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INSTRUMENTS AND TECHNIQUES

Optical Masers in Science and Technology

Advances in the control of light waves give promise of important applications in science and technology.

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The use of light waves in science and in technology is almost as old as science itself. Many of the laws of optics were known to Newton, and we see around us the many ways in which the science of optics has contributed to technology. The telescope and the microscope, for example, are among the most powerful tools which man has had available for studying the universe in which he lives.

Recently, however, with the invention of the optical maser, a new dimension has been added to the science of optics. For the optical maser makes it possible to control light waves in much the same way that it has previously been possible to control electromagnetic radiation at lower frequencies in the radio or microwave part of the spectrum, and with the same degree of sophistication. This device, first suggested by Schawlow and Townes (*1*), was experimentally demonstrated for the first time only a little over a year ago (*2*). However, progress in this field has been extremely rapid, and already it is possible to say with some certainty that this device will have a broad applicability in many fields of science and technology.

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History

The history of man's use of electromagnetic waves has been one of a continual pushing upward in frequency. The widespread use of broadcast radio and, more recently, television has given rise to our increasing requirement for frequency space and has thus added impetus to the push for higher frequency. The standard techniques, in which resonant circuits constructed of coils, condensers, and the like are used, became increasingly impracticable, however, at higher and higher frequencies, because the resonators had to be so small as to make construction difficult. Many ingenious ways around this difficulty were found. However, it was not until 1951 that C. H. Townes suggested a means by which the vast supply of natural resonators available within the atoms and molecules of matter could be put to use. He called this invention the maser—an acronym for *m*icrowave *a*mplification by the *s*timulated *e*mission of *r*adiation.

The first operating maser was described by Gordon, Zeiger, and Townes, in 1954 (*3*). These workers used an ammonia gas beam passing through a microwave cavity tuned to about 24,000 megacycles per second. This frequency corresponds to one of the natural resonances in the ammonium molecules and provides a very precise frequency. In fact, the major application of the ammonia-beam maser is as a frequency standard.

In 1956, Bloembergen (*4*) proposed using a solid-state crystal, and this type of maser was demonstrated by Scovil, Feher, and Seidel in 1957 (*5*). Since that time a large number of different masers have been demonstrated by many workers in the field. However, all of these devices operated in the microwave part of the spectrum.

In 1958, Schawlow and Townes described means by which the maser principle could be extended into the optical part of the electromagnetic spectrum. Last year an experimental verification of this suggestion was made, and since that time the field has been a very rapidly moving one indeed. There now exist masers in several different solid materials, including ruby, calcium fluoride doped with samarium, and calcium fluoride doped with uranium. Furthermore, Javan, Bennett, and Herriott (*6*) have recently demonstrated the operation of a continuous infrared maser, in which they utilize a helium-neon gaseous system.

Principle of Operation

Since the optical maser is a relatively new device, I present here a brief description of the principle of operation, as background material for the sections describing potential applications. As I have said above, the optical maser depends for its operation on the use of atoms as natural resonators. The optical behavior of atomic systems can be described in terms of the quantized amounts of energy, or the "energy levels," which atoms are allowed to possess. An atom in thermal equilibrium will ordinarily occupy the lowest of these possible energy levels, from which it can be raised to a higher level by the absorption of energy. From this "excited state" it may then return to a lower energy level by the

