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THE SOLID STATE MASER

Principles, Applications, and Potential

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ABSTRACT

Maser development has matured to where we now have examples of applications to a number of systems. The problems associated with these applications are receiving more and more attention. Recently, significant advances have been made, making the application of masers to systems more feasible under more diverse environmental circumstances. Included is a description of the fundamental aspects of masers and a summary of the present state of development. To reveal areas where important contributions can be made to facilitate maser applications, advantages and disadvantages of masers as low-noise amplifiers are reviewed. The results of a number of applications are briefly surveyed to illustrate the maser's potential, and an indication is given of some of the application possibilities of the future.

Accepted for the Air Force
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THE SOLID STATE MASER*

Principles, Applications and Potential

Introduction

The discussion that follows includes an outline of some basic principles of maser operation, some practical applications to which masers have been put, a survey of the type of auxiliary apparatus required for effective maser application, a review of some of the current problem areas, and some indication of the maser's future potential in space radar, space communications,and in the improvement of existing electronic systems.

As a device, the solid state maser amplifier is relatively young. Following the original proposal by Bloembergen in 1956,[1] the concept was tested in the laboratory by Scovil and co-workers in 1957[2] and shortly thereafter arranged to function as an amplifier on which noise measurements were made at Lincoln Laboratory.[3] The maser had already been put to work at Lincoln Laboratory by February 1958.[4] It played an essential role in the radar detection of the planet Venus. Since then, there have been at least five other important applications of masers to electronics problems.**

The solid state maser has had many fringe benefits. A most important benefit is the basic research into the properties of paramagnetic materials it has stimulated. It has also shown the importance of the further development of low noise components and efficient microwave circuits. The development of improved cryogenic apparatus and experimental techniques has been encouraged by potential maser users. The

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* This report is based on a talk presented by the author at a panel discussion entitled "Broadening Device Horizons" held at the 1960 IRE International Convention March 22, 1960.

** See appendix for tabulation.

very existence of the solid state maser with its extremely low noise properties has stimulated significant advances in the development of competing methods of low-noise microwave amplification.

In a larger sense we have only begun to realize the maser's potential. What lies ahead is hard work. The glamour of novelty is beginning to wear off. We are faced with the problem of converting laboratory prima donnas that require meticulous adjustment and careful handling into the rugged frontier-type women ultimately able to face the hard facts of life in the field. We must become familiar with the advantages and disadvantages of masers from many points of view, for competitive methods exist for doing the low-noise amplification jobs; hence it is only on the basis of a broad understanding of the subject that we can make intelligent and economical decisions regarding specific applications. As is usually the case, masers offer no panacea but they have demonstrated their ability to make significant improvements in existing systems, and their further exploitation depends on our ingenuity and our application to the work ahead.

Maser Principles

The basic problem in a solid state maser is to get a net emission of microwave energy from a solid. Incident radiation that is resonant with the separation of energy levels in this solid stimulates not only emission of energy, but also absorption of energy. In the usual equilibrium situation, the absorption always exceeds the emission. The reason for this is that in equilibrium the population of a lower energy level always exceeds that of an upper. To get a net emission of microwave energy, we must populate a higher energy level in excess of a lower level. There are a number of ways of doing this. In the case of the gaseous maser, for example, particles in the lower energy level are sorted out

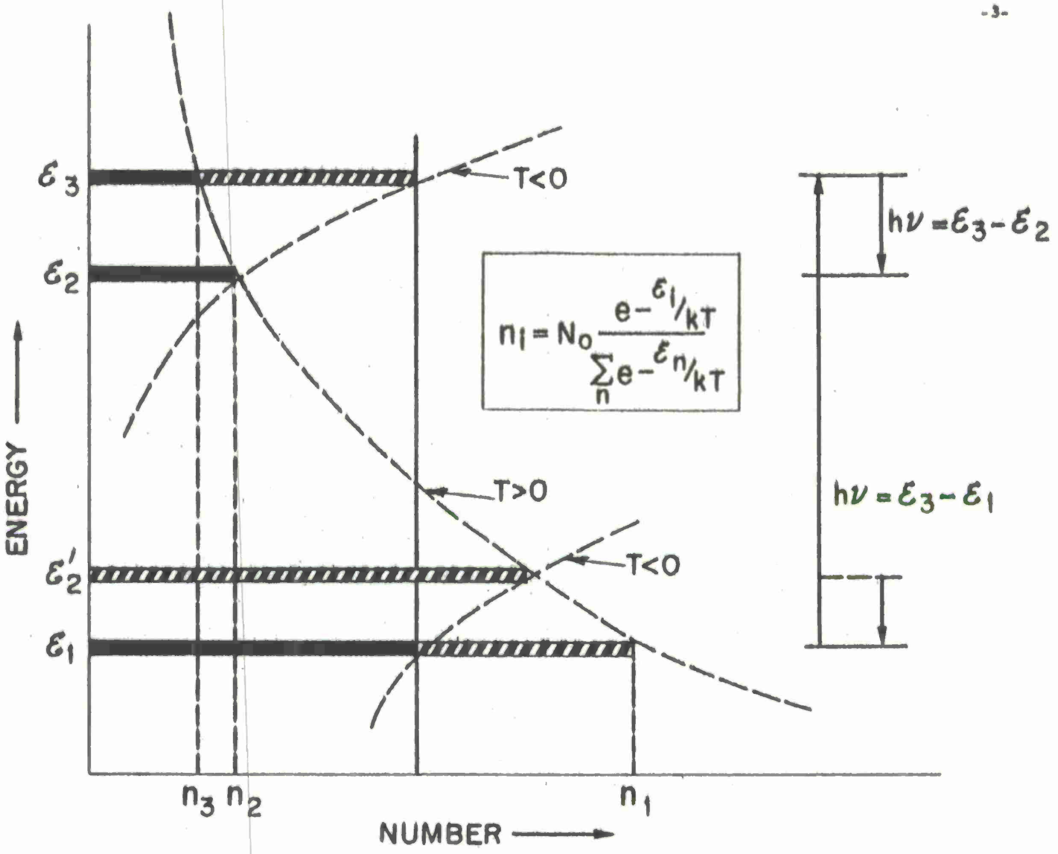

Figure 1. Energy Level Populations in a Paramagnetic Solid, and the Creation of Population Inversion

