LASERS and COHERENT LIGHT

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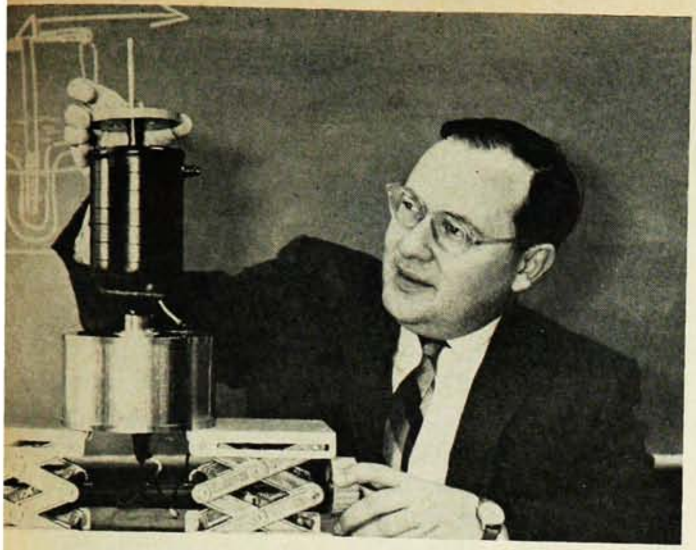
By A. L. Schawlow

It is often possible to make a clear division between pure and applied physics, although at times the dividing line is indistinct. Seldom has the distinction been so completely blurred as it is in those areas of research related to optical masers, or lasers. In this field new advances in devices and techniques immediately make possible new experiments of fundamental importance. New scientific knowledge is very quickly translated into new devices.

Perhaps this close connection between scientific knowledge and devices arises in part because the devices are not yet closely tied to specific applications. This is somewhat discouraging to those who do have specific applications in mind. However, there is still considerable enthusiasm for any device which does something new, even if it falls short of immediate practicality. This attitude has permitted wide-ranging exploration of a vast variety of possibilities, and many of these possibilities have become accomplishments. Thus, when we do have in mind an application requiring a device with a certain set of properties, it may be possible to push the known techniques, or it may be better to look for or wait for a radically different approach. Nevertheless, those things which have already been achieved are enough to bring some applications to the verge of practicality, and to suggest other applications. It may well be that in this field, as someone remarked recently, "Invention is the mother of necessity."

While this is the situation with regard to technical applications, the scientific applications of lasers are in a similar position. Let us illustrate this by some examples of how laser research is adding to knowledge of science, and specifically of physics. First, however, let us recall what lasers are, and what they may be expected to do.

Lasers are masers, that is, atomic amplifiers or oscillators, operating in the infrared, visible, or ultraviolet regions. Like the earlier masers at lower frequencies, they make use of stimulated emission from an atomic or molecular system. The system is prepared so as to have more atoms in some upper energy state than in another state of lower energy. A wave passing through such an active medium is amplified rather than absorbed. Usually, the active medium is contained in some sort of a reflecting enclosure. At microwave frequencies this enclosure is a box, usually of metal, and constitutes a cavity resonator. The resonator dimensions are such that it can only support one mode



Arthur L. Schawlow, professor of physics at Stanford University, was the co-author, with Charles H. Townes, of the first paper to be published describing optical masers. For that work they have been awarded the Stuart Ballantine Medal of the Franklin Institute and the Thomas Young Medal and Prize of the Institute of Physics and Physical Society in England. A former research physicist at the Bell Telephone Laboratories, Dr. Schawlow has been a member of the Stanford physics faculty since the fall of 1961.

of oscillation. When excited atoms are stimulated to emit, they are forced to contribute to whatever wave exists in this mode. Thus, the phase of this wave is preserved, and it has time coherence even though the atoms were excited incoherently. Since a single resonator mode is excited, the wave also has spatial coherence.