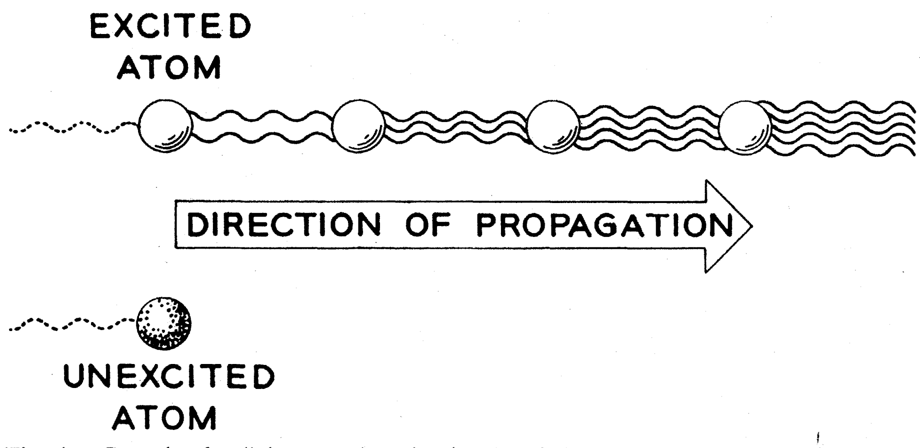

Fig. 1. Growth of a light wave by stimulated emission. The wave striking an excited atom at the same frequency forces it to "join" the original emission. An unexcited atom absorbs the wave and ends the emission.

emission of light. This is the sequence of events which takes place in the well-known phenomenon of fluorescence. The energy which must be supplied in "pumping" the atom to a higher energy level may in turn come from the absorption of a quantum of light of an appropriate frequency corresponding to the difference between two of the possible energy levels of the atom.

In the phenomenon of fluorescence the absorbed light is, in general, of higher frequency than the light which is emitted. Furthermore, the emission of light takes place largely by the process of "spontaneous emission." The spontaneously emitted light is random in direction and phase.

The optical maser, however, makes use of another form of emission, in which the atoms are *stimulated* to emit their light, in the same phase and in the same direction as a standing wave of light of the emission frequency of the medium in which the atoms are bathed. This process is called "stimulated emission." A medium in which more of the atoms are in the upper of two energy states than in the lower is capable of amplifying, by the process of stimulated emission, a light wave of the appropriate frequency passing through it. This situation is shown graphically in Fig. 1. In addition to providing amplification, a medium of this type can be used to provide coherent light oscillations if a feedback path is provided. The particular feedback arrangement suggested by Schawlow and Townes is illustrated in Fig. 2. In this arrangement two parallel coaxial mirrors are arranged in such a way that light waves traveling along the axis and bouncing back and forth through an amplifying medium between the mirrors will set up a coherent standing wave of light. Waves traveling in any other direction, however, soon miss the mirrors and are lost. Thus, this "Fabry-Perot" type of structure serves as a resonant cavity for the oscillator. If one of the mirrors is partially silvered, light can emerge in the form of a beam which is highly directional, coherent, intense, and relatively monochromatic. These four properties make the optical maser attractive for potential applications.

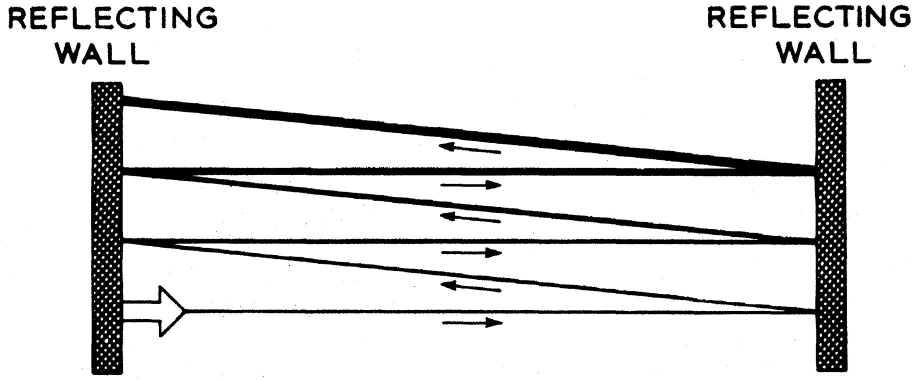

Fig. 2. One arrangement of the optical maser, in which a wave "grows" as it bounces back and forth between reflecting walls (the vertical dimension has been greatly exaggerated for clarity).

Status of the Optical Maser

At the present time, optical masers have been demonstrated in a variety of substances. Some of these are attractive for some applications and some for others. In Table 1 are summarized the properties of various optical maser systems that exist as of this writing. It may be seen that, in general, the solid-state systems have the advantage of higher peak power output, while the gaseous system is more highly monochromatic. The gaseous system can be operated continuously, whereas the solid systems (at least to date) have only been operated on a pulsed basis. In the following sections I discuss the various applications of the optical maser which now seem feasible.

