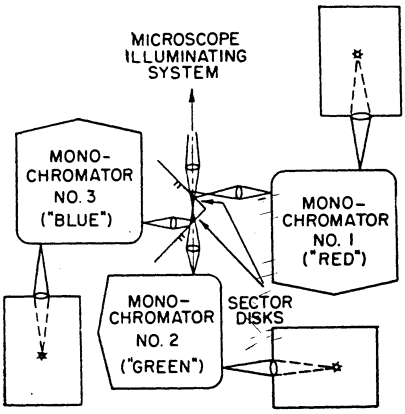

Fig. 13. Sector-disk illuminator for television color-translating microscope.

into color differences can make it a valuable tool in the rapid diagnosis of any disease whose onset is characterized by intracellular chemical changes. The detection of small quantities of a specific absorbing material can be further facilitated by modulating the gun cathode bias for the color channel correlated with the absorbed wavelength at a low frequency (of the order of 1 cycle per second), since the eye is very sensitive to the resulting flicker.

Modifications

An immediate improvement considered for the construction of the instrument is the replacement of the quartz lens in the illuminating system by quartz-fluorite achromats. This should eliminate the need for readjustment of the optical system of the illuminator with changes in wavelength selection and should lead to more nearly identical illumination at the three wavelengths.

A second change under consideration is the replacement of the single-image-orthicon camera by a three-Vidicon camera, as indicated schematically in Fig. 12. The beam of radiation from the microscope is directed successively to the "red," "green," and "blue" Vidicon—all of them, of course, of the experimental ultraviolet-sensitive type—by a pair of coupled sector disks synchronized with the vertical deflection; in Fig. 12, the shaded areas represent minor surfaces, while the clear areas transmit incident radiation unhindered. With such an arrangement, the camera becomes a simultaneous camera, and a standard simultaneous color monitor can be employed to view the picture. Vidicon lag no longer has an adverse effect on color purity (except in the viewing of objects in rapid motion), but merely serves to reduce flicker effects observed in the reproduced picture.

A similar system of sector disks (eventually rigidly coupled to those in the camera) may be employed in the illuminator to direct radiation from the three monochromators into the substage of the microscope (Fig. 13). This system possesses the advantage of rendering the timing of the pulsing of the light sources relatively uncritical and of achieving exact optical superposition of the three illuminating sources (*12*).

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12. We are indebted to a number of workers at the Rockefeller Institute for Medical Research and at New York Hospital for supplying material for examination with the new instrument—in particular, to P. Weiss and A. C. Taylor for tissue cultures, M. A. Rudzinska for protozoans, E. L. Tatum for fungi, and G. N. Papanicolaou for cancer cells. The television equipment employed was made available on loan by RCA Laboratories. Carl Berkley made most of the preparations and contributed suggestions on the equipment. Other suggestions with respect to receiver modifications and the optical system were made by L. E. Flory and E. G. Ramberg of RCA Laboratories. The illuminating system was designed by P. Nolan of the Farrand Optical Company. The instrument represents an example of the effectiveness of cooperation between biologists and physical scientists in the development of new methods of biomedical investigation which could not have been achieved by either group working alone. It is now available at the Rockefeller Institute for Medical Research for cooperative investigations. Collaboration in the development of its uses and applications is welcomed.

The Maser

A Molecular Amplifier for Microwave Radiation

W. H. Culver

Electrical amplifiers in use today usually employ the motions of charged particles in electric or magnetic fields, as in vacuum tubes and transistors, or some nonlinear macroscopic property of matter, as in the case of the magnetic amplifier. An altogether different method of amplifying electrical signals is by stimulated emission of radiation. A device which uses this principle is called a maser (rhymes with razor). The word was coined by Townes and associates at Columbia University from the words *microwave amplification by stimulated emission of radiation* (*1*).

The maser principle was suggested by Weber in 1953 (*2*) and again independently by Bassov and Prokhorov in 1954 (*3*). The idea was used in a microwave spectrometer by Gordon, Zeiger, and Townes in 1954 (*4*). Within about the last year a large number of papers have been published on the subject, analyzing the theory and proposing new ways of incorporating the idea into practical devices (*5–17*).