In the optical region, the resonator is much larger than a wavelength, and is usually simplified to consist only of a pair of mirrors facing each other. Typically, the diameter of the mirrors is small in comparison with their separation, and they are flat or slightly concave. The active medium occupies all or part of the space between the mirrors. Such an arrangement has a high Q only for those modes which can be generated by waves traveling back and forth along the axis of the system. Waves traveling in other directions are lost at the edges of the plates. Output coupling is obtained by leaving one of the mirrors partly transparent. Then the radiation which emerges from the end of the column of active material is a well-collimated beam (Fig. 1).

From even this simplified description, it is evident that optical masers should produce a very directional output beam. Indeed they do, and the divergence of the output beam can be as small as the diffraction limit, given by the wavelength divided by the diameter, or about 10^{-4} radians. Even better collimation can be attained, at the expense of a larger initial beam diameter, by running the light backward through a telescope.

Because the excited atoms in an optical maser are stimulated to emit faster than they would normally do, lasers should be more intense than ordinary sources. This is particularly true when the active material is a solid, where the density of active ions is very high. Lasers should be monochromatic because stimulated emission is a resonance process, and takes place most strongly at the center of the spontaneous emission line. There is a threshold condition for laser oscillation determined by the requirement that a wave traveling back and forth along the axis receive enough amplification to make up for the losses at the ends. If there is not much gain to spare at the peak of the line, the threshold of oscillation will not be attained at frequencies off the peak. Thus, it is possible to obtain very monochromatic oscillation in a single

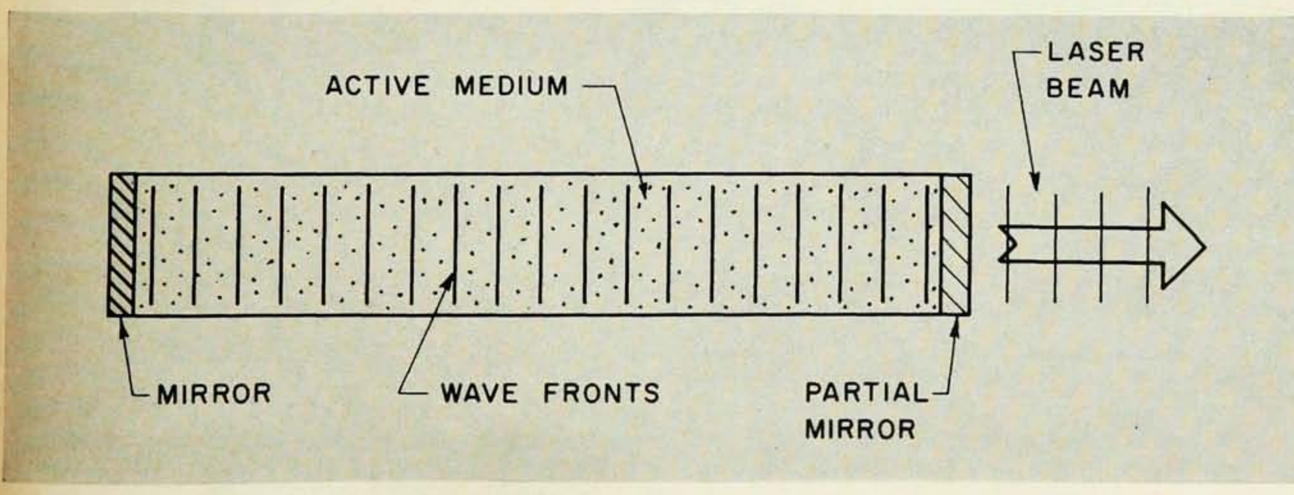


Fig. 1. Structure of a laser using a long column of active material with mirrors at the ends

