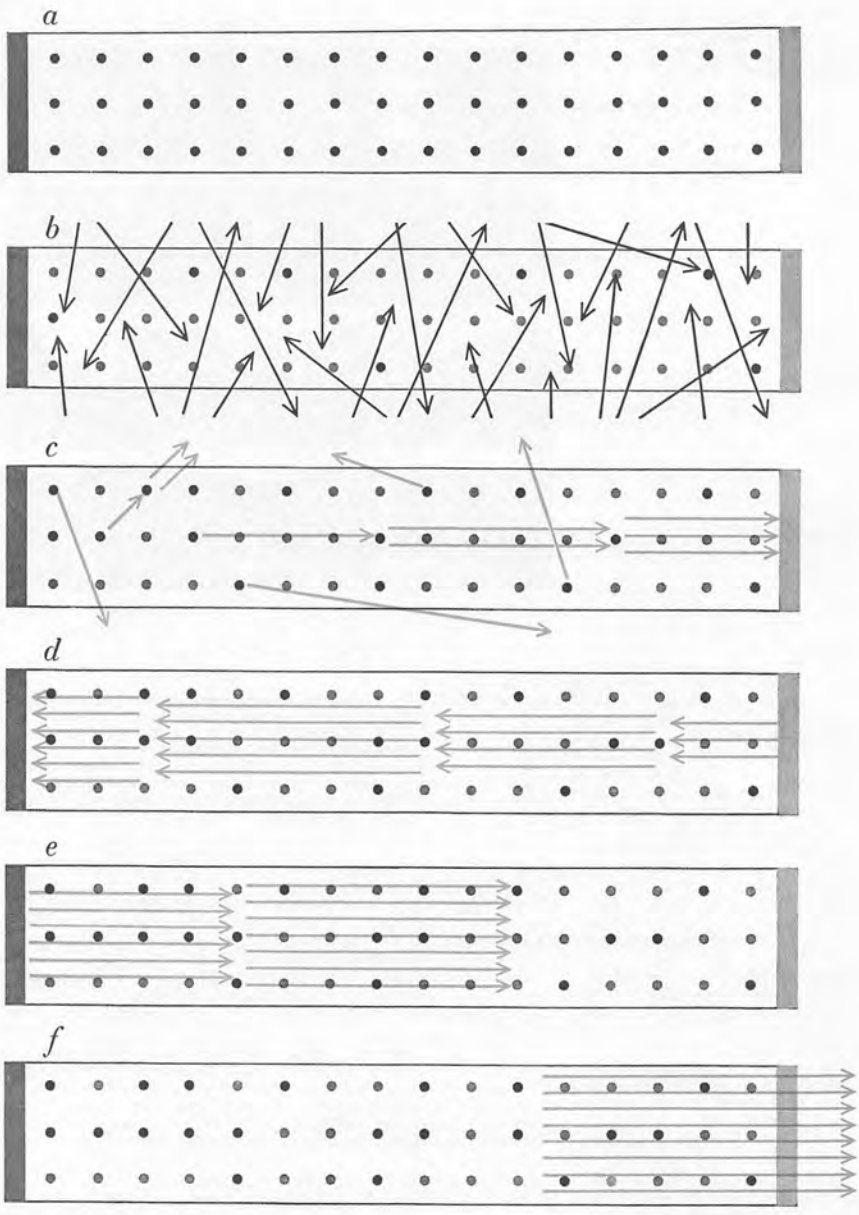


RUBY-MASER SPECTRA in three lower photographs are compared with spectrum of spontaneous (unstimulated) ruby fluorescence at top. As pumping power reaches first threshold for maser action (*second from top*), the ruby "mases" at 7,009 angstrom units (A.), at two wavelengths as power increases (*third from top*), then at three (*bottom*). Maser oscillation never occurs at 6,919 A. Sequence in which spectral lines appear varies with the maser crystal used and operating conditions. A 30-second exposure was required to photograph the fluorescent spectrum. Three lower photographs show single flashes of .0005 second.

to repeat the classic two-slit interference experiment first performed in 1806 by Thomas Young to show that light consists of waves. In Young's experiment light passes through two parallel slits and then falls on a distant screen. If light waves from one slit reach a point on the screen in phase with light waves from the other slit, the two sets of waves reinforce, producing a bright spot. At a nearby point on the screen, where the light from one slit has traveled half a wavelength farther than the light from the other slit, the waves cancel out, producing a dark spot. Thus a pattern of alternating light and dark spots appears on the screen.

As the experiment is usually performed, a small light source is placed some distance from the slits, so that the wave fronts reaching them travel nearly perpendicularly to their plane. If the source is too large or too close to the slits, the pattern fails to appear. Young's experiment is therefore a good test for the perpendicularity of wave fronts and for wave coherence.

When the experiment is performed with an optical maser, the slits can be placed directly against the surface from which the beam emerges and a clear interference pattern will result [*see illustration on page 11*]. The pattern agrees well with one calculated on the assumption of perfect coherence across the distance between the slits. Actually, in a ruby rod the region of coherence is usually limited by crystalline imperfections


a
b
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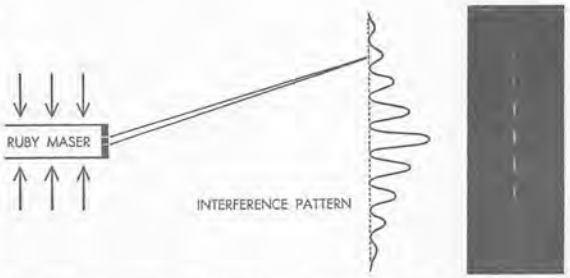
to about a tenth of the rod's diameter. In the gas maser, however, coherence extends across the whole width of the end plates.