Although the concept of this method of amplification is only a few years old, and although its successful embodiment into an instrument that can be used outside the laboratory awaits further development, its promise for future applications has aroused great interest in many technical fields. The main reason for this is that masers can operate with very low internal noise, much lower than the noise of the microwave amplifiers presently used. Thus, masers offer the possibility of greater ultimate sensitivities in the fields of radio astronomy, communications, and radar. Microwave spectrometers using the maser principle have already established their usefulness. Masers can be designed to oscillate at a very stable frequency, thus providing a basis for very accurate time standards.

The development of the maser was made possible by recent research in

The author is a member of the staff of the electronics department of the RAND Corporation, Santa Monica, Calif.

microwave spectroscopy. It is a very dramatic example of the unpredictable contributions made by basic research to many fields of technology.

Principle of Operation

The way in which a maser amplifies an electrical signal must be described in terms of the interaction of individual atoms and molecules with electromagnetic fields. Atoms and molecules can possess different amounts of internal energy which are determined by their electron configurations. They can exist for appreciable times only in a definite set of configurations called "stationary states," each of which is characterized by a definite internal energy. In general, an atom may not possess arbitrary amounts of internal energy, for only energies associated with the stationary states are allowed. In free atoms and molecules, and also sometimes in atoms in a solid, the allowed energies, called energy levels, are narrow, discrete levels separated by ranges of unallowed energies.

Under certain conditions an atom in one state may interact with its environment, losing or gaining the correct amount of energy to allow it to make a transition to another state. The amount of energy exchanged is just that required to make up the difference in internal energy of the atom in the initial and final states.

An atom can lose or gain energy by interaction with an electromagnetic wave or by interaction with other atoms. It may also change spontaneously to a state of lower energy by emitting a photon of electromagnetic radiation of energy ΔE and frequency $\nu = \Delta E/h$, where ΔE is the difference in energy between the initial and final states, and h is Planck's constant.

A very general thermodynamic argument due to Einstein proves that P_{AB}, the probability that radiation will induce an atom that is in state A to make a transition to state B, is equal to P_{BA}, the probability that the same radiation will induce an atom in state B to make a transition to state A. From quantum mechanics we find that such a transition is likely only when the frequency of the radiation is nearly equal to the difference in the energy of the two states divided by h—that is,

$$|E_A - E_b| = h\nu_{AB}$$

When electromagnetic radiation induces a transition in which the atom gains energy, this energy is taken from the electromagnetic wave. Likewise, when the radiation induces a transition in which the atom loses energy, this energy is added to the electromagnetic

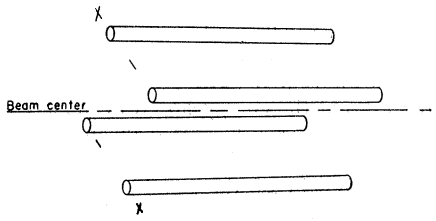

Fig. 1. Electrostatic focusing system for NH_3 molecules.

wave. This addition to the electromagnetic wave is in the form of one photon of frequency ν_{AB} that is coherent with the exciting wave (has the same phase, direction, and polarization).

When matter is in thermal equilibrium, the number of atoms in the ith state is proportional to

$$e^{-E_i/kT}$$

where E_i is the energy of the ith state, k is the Boltzmann constant, and T is the absolute temperature. Thus, the number in the state goes down exponentially with an increase in the energy of the state. If state B has greater energy than state A, the ratio of the number of atoms in the two states will be

$$N_B/N_A = e^{-\frac{h\nu_{AB}}{kT}}$$

If material in thermal equilibrium is irradiated with an electromagnetic wave of the proper frequency, the number of induced transitions that absorb energy from the wave is given by $N_A P_{AB}$, while the number of induced transitions that take energy from the atoms and give it to the wave is

$$N_B P_{BA} = N_B P_{AB} = N_A P_{AB} e^{-\frac{h\nu_{AB}}{kT}}$$

Thus, if the atoms are in thermal equilibrium at any temperature T, there are more atoms in the lower state than in the upper state, and therefore there are more transitions from the lower state to the upper than there are in the reverse direction. This means a net absorption of energy from the radiation by the material. However, if by some means the thermal equilibrium can be destroyed in such a manner that there are more atoms in state B than in state A, there will be a net loss of energy by the atoms and an amplification of the power in the electromagnetic wave. This is the principle of operation of the maser amplifier.