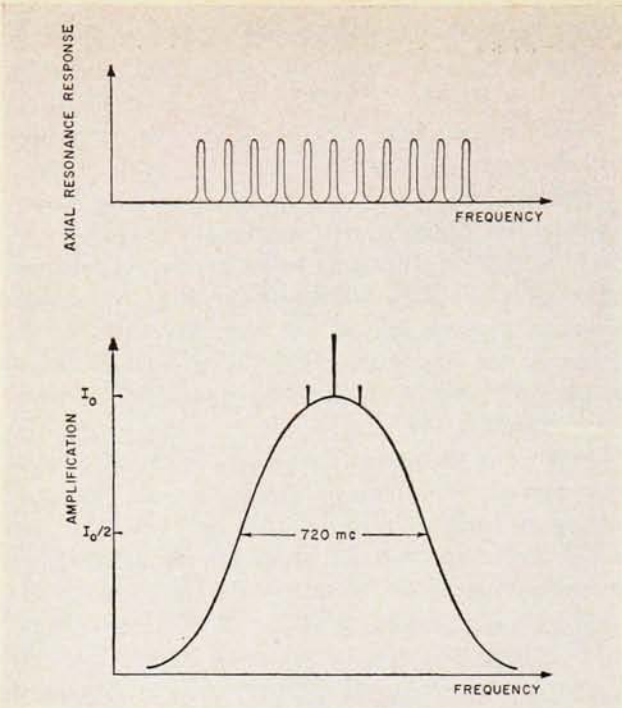


Fig. 2. Axial modes of resonant system within the spontaneous-emission line width

resonator mode close to the peak of the spontaneous emission line (Fig. 2).

Thus, lasers should be powerful, monochromatic, directional, and coherent. These properties were implicit in the discussion of optical masers by Townes and the author in 1958. Before discussing how far these characteristics have been realized, let us look at some of the materials which can give amplification by stimulated emission, and the ways by which the necessary excited atoms, molecules, or electrons are produced. The first class of laser materials uses optical pumping for this excitation. Incoherent light, of the proper wavelength, from a bright lamp is absorbed in the material. Three variations of the optical pumping method are shown in Fig. 3. The energy levels shown are all far enough apart so that initially all the atoms are in the lowest level, and the higher levels are empty. In the first case, shown in Fig. 3a, light of frequency $\nu_{13} = (E_3 - E_1)/h$ excites atoms from level 1 to level 3. Then, since level 2 is initially empty, as soon as any atoms are excited to level 3, amplification by stimulated emission can occur in the transition from E_3 to E_2. Since the amplification is inversely proportional to the width of this line, level 3 should not be too broad. This, in turn, implies that the pumping transition from E_1 to E_3 is also fairly narrow, and so only a narrow range of pumping wavelength can be used. However, this system can be used when a lamp of just the right wavelength is available. It has been applied to atomic cesium vapor where the pumping light is supplied by a helium discharge lamp which happens to produce just the required wavelength.

If the active substance has levels like those of Fig. 3b, the pumping light raises atoms from level E_1 to level E_3. From E_3 they very quickly relax to E_2, often by a nonradiative process if the active atom is in a solid. Thus, pumping can continue until more than half of the atoms are raised to level E_2, and stimulated emission occurs in the transition from E_2 to the ground level E_1. In this arrangement of levels, there is absorption, rather than emission, in the transition between E_1 and E_2, until about half of all the active atoms have been excited. However, there is the advantage that the functions of emitting and absorbing are sep-