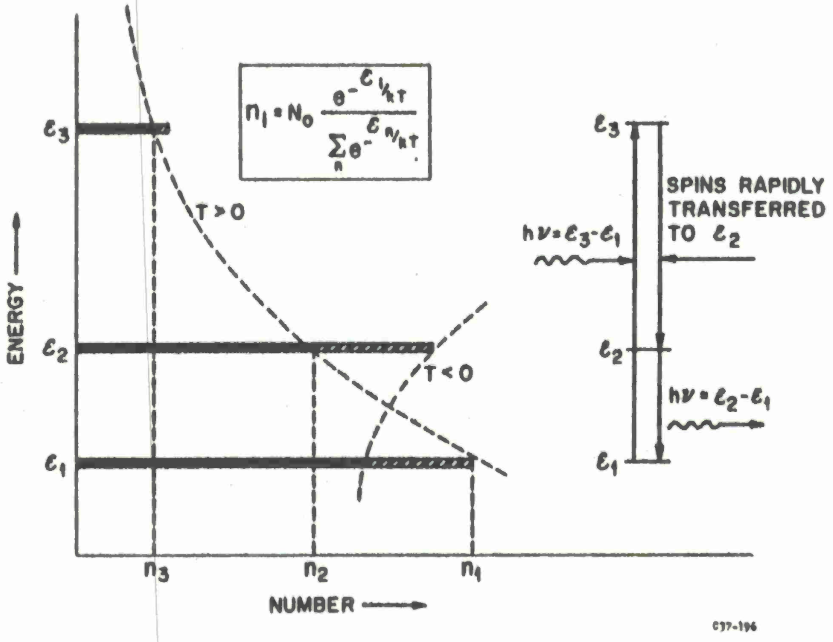

Figure 2. Population Inversion Through the Use of Impurity Relaxation Phenomena

and removed by selective electrostatic focusing. In the solid state maser, we use a method of selectively depleting the population of a lower lying energy level.

For a paramagnetic solid, the energy levels of primary interest to us are those corresponding to the several possible orientations of the magnetic moment of a spinning electron in a magnetic field. The spacing of these levels, and,therefore, the frequency of the radiation resonant with this spacing, can be changed by varying the magnitude and orientation of an applied magnetic field.

The orientation of the assembly of electron spins relative to the applied magnetic field is described in terms of the number of spins (particles) occupying the several energy levels. A nearly aligned electron spin with the applied magnetic field is represented by one occupying the lowest energy level. Higher levels represent poorer alignment.

Perfect alignment (all spins in the lowest level) is prevented by the effect of thermal vibrations in the solid. These thermal vibrations have an amplitude and frequency distribution determined by the absolute temperature of the solid, T. At high temperatures, the large amplitudes of these vibrations prevent much spin alignment even in the presence of fairly large magnetic fields. The distribution, at equilibrium, of spins over the energy levels is given by what is known as a Boltzmann distribution. This equilibrium distribution is illustrated graphically in Figure 1. Boltzmann's equation for the number of particles n_i, having the energy $\mathcal{E}_i$, at an equilibrium temperature T is also shown. The constant, k, (Boltzmann's constant) relates the absolute temperature to energy. We see that for positive temperatures T the population of higher energy levels will always be less than that of lower levels. If microwave energy is applied to the solid resonant with the separation between two of the energy levels, say $\mathcal{E}_1$ and $\mathcal{E}_3$, there will be an absorption of energy. The absorption is accomplished by the elevation of particles in the lower state to the upper state.

There are three ways by which particles return to the lower levels; (1) by spontaneous emission (2) by transitions stimulated by the incident energy and (3) by the transfer of energy between the particles and the vibrations of the solid lattice. If the incident microwave energy has sufficient power, the rate at which the particles are taken from the lower level to the upper level will exceed rate at which they are returned to a lower level. By further increase of incident power, it is possible to equalize the population of the two energy levels. This is known as saturation. When the populations are equalized, the incident radiation stimulates absorption and emission by an equal amount and no further change can be made by increasing power.

With the saturation accomplished, it is seen that levels lying intermediate to those being saturated exhibit a relative population inversion. If, for example, the intermediate level lay close to the upper level, then the upper level is populated in excess of the intermediate level. If, on the other hand, the intermediate level is located close to the lower level, this intermediate level is populated in excess of the lower level. Thus by the selective depletion of a low-lying energy level, we have accomplished what we set out to do - create an inversion of the population. An inverted population distribution can be thought of in terms of a negative temperature because a negative temperature inserted in Boltzmann's equation gives the increasing exponential characteristic bounding the inverted energy level population. (Figures 1 and 2)