In order to make a maser that will amplify an electromagnetic wave of a given frequency, it is necessary to find an atom or molecule with energy levels separated by the proper energy and between which the probability of induced transition, P_{AB}, is sufficiently large. Then it is necessary to use some trick to get more atoms in the upper state than in the lower state. Finally it is necessary to provide a method by which the electromagnetic energy can interact with the material. Because of the very low noise level possible in this type of amplifier, it would be desirable to build it to operate at all frequencies from low-frequency electrical signals up to optical frequencies. However, it appears that the necessary requirements for maser operation can be met only in the microwave region of the spectrum. This is due in part to the need for resonant cavities to increase the interaction of the material with the radiation. A number of ingenious masers have been built or proposed. We will investigate the problems of making masers by discussing some of them.

Molecular Beam Maser

The original maser built at Columbia University by Gordon, Zeiger, and Townes used ammonia gas as the working substance. The two energy levels of the ammonia molecule used were the "ground" level, the lowest energy level of the molecule, and an energy level lying slightly above it. The energy separation of these levels is such that transitions between them are caused by microwave radiation with a frequency of 24,000 megacycles per second or a wavelength of 1.25 centimeters.

The method used to obtain an excess of ammonia molecules in the upper state was to separate physically the molecules of the two states and discard the molecules that were in the lower state. This was accomplished by making use of the Stark effect, the change in energy of these two states when they are placed in an electric field. When an ammonia molecule is placed in an electric field, the energy of the lower state is lowered and the energy of the upper state is raised. Thus there will be a force on a molecule in the lower state that is in the direction of the gradient of the electric field strength, while there will be a force that is in the direction opposite to the gradient of the electric field strength on a molecule that is in the upper state.

The ammonia molecules issue from a source into an evacuated chamber in a well-collimated beam. This beam is directed down the axis of an electrostatic focusing system made of four or more electrical conductors that are made alternately positive and negative as shown in Fig. 1. In such a configuration the gradient of the electric field strength is away from the center of the beam. Thus molecules in the upper state are pulled in toward the beam axis while those in the lower state are expelled outward from the beam, and physical separation of the molecules in the two states is accom-

plished. Molecules in the upper state are allowed to flow into a microwave cavity that is resonant at 24,000 megacycles per second.

If microwave energy of this same frequency is fed into the cavity, it will induce transitions of the ammonia molecules from the upper state to the lower state, releasing photons of microwave energy. Although the radiation can also induce transitions in the reverse direction and thereby absorb microwave energy, there are so few molecules present in the lower state that this seldom occurs. Thus, on the average, energy from the molecules is added to the energy of the electromagnetic wave. If this gain in energy is greater than the electrical losses in the cavity, more microwave energy can be taken from the cavity than is supplied to it. Thus the microwave signal has been amplified.

The gain of such an amplifier is proportional to the probability that the input radiation will stimulate the emission of a photon of radiation. This probability is of course proportional to the excess number of molecules in the upper energy level over the number in the lower energy level. It increases as the Q of the cavity increases because the higher electromagnetic energy density in a cavity of higher Q interacts more strongly with the ammonia molecules. (The Q of a cavity is the ratio of the energy stored in the cavity to the energy dissipated during each cycle of oscillation.)