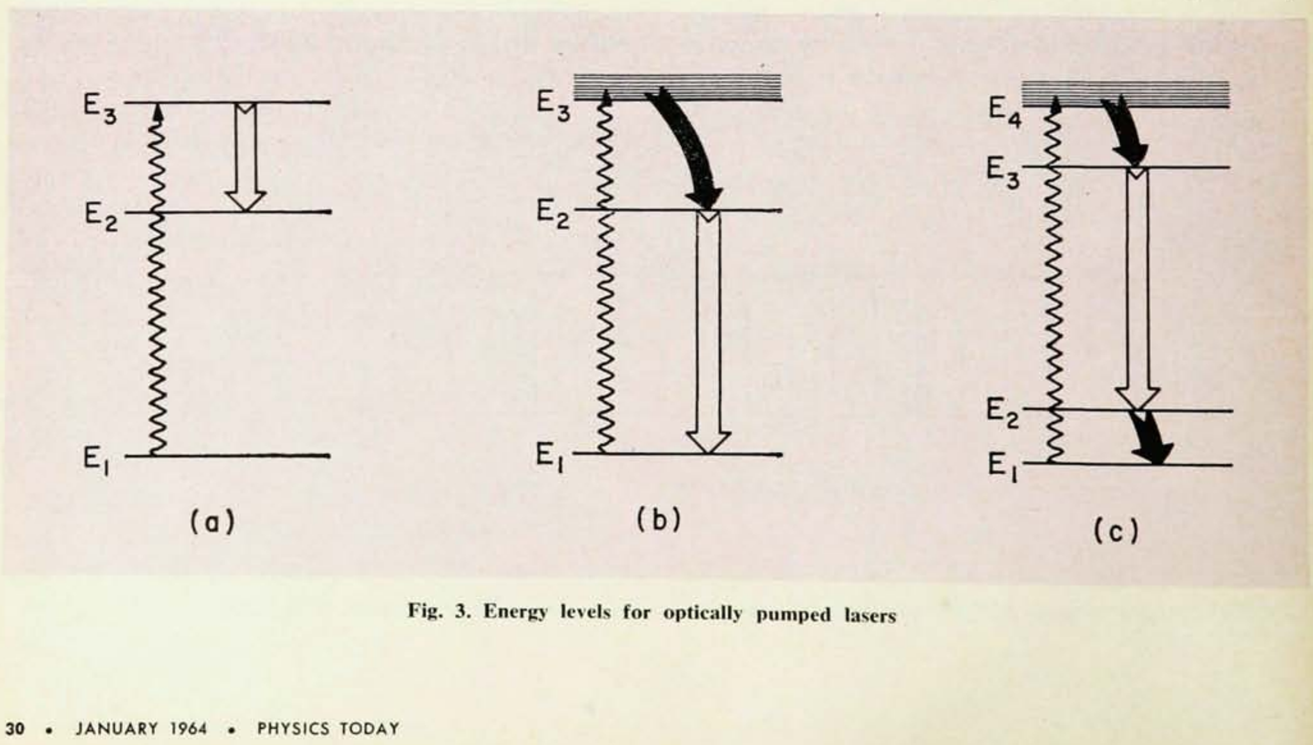


Fig. 3. Energy levels for optically pumped lasers

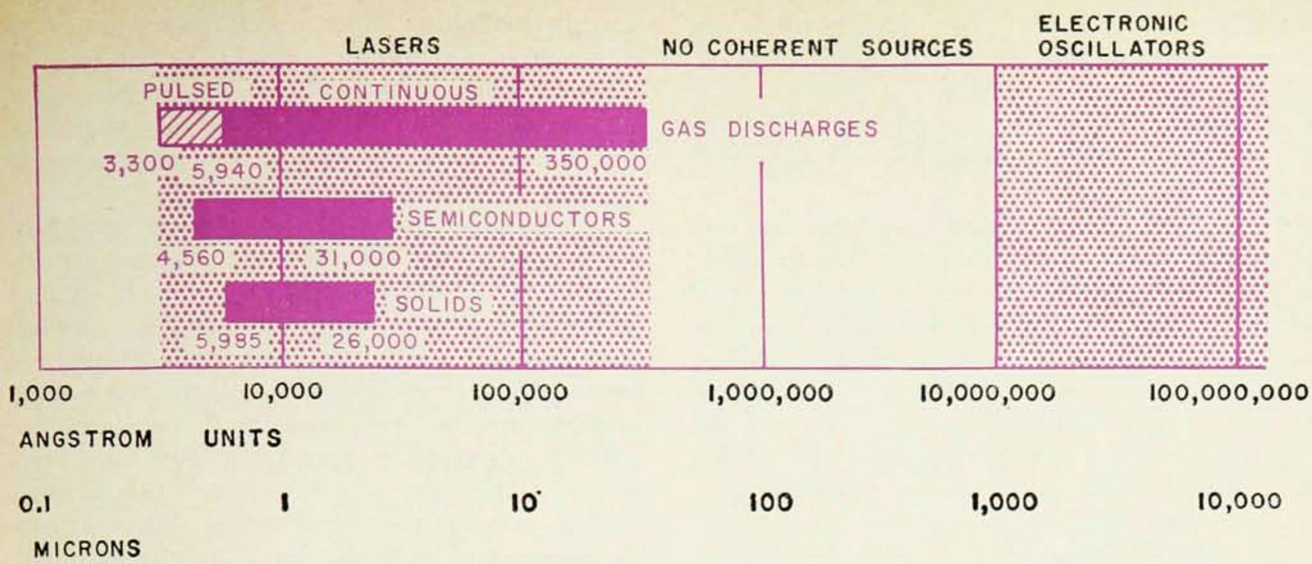


Fig. 4. Spectral range spanned by various types of coherent oscillators

arated. Thus, the emitting line can be sharp, while the pumping band can be wide, so as to make effective use of a large range of wavelengths. This is the arrangement of levels in pink ruby (about 0.05% of trivalent chromium ions in aluminum oxide), which was the substance used by T. H. Maiman when he first reported successful operation of a laser in 1960.

The four-level scheme of Fig. 3c combines the advantages of both of the others. A broad band or many separate lines can be used for pumping, while the stimulated emission takes place in a single, narrow transition to an empty lower level. This four-level arrangement is used for lasers with many different rare-earth ions in crystals, glasses, plastics, and even liquids. To give just one example, trivalent neodymium ions in hosts such as calcium tungstate have the expected low threshold pumping power requirement for laser oscillations.

Except for the cesium vapor, all of these optically pumped materials are solids, so that they can have a much higher density of active ions than could be obtained in a gas. Thus, a considerable amount of energy can be stored in excited atoms, and it can be released in one or more large bursts of well-collimated, monochromatic light. Lasers using ruby have given short bursts as high as 100 kilowatts for a few microseconds, or delivered energy of as much as 1000 joules in a few milliseconds.