Applications to Communication

The use of electromagnetic waves in communication, as in telephony, radio, television, and radar, is of course a familiar feature of modern life. It seems certain that the availability of the optical part of the spectrum will have an equally profound effect upon communications. Optical frequencies are attractive for several reasons. In the first place, the amount of information which can be carried by an electromagnetic wave is proportional to its frequency. At the extremely high frequencies of the optical region of the spectrum (of the order of 10^{14} to 10^{15} cy/sec), an extraordinarily larger bandwidth becomes available. This statement can be illustrated by the observation that the optical part of the spectrum could carry 100 million simultaneous television programs (the desirability of 100 million simultaneous television programs need not concern us here).

Second, the high carrier frequency of light waves means that very narrow beams may be transmitted without the use of extremely large antennae. The divergence angle of a beam of radiation is inversely proportional to the diameter (measured in wavelengths) of the antenna from which it emerges.

Light beams only 1/20 degree in angular divergence have been obtained from a ruby optical maser only ¼ inch in diameter. To obtain equivalent directivity with a microwave antenna would require a diameter of more than 1000 feet.

The availability of such light beams as these may make possible local transmission of power for specialized purposes—for example, for powering a satellite from the ground. It has also been suggested that optical maser beams may provide an attractive means of interplanetary communication.

Before any of the attractive potentialities for communication can be realized, however, it is necessary to devise suitable means for modulating and detecting the output of an optical maser. Already a certain amount of progress has been made in these directions. Recently Kaminow has succeeded in modulating light at a frequency of 18,000 megacycles per second by making use of the magneto-optic effect in potassium dihydrogen phosphate (*7*). Although the particular structure which he used had a relatively narrow bandwidth, straightforward means are available for extending his technique to broader bands.

Considerable current research work is also directed toward the development of broad-band detectors. It is felt that traveling-wave techniques can be used with broad-band photomultiplier devices. Furthermore, there is good reason to hope that solid-state devices can be made with low noise and broad bandwidth.

In view of the rapid progress being made, it does not seem unreasonable to expect that at least some limited experimental demonstration of communication via coherent light beams will be made in the not too distant future.

Applications to Science and Technology

I mentioned above that the properties of high power density, coherence, monochromaticity, directionality, and high frequency were those which made the optical maser attractive for potential applications to science and technology. Table 2 gives a listing of some of the possible applications. Most of these will depend upon more than one property. However, an attempt has been made to list them under that property which is most directly relevant.

The first property considered is power density. Ruby masers have been operated with a peak power in the beam of some 10 kilowatts (available during a pulse of about 1-millisecond duration). Since the beam is coherent and directional, it can be focused by a simple lens into a very small spot. In this way it is possible to obtain power densities within the focused spot of greater than 10^{10} watts per square centimeter. Such enormously high power densities have not been previously available in the laboratory and make possible a variety of applications, some of which are listed in Table 2.

Porto and Wood (*8*) have used a ruby optical maser beam as a Raman source and have observed the Raman spectra of benzene. It is anticipated that as the optical-maser art advances, many other applications to Raman spectroscopy will be made possible.

Franken, Hill, Peters, and Weinreich (*9*), using a focused ruby maser beam, have demonstrated nonlinear dielectric effects in quartz by observing the production of second harmonics of the exciting light frequency. It is, perhaps, fair to predict that the observation of nonlinear optical effects in these experiments is only the first of many observations of new interactions between electromagnetic radiation and matter which can be observed now that such intense sources are available. For example it should be possible to produce new kinds of photochemical reactions, and perhaps new effects in the interaction of radiation and biological material.