If the gain of the amplifier is high enough so that input radiation is not required to make up for electrical losses in the cavity, the maser will act as a microwave oscillator. It will give a microwave output even without a microwave input. Since the frequency of oscillation is determined primarily by the spacing of the energy levels of the ammonia molecule, there is very little frequency drift due to macroscopic changes in the maser. The frequency of such an oscillator has been observed to have a random drift of only one part in 10^{13} in a period of two hours (*17*). (The limit of stability of a temperature-stabilized quartz oscillator is about one part in 10^9.)

The power output of the ammonia maser amplifier is low—of the order of 10^{-10} watt. Because of the sharpness of the ammonia energy levels, these amplifiers also have a very narrow bandwidth —of the order of a few kilocycles per second or less. The only advantage they have over conventional amplifiers is that they have much lower internal noise and can therefore amplify much weaker signals.

Noise in masers comes from several sources. Two sources of noise that can be illustrated with ammonia masers are given below. If the walls of the cavity can absorb microwave radiation, then, from general equilibrium considerations (Kirchoff's Law), they will also emit similar radiation. The rate of emission can be calculated from the black-body formula if the temperature and emissivity of the walls are known. If the emissivity is low the emission from the walls will be much less than it is from a black body at the same temperature. This radiation contributes to the background against which a signal must stand out.

Another source of noise in masers is spontaneous emission of microwave photons by molecules in the upper state. The probability of a free atom or molecule radiating spontaneously is proportional to the cube of the frequency of the radiation. Although a free atom may emit an optical photon spontaneously in 10^{-8} second, the spontaneous radiation of a microwave photon in a molecular beam maser is usually very improbable compared with the probability of stimulated emission by the input signal. This is not necessarily true for some types of masers considered below in which cooperative effects of many atoms may increase the probability of spontaneous emission (*18*).

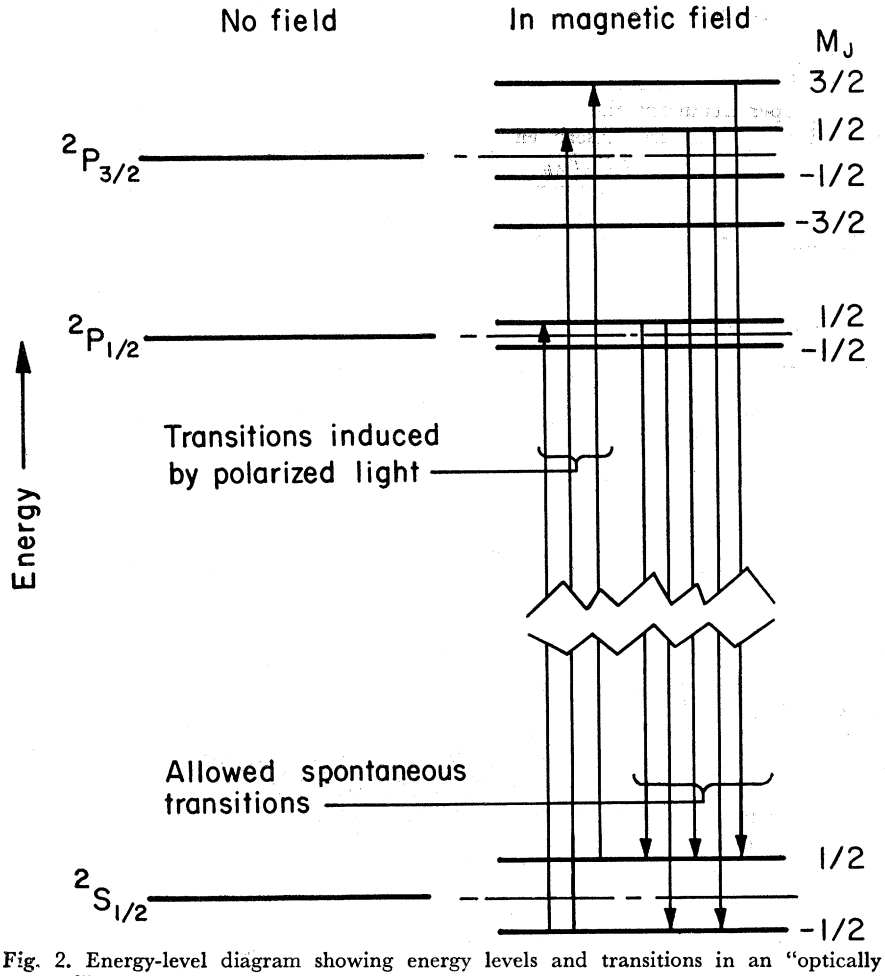

Fig. 2. Energy-level diagram showing energy levels and transitions in an "optically pumped" maser.