Still higher peak light-power outputs can be obtained by the giant-pulse scheme originated by R. W. Hellwarth (Fig. 4). At least one of the mirrors is detached from the laser rod, and a shutter is placed between the rod and the mirror. Initially the shutter is closed, when the exciting lamp is turned on. Thus, laser action cannot start even though many atoms are excited, because the feedback path to the mirror is blocked. Then the shutter is suddenly opened, and much of the stored energy is released in a single giant pulse. In this way light pulses of the order of 100 megawatts, lasting a few nanoseconds, have been generated.

Still higher peak light intensities can be obtained by using traveling-wave amplifiers after the giant-pulse light oscillator. Powers as high as one thousand megawatts have been obtained, and it should be possible to exceed this by one or two orders of magnitude.

Since this intense light is contained within a beam with a divergence of about 1 milliradian, a lens of 1 cm focal length would focus it to a spot of no more than 10^{-3} cm diameter. Within this focal spot, the power density would be 10^{15} watts per square centimeter, with a corresponding electric field intensity of nearly 10^{9} volts per centimeter. This is by no means an ultimate limit; it is what can be done now. Even so, it is a higher electric field strength than can be obtained at any other frequency. If we tried to produce such a large field at lower frequencies, intense cold emission of electrons from the electrodes would result. At optical frequencies, the intense field is produced in free space, far from any electrodes.