Other possible uses for the high pow-

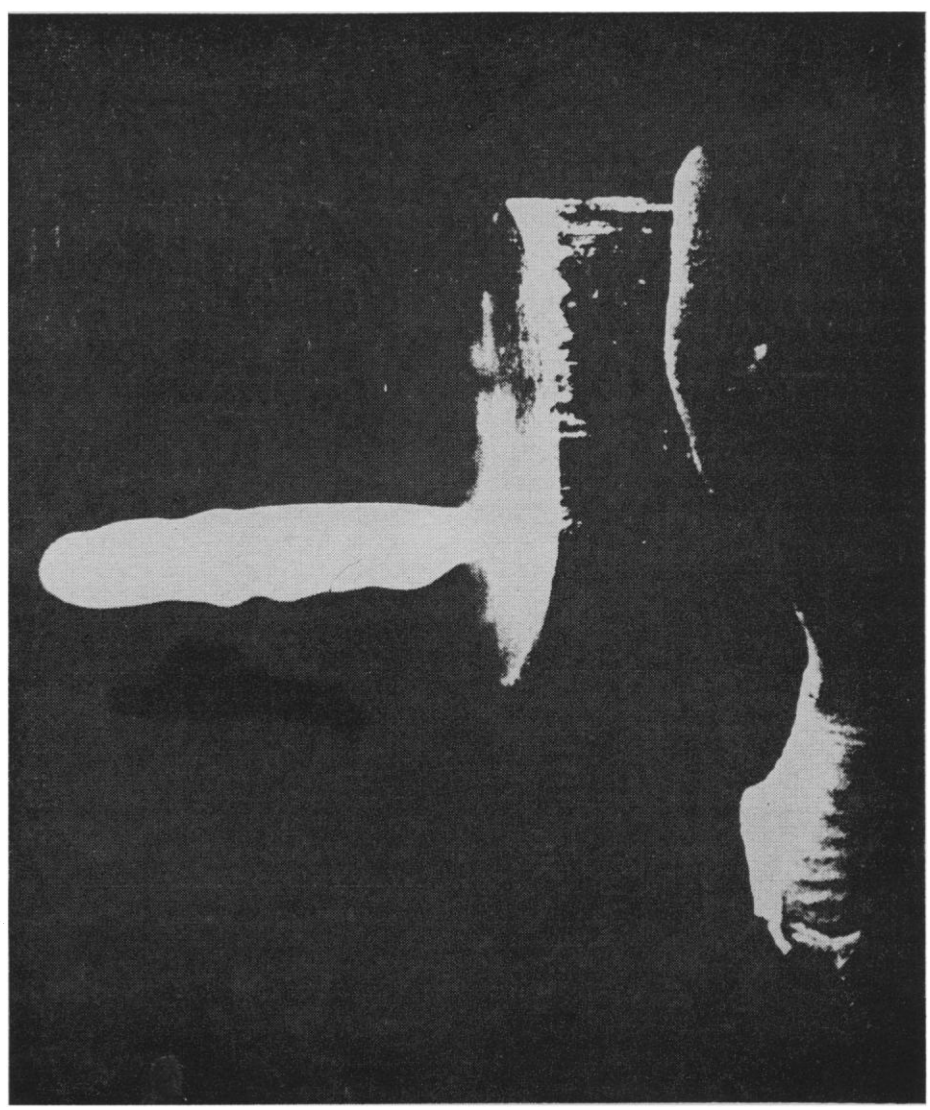

Fig. 3. A jet of self-luminous carbon vapor being ejected from the focal point of a ruby maser beam incident upon a carbon rod. The rod is of about 1-centimeter diameter.

Table 1. Summary of the properties of various existing optical maser systems.

Type	Present mode of operation	Frequency of operation (10^{14} cy/sec)	Temperature of operation (°K)	Pumping method	Power output (watt)	Fractional maser output line width ($\Delta\nu/\nu$)
			Solids			
Al_2O_3:Cr	Pulsed	4.320	300	Light	10^4	7×10^{-6}
Al_2O_3:Cr	Pulsed	4.282	77	Light		
Al_2O_3:Cr	Pulsed	4.261	77	Light		
CaF_2:Sm	Pulsed	4.21	77	Light	10^2	10^{-6}
CaF_2:U	Pulsed	1.21	4	Light		
BaF_2:U	Pulsed	1.15	4	Light		
			Gases			
He + Ne	Continuous	2.683	300	Gaseous discharge	0.01	$<10^{-13}$
He + Ne	Continuous	2.601	300	Gaseous discharge	0.01	$<10^{-13}$
He + Ne	Continuous	2.586	300	Gaseous discharge	0.01	$<10^{-13}$
He + Ne	Continuous	2.502	300	Gaseous discharge	0.01	$<10^{-13}$
He + Ne	Continuous	2.485	300	Gaseous discharge	0.01	$<10^{-13}$