"Negative-Temperature Maser"

A second type of maser uses a method to obtain an increase in population in the upper state similar to that used by Purcell and Pound in obtaining "negative temperatures" (*19*). In this method the atoms used are placed in a magnetic field B, where the ground state will split up into a number of magnetic sublevels of different energy. The energy of the ith sublevel with respect to its zero field value is given by

$$E_i = \mu_0 g M_{Ji} B$$

where μ_0 is the Bohr magneton (this is a constant equal to 9.27×10^{-21} erg/gauss), g is the Lande g factor, and M_{Ji} is the component of the total angular momentum of an atom in ith state in the direction of the magnetic field in units of $h/2\pi$. When thermal equilibrium is established, the number of atoms in each level becomes proportional to $e^{-E_i/kT}$. Now if the direction of the magnetic field is suddenly reversed, the value of M_{Ji} for each state is suddenly multiplied by -1. A state that previously had energy E_i now has energy $-E_i$. Thus the population of each of these states is proportional to $e^{+E_i/kT}$, the distribution they would have according to the Boltz-

mann formula for a temperature of $-T$; hence the term *negative temperature*. Thus we have the condition for maser operation—namely, a greater number of atoms in the upper states than in the lower states.

The negative-temperature maser has the advantage over the ammonia maser that, when it is used as an amplifier, it can be tuned to a different frequency range. Varying the magnitude of the magnetic field varies the energy-separation of the energy levels, and hence, the frequency of operation. Inhomogeneities in the magnetic field and in the natural breadth of the energy levels of many of the substances which might be used would also increase the bandwidth over that of the ammonia maser.

This type of maser has two main disadvantages. Since its gain decreases exponentially as the atoms approach thermal equilibrium, it is necessary to recharge the energy source periodically. Thus the operation of the maser will be intermittent. In addition, a very low temperature is required in order to obtain a large population difference between the states. For this type of maser the noise due to spontaneous emission may be relatively important (*18*).

"Optically Pumped" Maser

A third class of masers uses the method of optical pumping (*20, 21*) to excite the atoms of the working material into an upper energy level. A simplified example of the optical-pumping process as applied to sodium is illustrated in the energy-level diagram in Fig. 2. The energy levels produced by the interaction of the nucleus with the electronic structure of the atom are neglected here, for they only complicate the problem without changing its basic character.

The familiar yellow lines in the spectrum of the sodium atom are produced by transitions from $^2P_{3/2}$ and $^2P_{1/2}$ states to the ground $^2S_{1/2}$ state. When a sodium atom is placed in a magnetic field, each of these levels splits up into sublevels as shown in the diagram. The frequency that causes a transition between the $M_J = 1/2$ and $M_J = -1/2$ sublevels into which the ground state splits is 5.6 megacycles per gauss of the applied magnetic field. The optical-pumping process is used to obtain an excess population in the upper of these two levels, and thus it permits a maser to operate between them.

If circularly polarized light from a sodium lamp is directed into the sodium vapor in the maser along the direction of the applied magnetic field, the light is absorbed by the sodium atoms in the ground levels and excites them into one or the other of the ^2P levels. Because of the circular polarization of the light, only transitions in which M_J changes by +1 are allowed (see Fig. 2). These excited atoms spontaneously emit a light photon and drop down to one of the ^2S levels. The allowed spontaneous transitions are those for which M_J changes by ± 1 or 0, as indicated in the diagram. It can be seen by following through the allowed transitions that atoms in the lowest ^2S level may be "pumped" into the upper ^2S level, but once an atom is in the upper level it cannot get back to the lower level by this process. In this way the number of atoms in the upper level can be increased over the number in the lower level.