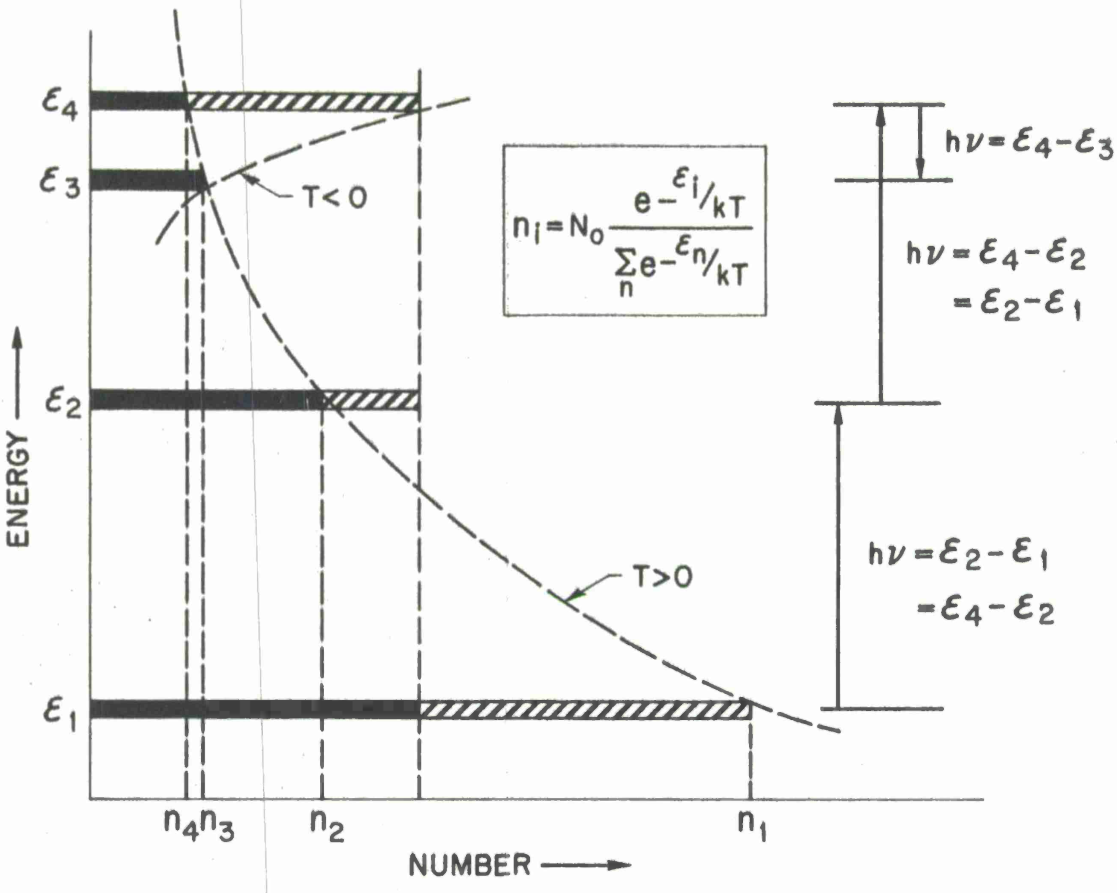

Figure 3. Population Inversion by means of Push-Push Pumping

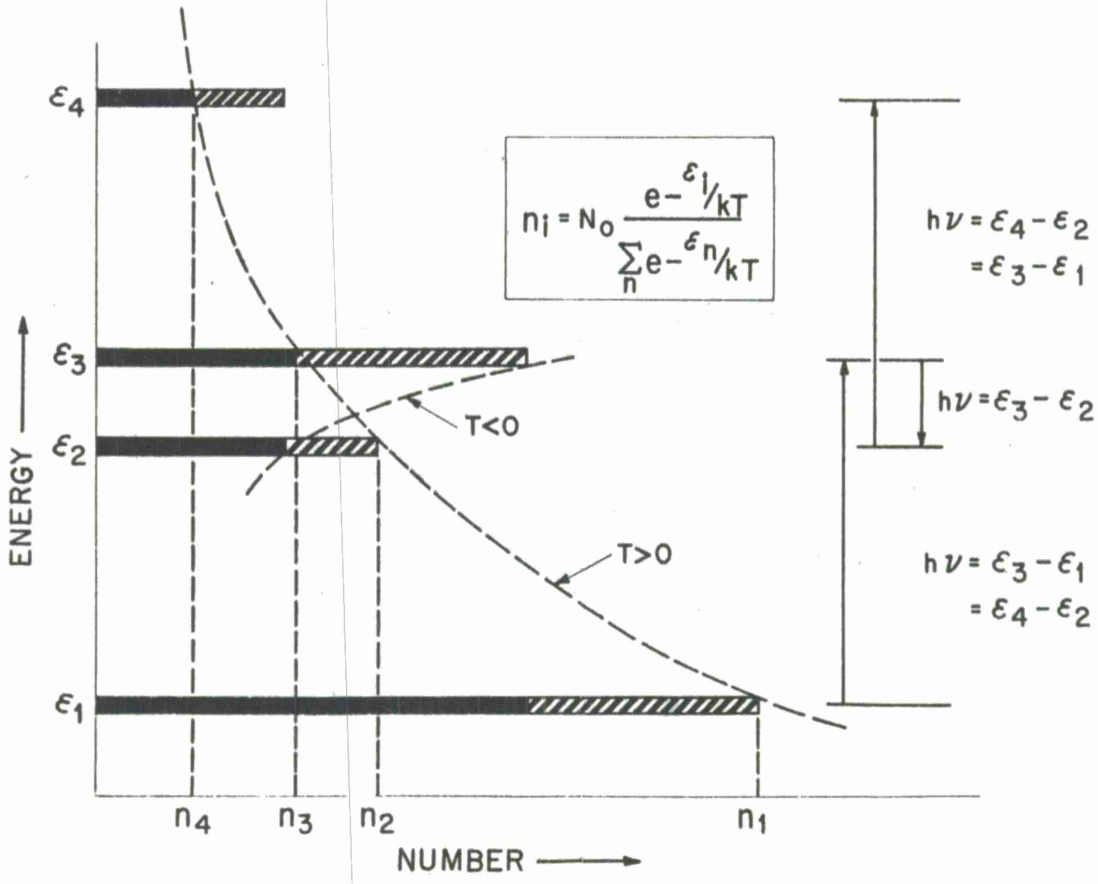

Figure 4. Population Inversion by means of Push-Pull Pumping

With the population inversion accomplished for a pair of levels, weak incident radiation resonant with the inverted levels' separation will stimulate a net excess of coherent radiation, hence produce amplification.

In Figure 1, we note further that there is a location for the intermediate energy level that would not result in a population inversion. This occurs when its equilibrium population as given by its position on the diagram is coincident with the population of the two extreme levels when saturated. What can be done should this situation arise is illustrated in Figure 2. If by some means, natural or artificial, the spins that have been raised to the upper level by the saturating power are rapidly transferred to the intermediate level, a population inversion can be created, as illustrated, between the intermediate and lower levels. This technique was used in the first laboratory demonstration of the maser principle.