These fields are quite comparable with the fields binding electrons in atoms. Investigation of their effects is only beginning, but already some striking results have been obtained. At much lower field strengths, around a million watts per square centimeter, the dielectric constant or refractive index of many materials begins to be noticeably nonlinear. This leads to generation of optical harmonics having twice or three times the frequency of the input light. Light of two different colors can be mixed to give sum and difference frequencies. When care was taken to keep the generated harmonics in phase with the fundamental, as much as 20% of the fundamental power has been converted to second harmonic light.

Another new effect produced by high intensity light from lasers is the coherent Raman effect. When a beam of monochromatic light is passed through a medium, usually a molecular liquid or solid, intense beams are produced which are shifted in frequency by a molecular vibration or rotation frequency. Such sidebands can occur on both the high-frequency and the low-frequency side of the input light. Conversion efficiencies as much as 50% are sometimes obtained. It is possible now to get a strong Raman spectrum in a single flash of less than 10^{-7} seconds duration. However, the selection rules for this process are not yet fully understood. Some lines are produced strongly. Other lines, important in ordinary Raman spectra, are completely absent in the coherent Raman spectra.

For applications where extremely high power is not important, gas-discharge masers have advantages such as excellent collimation and monochromaticity. Even the first gas-discharge maser, constructed by Ali Javan, W. R. Bennett, Jr., and D. R. Herriott in 1960, gave continuous output. It is only rather recently that much attention has been given to laser operation in pulsed gas discharges. While the continuous-wave gas masers are limited to about 100 milliwatts so far, peak pulsed powers around a kilowatt have been obtained. Continuous-wave operation has been attained in a number of gases at wavelengths from 0.59 microns in the orange portion of the visible spectrum to 35 microns in the infrared. With pulsed operation, maser operation has been extended to wavelengths as short as 0.33 microns in the ultraviolet.

All gas-discharge masers use a long narrow column of discharge, with mirrors at the ends. If the atomic levels were in equilibrium with electrons in the discharge, there would always be more atoms in lower states than in upper, and amplification by stimulated emission would not occur. However, at moderately low pressures, several processes can produce the necessary departures from equilibrium. In fact, population inversions are quite common in gas discharges. Usually, the gain produced is rather small, a few percent per meter, although a few infrared transitions give large gains. A number of helium-neon gas-discharge masers operating at the visible wavelength of 6328 angstroms are now available commercially. Some are compact enough to use as pointers for slides, and one was so used in this lecture. They are convenient sources of monochromatic, collimated light for all sorts of optical alignment and testing. For instance, with such a source it is almost trivially easy to align a Fabry-Perot interferometer with plate separations of many centimeters or even meters.

Gas-discharge masers can be extremely monochromatic. Ordinarily, the sharpest resonance, which determines the exact oscillation frequency, is that of the axial modes between the highly reflecting mirrors, as in Fig. 3. Thus, for high stability, extreme precautions are needed to keep the spacing between mirrors exactly constant. So far, short-time stabilities as great as one part in 10^{13} have been reached. This corresponds to a constant average spacing between the mirrors of a thousandth of the diameter of an atom. Such carefully stabilized lasers are being used to repeat the Michelson-Morley experiment with greatly improved accuracy. If the velocity of light were to change when the direction of the maser axis is rotated, it would cause a proportionate change in the maser output frequency. This could be observed by combining the light from the moveable maser at a photodetector with that of a reference optical maser, and measuring the beat frequency.

Another application of stable gas masers is to sense absolute rotation in space. This is a modern version of another classic experiment by Michelson. For this purpose, four gas-discharge tubes are on the sides of a square. Mirrors are placed diagonally at the corners, so that light can make a circuit around the square in either direction. If the square is rotating around an axis perpendicular to its plane, light takes longer to complete the circuit in one direction than in the other. This is indicated by two maser output frequencies, whose difference is proportional to the rotation rate. Small difference frequencies can be measured by the beat method, so that it should be possible to measure quite slow rotation rates.