Attempts to make a maser of this type have thus far been unsuccessful because the excess number of atoms in the upper state could not be made large enough. A slightly altered technique being applied by Wolfgang Franzen at Arthur D. Little, Inc., promises to be more successful.

Solid-State Maser

The most successful maser amplifiers developed so far have been solid-state, three-level masers. The method of operation was first proposed by Bassov and Prokhorov (*5*) and was developed in greater detail by Bloembergen (*7*).

The use of a solid in a maser has the advantage of providing a much greater density of participating atoms. The operation is made more complicated and in some instances is hampered by the interactions of the participating atoms with the lattice of the crystal.

Although most solid materials have broad energy bands rather than sharp levels, there are some atoms, notably those of the transition and rare-earth elements, that possess levels that are narrow enough to be used in masers. The position of these levels is influenced by the environment of the atom in the crystal. These levels may be split into a larger number of levels, and their position may be altered by application of a magnetic field.

The method proposed by Bassov and Prokhorov and by Bloembergen for obtaining more atoms in the upper of two energy levels is as follows. Consider three unevenly spaced energy levels of an atom in a crystal as shown in Fig. 3. If the energy levels are in thermal equilibrium, the number of atoms in levels B and C will be

$$e^{-\frac{h\nu_{AB}}{kT}}$$

and

$$e^{-\frac{h\nu_{AC}}{kT}}$$

times the number in level A. If the material is then exposed to intense radiation of frequency ν_{AC} a new equilibrium will be established in which there are the same number of atoms in the two levels A and C. The number of atoms in level B can be either less than or greater than the number in levels A and C, depending upon the relative transition probabilities between the three levels. These transition probabilities are determined by the interaction of the atoms with the crystal lattice and are very much greater than the spontaneous transition probabilities of a free atom. We will use the notation W_{ij} to denote the probability that a lattice-induced transition from state i to state j will occur.

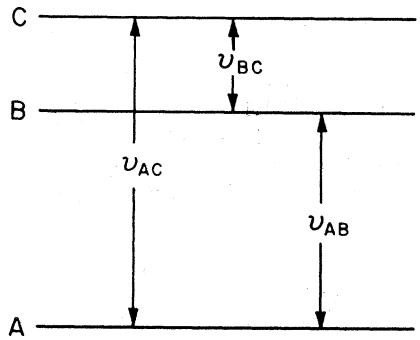

Fig. 3. Energy-level diagram showing energy levels and transitions in a solid-state maser.

If $W_{CB} \gg W_{BA}$, the population of level B will be in thermal equilibrium with the population of state C above it. Thus there will be more atoms in state B than in state A, and it will be possible to operate a maser at frequency ν_{AB}. Likewise, if $W_{BA} \gg W_{CB}$, it will be possible to operate a maser at frequency ν_{BC}.

Solid-state masers are operated at liquid helium temperatures (4°K and below) for several reasons. First it should be noted that the maximum population difference $N_B - N_A$, and hence the maximum gain, is achieved when the ratio N_B/N_A is as large as possible. The maximum value this ratio can have is

$$e^{+\frac{h\nu_{BC}}{kT}}$$

This is possible when state B is in thermal equilibrium with state C. Thus it is desirable that the ratio ν_{BC}/T should be large. Unfortunately ν_{BC} must be less than the frequency ν_{AC} at which power to operate the maser is delivered. Since $k/h = 2.1 \times 10^{10}$, the ratio N_B/N_C is only e when ν_{BC} is 20,000 megacycles per second and the temperature is 1 degree Kelvin. Because sufficiently powerful sources of microwave energy are not available at frequencies above 30,000 megacycles per second, it is necessary to operate this type of maser at a very low temperature in order to realize its maximum gain.