[2] The rapid transfer of spins was accomplished by the inclusion of an impurity material in the maser crystal.

In those solids having more than three energy levels, we can do other things to create a population inversion. In Figure 3, we see an example of what has been called push-push pumping. The separations of energy levels 1, 2 and 2, 4 are made resonant with the incident pumping radiation. The populations of these levels are equalized in the manner shown resulting in an excess population of $\mathcal{E}_4$ over $\mathcal{E}_3$. As has been perhaps intuitively apparent, one gets a greater population inversion and hence a greater emission of microwave energy the larger the spacing between the levels being pumped compared to the energy spacing of the signal levels. Push-push pumping provides a means of getting this improved ratio without the necessity of having to use high

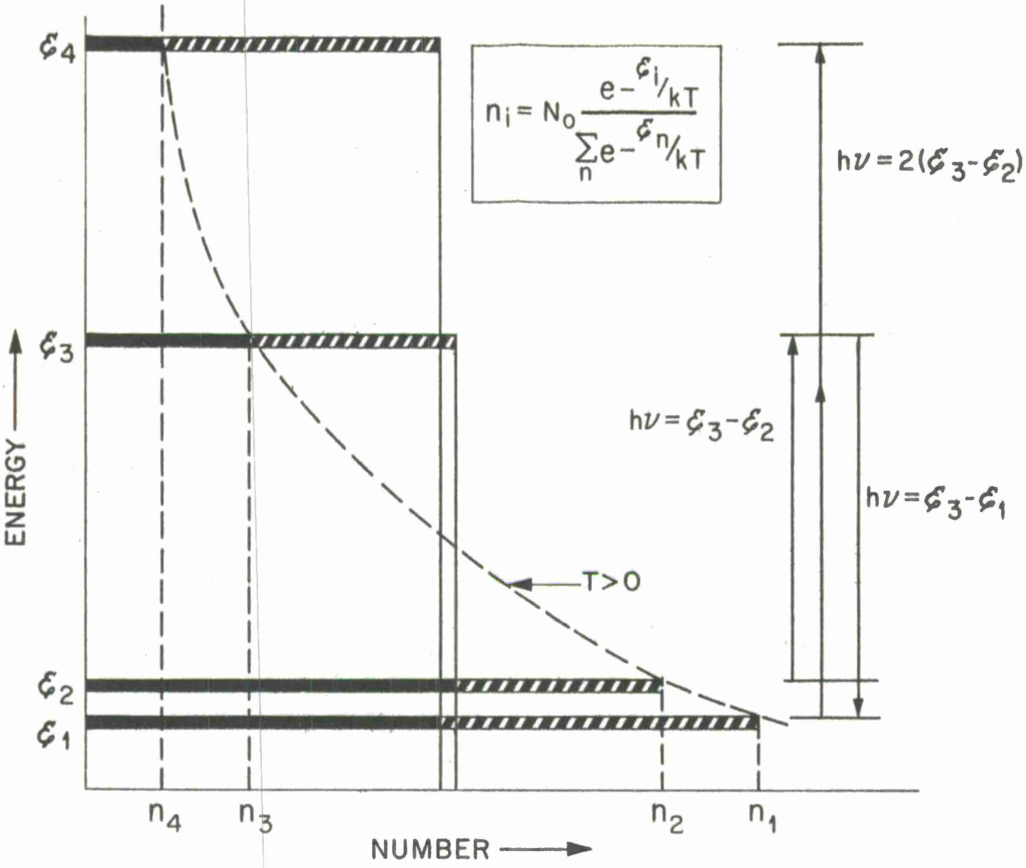

Figure 5. Operation with the Signal Frequency Higher than the Pump Frequency through Harmonic Pumping