A third class of system, in which stimulated emission of light can occur, is constituted by certain semiconductors. In particular, they are the "direct-gap" semiconductors, in which an electron excited to the conduction band can recombine with a hole and simply radiate its excitation energy. This class includes such materials as gallium phosphide, indium arsenide and indium phosphide. On the other hand, germanium and silicon are "indirect-gap" semiconductors, and require the simultaneous emission of a photon and a crystal-lattice phonon for recombination. Thus, in indirect-gap semiconductors, recombination radiation is quite weak, so that little amplification by stimulated emission can be obtained. A possible exception is silicon carbide, in which laser operation at 4560 angstroms has recently been obtained.

To construct a laser from one of these suitable materials, a flat *p-n* junction is prepared in it. On one side of the junction, in the *n* region, donor atoms provided many free electrons; in the *p* region acceptors provide large numbers of holes. When a voltage in the forward direction is applied across the junction, electrons and holes are drawn into the junction region. There they meet and can be stimulated to emit recombination radiation. Amplification thus occurs in a narrow layer around the plane of the junction when current passes. End mirrors perpendicular to the junction can be provided by polishing or cleaving the ends, while the sides are roughened. The whole junction laser can be less than a millimeter in any dimension, while the active layer is only a few microns thick.

Semiconductor junction lasers are relatively efficient, particularly when operated at very low temperatures. As much as one watt of continuous wave output has been obtained, with an efficiency of thirty percent. Moreover, the output wavelength can be adjusted over a large range by varying the composition of the semiconducting alloy. Smaller, but still substantial, ranges of tuning can be obtained by variations of temperature, pressure, and magnetic field.

Figure 4 summarizes the ranges of wavelength which are currently available from the different kinds of lasers. It is seen that a wavelength range from 0.33 microns to 35 microns is now spanned by coherent light generators—a frequency ratio of around 100 to one. The far-infrared gap remaining between the present infrared-maser limit and the shortest wavelength electronic oscillators around 1 mm has a frequency ratio of about thirty.

Output and frequency stability have already been outlined. However, one should not take the present state of the art too seriously as indicating ultimate limitations of the several kinds. Thus, for a wavelength standard, gas discharge masers are eminently suitable because of their low-power, stable, continuous operation and relatively narrow spectral lines. However, these lines do have a fractional width of a few parts in 10^6 because of Doppler broadening from thermal agitation. By a thorough analysis and understanding of the line shape and its effect on the output frequency, the maser can be set and reset on the center of the line to about one part in 10^9. This is about one thousandth of the line width.

Spectral lines from ions in solids are generally broader than this, but there may be some exceptions. After all, ions in solids are not subject to Doppler broadening, since they are fixed. Ruby has a fractional line width of about 6×10^{-6} at 4°K, and several rare-earth lines are known to be considerably sharper. The ultimate limitations are not yet known, and it may ultimately be possible to find lines in some solids sharp enough for a good wavelength standard. Similarly, gases have been considered to be most suitable for low powers while solids, because of their greater density of active ions, have been best for high powers. However, the high-power solid laser is pumped by a gas-discharge lamp, and one cannot help wondering whether high-power laser light can be extracted directly from the gas discharge.

Optical masers have already made possible a number of important investigations, such as those of nonlinear optics and double-quantum absorption. As the devices are improved, more experiments will become practical. However, the existence of the devices raises many questions related to the physics of their operation. Thus, there is a fresh viewpoint and a new impetus for the study of some older topics. For example, the existence of these light sources, whose output has a high degree of spatial and temporal coherence, has stimulated searching examinations of the theoretical meaning of coherence and its experimental consequences. In another area, widths and intensities of spectral lines, and the influence of environment on them, are being studied, which may give new information about this environment, about crystal fields and lattice vibrations, and about interactions between ions. This list of peripheral topics under study could be extended considerably.

Research on optical masers has proved attractive to many physicists, and there is a very large volume of publications ensuing. In a short review it is impossible to do justice to this great variety of original contributions, and especially hopeless to give proper credit for individual discoveries. In fact, no review could be really comprehensive, but some guides to further reading are listed below.

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