Although the gain of a maser is pro-

portional to only $N_B - N_A$ and is not a function of the total number of atoms of the active material present, fluctuations in the gain result when the total number of atoms is large (*22*). Thus, if we wish to achieve the ultimate performance from the maser, we cannot compensate for the gain lost by using a warm crystal simply by using more material.

Another important reason for operating solid-state masers at low temperatures is that the desired low values for the lattice-induced transition probabilities have been achieved only at low temperatures. If these transition probabilities are increased, more power is required to maintain the equilibrium of population densities that permit maser operation. If these transition probabilities are high, they also contribute to the noise level of the amplifier.

In spite of all the difficulties associated with the design and operation of a solid-state maser, successful amplifiers of this type have been constructed at Bell Telephone Laboratories by Scovil, Feher, and Seidel (*13*) and by J. W. Meyers at the Lincoln Laboratory of Massachusetts Institute of Technology. The Bell Laboratory maser, which uses a gadolinium atom in a crystal of gadolinium ethyl sulfate, operates at about 9000 megacycles per second. The more recent solid-state maser operating at the Lincoln Laboratory uses chromium atoms in a potassium chrom cyanide crystal and operates at 2800 megacycles per second. It amplifies linearly up to an output of 10^{-6} watt with a maximum output of 10^{-5} watt. The amplifier has gains of 40 decibels and 10 decibels with bandwidths of 25 and 500 kilocycles per second, respectively. The noise temperature of the amplifier has been estimated conservatively to be under 100°K.

We can expect considerable progress in the field of solid-state masers. Research into the properties of solids will reveal new materials with more suitable properties. A better understanding of the effects of different lattice structures and of magnetic fields upon the position of energy levels and upon transition probabilities is needed. If more is known about the characteristics of very high energy states in crystals, perhaps some form of optical pumping can be used in a solid-state maser, thus removing some of the reasons for the present unfortunate requirement that it be operated at a very low temperature. This is a field where clever invention has played as important a part as basic research. Certainly no one can predict what part new inventions will play in the future.

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Finding Chemical Records by Digital Computers

Louis C. Ray and Russell A. Kirsch

The National Bureau of Standards and the United States Patent Office are actively collaborating in a long-range program to develop and apply automatic techniques of information storage and retrieval to problems of patent search. An important preliminary phase of this program has been the carrying out of experiments with methods for locating information in large files of technological and scientific information.

In the granting of United States patents, it is necessary for patent examiners to refer to collections that may, in principle, contain from 10^6 to 10^7 documents. When an examiner conducts a literature search to determine whether a patent application represents a novel idea, which then must be tested against established criteria for patentability, he must search insofar as possible through all literature in the public domain that might possibly contain any information pertinent to the given application. It has been estimated that 60 percent of the time spent by an examiner in processing a patent application is devoted to searching the technical literature. In an attempt to reduce this expenditure of time, the National Bureau of Standards–Patent Office group has considered, among other techniques, the use of automatic data-processing systems.

By an automatic data-processing system (ADPS) is meant a collection of machines, usually but not necessarily electronic in nature, which have the ability to process information in accordance with internally stored programs and which can perform a whole data-processing task involving the use of data-storage facilities of diverse natures without the necessity for manual intervention. The system also includes devices for the preparation of input data and the reproduction of output data. SEAC, the NB*S* *E*lectronic *A*utomatic *C*omputer, is an automatic data-processing system; it has been used in successful preliminary experiments wherein a collection of over 200 descriptions of steroid compounds is exhaustively searched to answer typical questions that may occur in evaluating patent applications for new chemical compounds. This article (*1*) describes some theoretical ideas on the use of automatic data-processing systems for literature searching; these ideas have resulted from experiments in searching through chemical information.

In considering any attempt to automatize the searching of technical literature in the U.S. Patent Office, it must be remembered that the historical nonautomatic or manual method of searching which is presently in effect at the Patent Office utilizes the best intellectual efforts

The authors are on the staff of the Data Processing Systems Division, National Bureau of Standards, Washington, D.C.