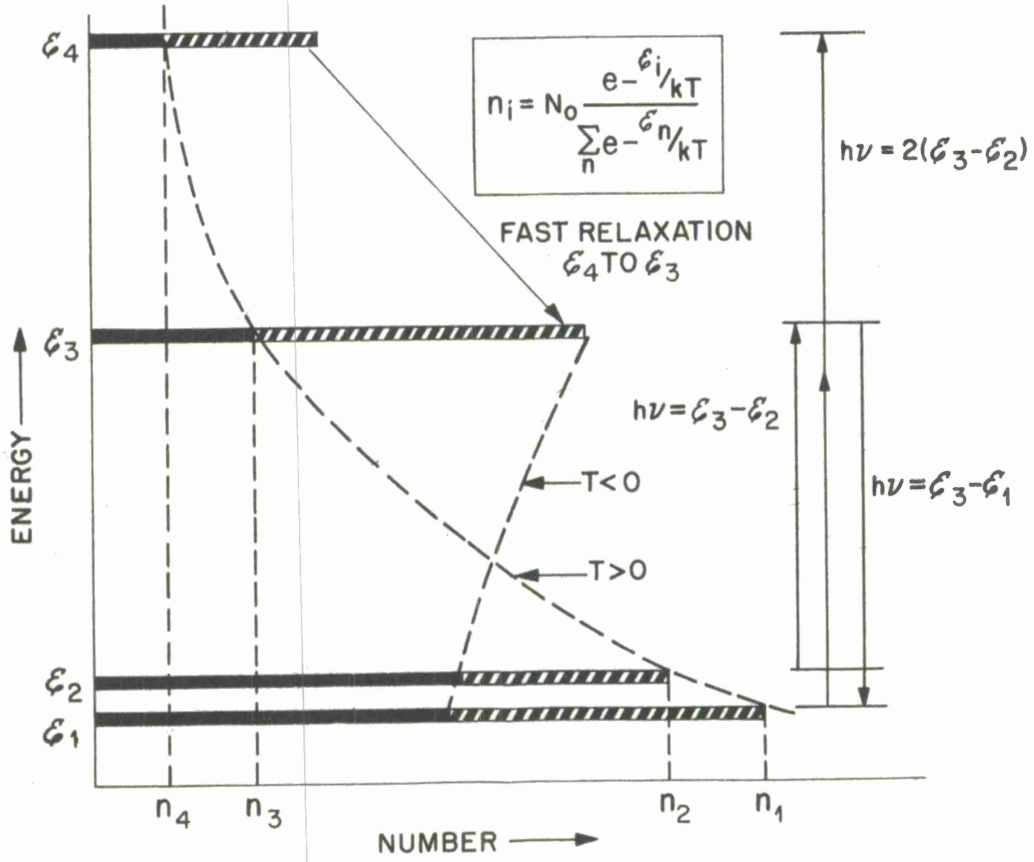

Figure 6. Harmonic Pumping in a Solid with Unequal Relaxation Times

frequency pumping energy. Only half the frequency required to produce a similar effect in a three-level maser crystal suffices. Figure 4 shows how this is accomplished using what is called push-pull pumping. Here spins in level 1 are "pushed" into level 3 and spins in level 2 are "pulled" into level 4. There results an enhanced population difference between levels 2 and 3.

In 4-level materials, it has also been shown possible to produce maser action at frequencies higher than the incident pumping frequency.[5] This method of operation is illustrated in Figure 5. The incident energy is resonant at the frequency corresponding to the separation between energy levels 3 and 2, but there is also a harmonic relationship between this and the separation between energy levels 4 and 1. As a result of complicated coupling within the solid itself, it has been shown possible to effectively saturate the transition between levels 1 and 4 and by this means create a population inversion between levels 1 and 3. The separation between levels 1 and 3 exceeds that between 3 and 2; hence the emitted energy is of higher frequency than the pump energy. Figure 6 shows how the emitted power can be increased if a fast relaxation occurs between levels 4 and 3. Recent measurements have indicated that this situation does indeed exist in at least one material, ruby.[6]

We have seen how it is possible to get a net emission of microwave energy from a solid. The power supplied to the solid was also in the form of microwave energy. The fact that we have emitted power permits us to define a negative magnetic Q in a matter analogous to the definition of a positive Q in ordinary circuits. As shown in Equation 1, this magnetic Q is equal to the angular frequency times the energy stored in the material divided by the power emitted.

$$Q_m = \frac{\omega \times \text{Energy Stored}}{\text{Power Emitted}} \tag{1}$$

The basic problem of the circuit designer is the utilization of this negative Q in a microwave circuit. It can be shown that the voltage gain bandwidth product for the cavity is approximately given by twice the signal frequency divided by the magnetic Q as illustrated in Equation 2.

$$G_v B \doteq 2f/Q_m \tag{2}$$

Where the interaction of the negative Q is with a traveling wave circuit, the gain in db is given by Equation 3.

$$G\,db = 27.3 \left(L/v_g\right) \left(f/Q_m\right) \tag{3}$$

In Equation 3, L is the length of the circuit, v_g is the group velocity, f the operating frequency and Q_m the absolute value of the negative Q. Effectively, the ratio $\frac{L}{v_g}$ is the time that the wave packet spends in the interacting circuit. The bandwidth of the traveling wave maser is given by Equation 4, wherein G is the numerical power gain;

$$B = \left(\frac{\ln 2}{\ln G/2}\right)^{1/2} \Delta f_m \tag{4}$$

In this equation, Δf_m is the width of the resonance absorption line in the maser material. This line width is just the bandwidth of the traveling wave maser if the gain of the maser is 4. As can be seen from these equations, the problem of relating emitted power to the constants of the