er density available in focused beams exist in the fields of melting refractory materials, of welding, and of micromachining. In unpublished experiments, W. S. Boyle has shown that it is possible to vaporize a small volume of carbon at the focus of a maser beam. In Fig. 3, this experiment is shown. A jet of luminous carbon vapor may be seen emerging from the end of the carbon rod. Examination of the rod shows that a small crater of about 0.001-inch diameter was created. Such a process might compete favorably with electron beam machining for producing small structures—for example, the spinnerettes used in the extrusion of textile fibers.

The focused maser beam can also be regarded as a highly brilliant light source. J. S. Courtney-Pratt (*10*) has applied this principle to high-speed photomicrography. Using a focused ruby maser beam, he succeeded in obtaining photomicrographs with a magnification of 1800 and an exposure time of 1/2000 sec. This does not represent by any means the limit that can be reached with this technique.

Table 2. Possible applications of the optical maser, listed according to the most relevant property.

Application: Science	Application: Technology
Power	
Raman spectra	Refractory melting
Nonlinear optical	Welding and cutting
Photochemistry	Photography
Spectral sources effects	Ophthalmology
Biological studies	
Coherence	
Superradiance	Communication
Intermodulation	Superheterodyne techniques
	Long-distance interferometry
Monochromaticity	
Spectral studies	Selective signaling
Selective photochemistry	
Relativity	
Directionality	
Focusing for superintensity	Space communication
	Radar (Colidar)
Frequency	
Infrared spectroscopy	Carrier communication

Preliminary experiments in several ophthalmological laboratories have indicated that the ruby optical maser may be useful as an "optical coagulator" for the treatment of certain diseases of the eye—for example, the so-called detached retina. In this application, the beam is brought to focus at the desired spot on the retina, where it essentially produces a tiny spot weld. It should be pointed out that studies are now in progress to determine possible pathological effects of the maser beam upon tissue. Nevertheless, it seems possible that coherent light may have medical applications comparable to those of light at lower frequencies, such as, for example, diathermy.

Let us now consider the properties of coherence and monochromaticity. That the optical maser beam is indeed coherent has been demonstrated by diffraction experiments (*11*) in which it was shown that the theoretically expected diffraction patterns were obtained when the maser beam was passed through a two-slit diffracting system. The negative feedback present in an optical maser oscillator narrows the spectral line of the emitted radiation and thus provides extremely monochromatic output. In the gas maser, Javan (*6, 12*) has estimated that the line width may, in fact, be only a few cycles per second—that is, only a few parts in the 10^{14}.

The existence of such highly intense coherent light sources should make possible a number of new and interesting experiments in optical pumping. For example, it should be possible to provide a direct test for some of the suggestions made by Dicke (*13*) concerning the behavior of systems which have been coherently excited (the so-called "superradiant" states). Then too, the availability of coherent radiation at light frequencies means that the familiar techniques of superheterodyning, so useful in radio, will become possible in the optical regions. Highly coherent beams of light may make possible the use of interferrometric methods of measuring length over very long distances—perhaps even miles. It has been suggested that such methods may lead to tests of the theory of relativity more sensitive than any previously possible.

It is in spectroscopy, however, that the greatest impact may very probably be felt. After all, such highly monochromatic spectral sources have never been before available. Then too, the optical maser constitutes a source of infrared radiation more intense than any previously available. In order to obtain from a hot body a beam comparable in intensity (within the solid angle of emission and within the spectral line width) to that already obtained from the ruby optical maser, it would be necessary to have a source more than 20 million times as hot as the sun.

The optical maser is a very new device, and the field is a very rapidly moving one. It is therefore too early to foresee all of the many things which will result. I have tried in this article to describe a few of these, in the hope that still others will suggest themselves to readers in the many disciplines of science which these words may reach.

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