The optical maser is such a radically new kind of light source that it taxes the imagination to canvass its possible applications. Message-carrying, of course, is the most obvious use and the one that is receiving the most technological attention. Signaling with light, although it has been used by men since ancient times, has been limited by the weakness and noisiness of available light sources. The amount of information light signals can carry is thereby quite limited. An ordinary light beam can be compared to a pure, smooth carrier wave that has already been modulated with noise by short bursts of light randomly emitted by the individual atoms in the light source. The maser, on the other hand, can provide an almost ideally smooth wave, carrying nothing but what one puts on it.

If suitable methods of modulation can be found, coherent light waves should be able to carry an enormous volume of information. This is so because the frequency of light is so high that even a very narrow band of the visible spectrum includes an enormous number of cycles per second; the amount of information that can be transmitted is directly proportional to the number of cycles per second and therefore to the width of the band. One must distinguish here between the spectral band-width of the unmodulated maser beam, or carrier wave (which, as we have seen, is extremely narrow), and the band-width after a signal has been impressed upon it.



TWO-SLIT INTERFERENCE EXPERIMENT demonstrates that the light waves leaving a ruby maser are spatially coherent, or in step. When two coherent waves strike a screen, after traveling paths of slightly different length, they reinforce and cancel each other in symmetrical fashion to produce an interference pattern. The photograph of the interference pattern at right was made by D. F. Nelson and R. J. Collins of Bell Telephone Laboratories.

In television transmission the carrier wave (which is also narrow) carries a signal that produces an effective band-width of four megacycles. A single maser beam might reasonably carry a signal with a frequency, or band-width, of 100,000 megacycles, assuming a way could be found to generate such a signal. A signal of this frequency could carry as much information as all the radio-communication channels now in existence. It must be admitted that no light beam will penetrate fog, rain or snow very well. Therefore to be useful in earthbound communication systems light beams will have to be enclosed in pipes.

There will certainly be other uses for optical masers. The very intense heat spot produced by focusing an optical maser might be used for fabricating all sorts of electronic devices. For instance, it would be possible to weld a small joint after the joint had been sealed inside a glass envelope. But, in addition to sheer power, the maser provides an intense source of coherent radiation with very high electric-field strength. In such strong fields atoms or molecules may react in strange and unpredictable ways. The beams should therefore be useful in many areas of research. One can also conceive of using maser beams in harmonic generators or mixers. With a suitable mixer one could put in two light waves of different frequency and take out a third wave whose frequency would be the difference of the two original frequencies. In this way it should be possible to synthesize wavelengths that cannot be produced directly. This should lead eventually to superheterodyne receivers capable of translating optical wavelengths into any desired longer wavelength.

It has been known for some years that if one had a strong enough source of infrared radiation of the right frequency, it would be possible to excite vibrations in a particular species of molecule. Any other molecules that might be present would not be affected. Because the excited molecules would react more vigorously than the others, it should be possible to exert a highly selective control over some chemical reactions. Up to now all available light sources have been far too weak for such possibilities to be taken seriously, but optical masers may eventually make such control a reality.

It should be realized that we are talking about a whole family of devices embracing a wide range of frequencies, power ratings and band-widths. The family will include not only oscillators but also amplifiers. One type will be useful for amplifying a light signal that has been weakened by traveling a long distance, perhaps through pipes or through interplanetary space. Another type of amplifier will be able to intensify an entire image—for example, the faint image of a star—that is fed into it.

The list of potential applications of the optical maser could be extended almost indefinitely. With the advent of the optical maser, man's control of light has reached an entirely new level. Indeed, one of the most exciting prospects for workers in the field is that this new order of control will open up uses for light that are as yet undreamed of.

PHOTON CASCADE in a solid optical maser amplifies a light wave by stimulated emission. Before the cascade begins (*a*), the atoms in the maser crystal are in the ground state (*black dots*). Pumping light (*black arrows in "b"*) raises most of the atoms to the excited state (*gray dots*). The cascade begins (*c*) when an excited atom spontaneously emits a photon (*colored arrow*) parallel to the axis of the crystal. (Photons emitted in other directions pass out of the crystal.) The photon stimulates another atom to contribute a second photon. This process continues (*"d" and "e"*) as the photons are reflected back and forth between the ends of the crystal. When the amplification is great enough, some of the beam passes out through partially silvered end of crystal (*f*).

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1 Mittelschnitt einer unter Massenkraft stehenden Pleuelstange

2 Blick „durch" einen Ventilteller unter Gaskraft

3 Ein durch Biegung beanspruchtes Kurbelwellenteilstück

4/5 Diese Bilder zeigen oben einen Radialschnitt durch das Turbinenrad eines Flugtriebwerkes und darunter eine spannungsoptische Aufnahme der Befestigung einer Turbinenschaufel