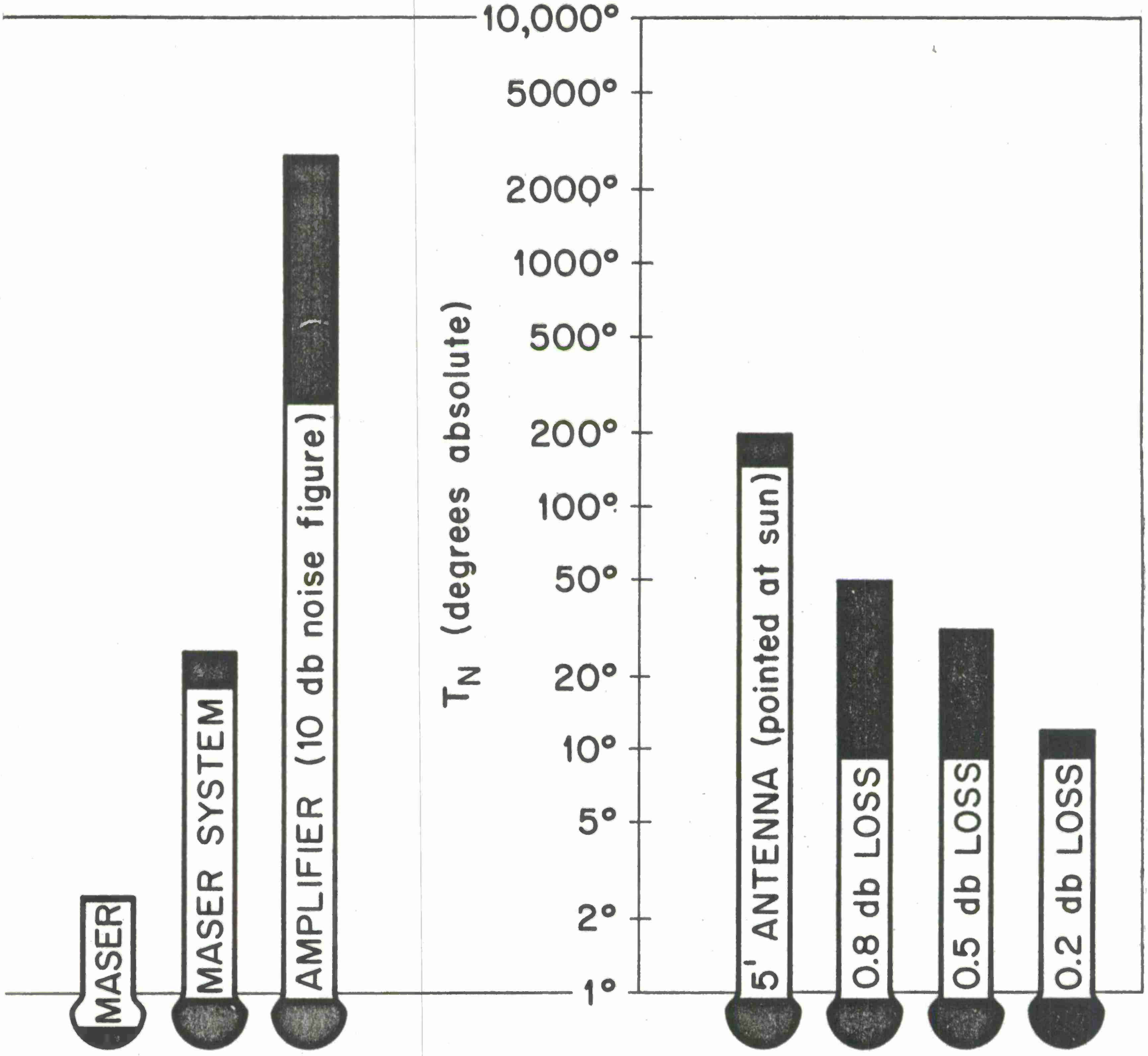

Figure 7. NOISE TEMPERATURES

NOISE POWER = kT_NB 3000 Mc/s

circuitry is one of getting the maximum power possible from the paramagnetic material and at the same time reducing the circuit losses to a minimum.

The low noise properties of maser amplifiers have been shown to live up to all expectations,[3, 7] The inherent noise in the maser is the result of spontaneous emission. A lower limit has been set on the effective noise temperature of a maser. This limit is indicated in Equation 5.

$$T \geqslant hf/k; \; h/k = 5 \times 10^{-11} \text{ sec}/^{\circ}\text{K} \tag{5}$$

An evaluation of h/k (the ratio of Planck's to Boltzmann's constant) shows that this limiting temperature is 5°K for a frequency of 100 kilomegacycles and is 50°K for a frequency of 1000 kilomegacycles. Frequencies in the microwave and millimeter wave bands are therefore low enough to make the lower limit of noise temperature inconsequential.

The significance of this level of noise is placed into context by Figure 7. Illustrated here are maser and maser system noise temperatures along with the noise temperature of an amplifier having a 10 db noise figure, a five-foot antenna pointed at the sun, and the noise temperatures corresponding to lossy components operating at an ambient temperature of ~ 300°K. A modest loss in a component of only 1/2 db has a noise temperature in excess of the maser system noise. This figure dramatically points up the importance of having low-loss components for operation with maser amplifiers. If the loss is unavoidable, then where possible the component should be operated at low ambient temperatures. These factors open up a whole new field of low-temperature, low-noise component design.

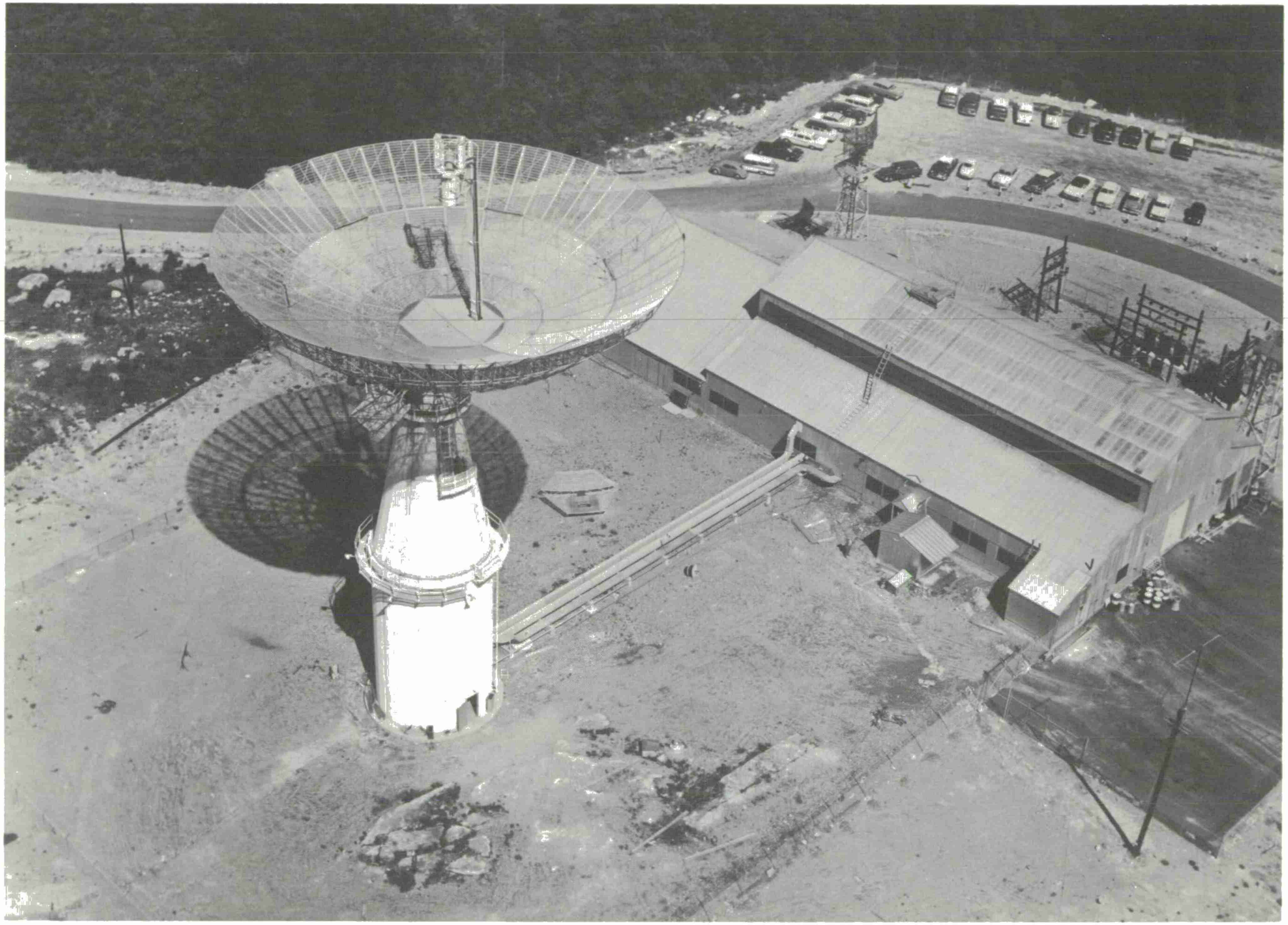

Figure 8. Lincoln Laboratory's Millstone Hill Radar Site

Applications

In February 1958, a UHF maser was installed in Lincoln Laboratory's Millstone Hill radar in an attempt to detect radar echoes from the planet Venus. This first application of a solid state maser is something of a paradox, for not only was there some doubt about the possibility of building a solid state maser at as low a frequency as 400 Mcs, but also the expectation of people working with masers was that they would be applied first to the passive detection of cosmic signals. The system features employed in the radar detection of Venus are tabulated below.

Frequency: 440 Mc/s
Ant: 84' parabola 2° beamwidth, 37db gain, dual polarization
Tx: 60 KW Ave. 1 MW Peak
Rx: $T_e = 200^{\circ}K$ (-133dbm MDS).

Table 1. Lincoln Laboratory's UHF Maser Radar

That the reduction of the effective noise temperature of the system from $700^{\circ}K$ before the application of the maser to the $200^{\circ}K$ obtained with the maser was essential to the successful outcome of the experiment is borne out by the fact that a year was spent with sophisticated data processing techniques extracting a usable signal from the background noise. In all fairness, we must say that this kind of system performance is now being achieved through the use of a parametric amplifier. But at the time of the Venus experiment, a parametric amplifier was not available. Figure 8 is a photograph of the Millstone Hill radar site.

The first application of a maser to the passive detection of cosmic noise was accomplished by workers at Columbia University and the

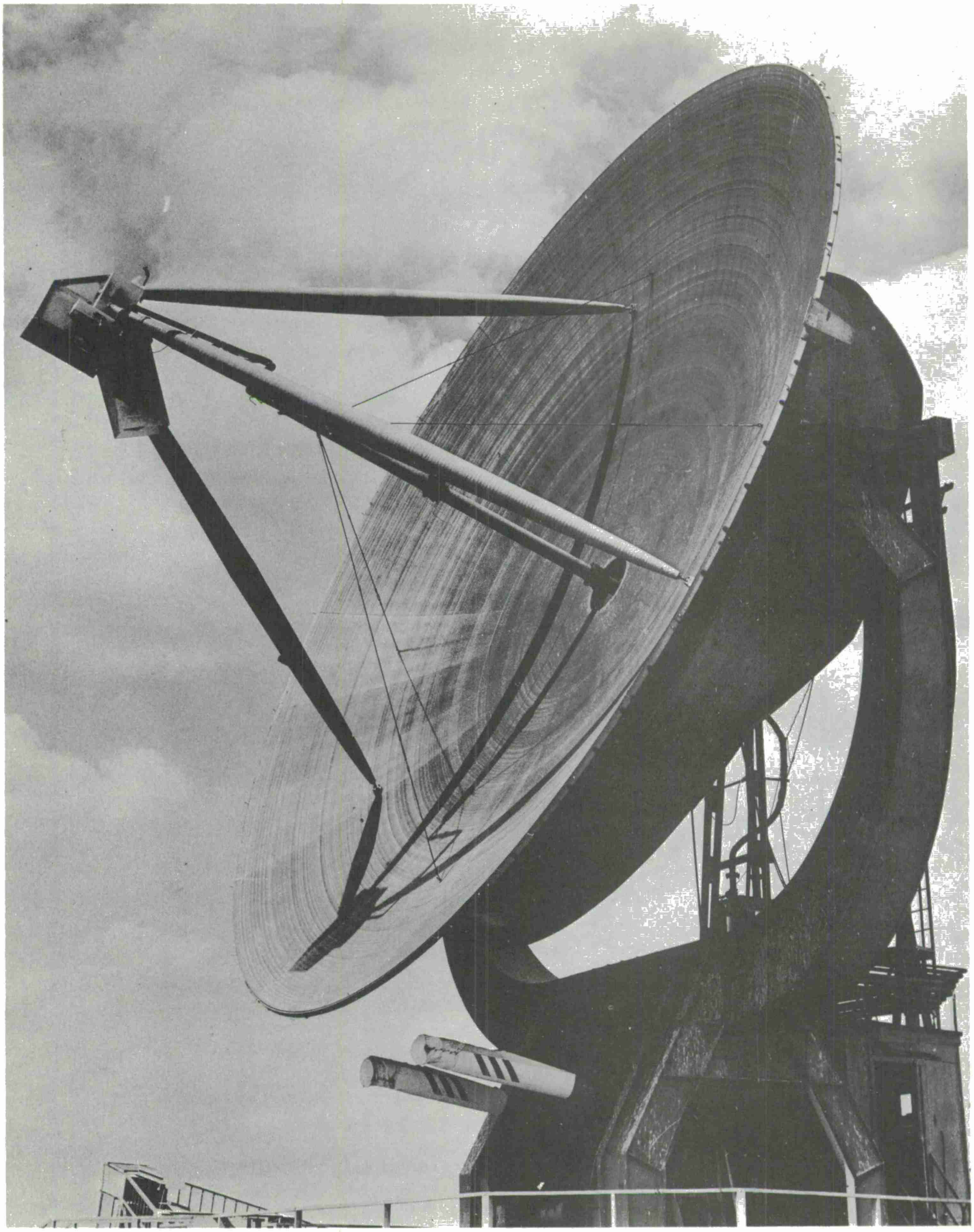

Figure 9. X-Band Maser at Prime Focus of NRL's 50' Parabola

Naval Research Laboratory. The essential features of this application are shown in Table 2.[8]

Frequency: 8700 - 10,000 Mc/s
System Noise: T_e 85°K
System Improvement about 12 Over System without Maser
Minimum Observed Fluctuation Level 0.04°K

Table 2. Columbia University - NRL Radio Telescope

In a system of this kind the minimum observed fluctuation level is proportional to the system noise temperature divided by the root of the bandwidth times the integration time. Here the somewhat limited bandwidth of masers begins to hurt. While the maser's advantage as far as noise temperature is concerned is still somewhat prodigious, the extreme bandwidths permitted by traveling wave tubes and their ever decreasing noise temperatures provides a challenging alternate method. Figure 9 shows the X-band maser package mounted at the prime focus of the Naval Research Laboratory's 50-foot parabola.

An X-band maser has been employed by workers at Hughes in a ground test of an airborne tracking radar.[9] This test also involved the development of a ferrite switch necessary for the additional protection required by the sensitive maser receiver. The features of this system are illustrated in Table 3.

Frequency: 9300 Mcps
On the Ground Test of Airborne Tracking Radar
$T_e = 170^{\circ}$K (overall)

Table 3. Hughes X-Band Maser Radar

Most of the noise represented by effective temperature of 170°K was contributed by the duplexer.

Workers at Bell Telephone Laboratories have applied a traveling wave maser to a very low noise horn-type antenna and have achieved the extremely low effective temperature of $\sim 17^{\circ}$K.[10] This system has permitted an accurate evaluation of the sky noise temperature as a function of the orientation angle of the antenna. The features of this application are shown in Table 4.

Frequency: 5650 Mcps 20 Mc/s BW
T_e (Min. Overall) = 17.2°K Including Sky Noise

Table 4. Bell Telephone Laboratory's TW Maser and Low-Noise Horn

Although early estimates of the value of a maser to systems pointed to the detection of the Hydrogen emission line as a most promising possibility, this application has been relatively long in coming. It has been recently accomplished by workers at Harvard University's Radio Astronomy Observatory.[11] The characteristics of this application are shown in Table 5.

Frequency: 1420 Mcps
Cavity Maser Mounted at Focus
$T_e = 85^{\circ}$K overall
Factor of 5 Improvement with Maser

Table 5. Harvard University's Hydrogen Line Maser on 60' Reflector

A photograph of the 1420 Mc maser mounted at the prime focus of Harvard's 60-foot reflector is shown in Figure 10. The metal low-

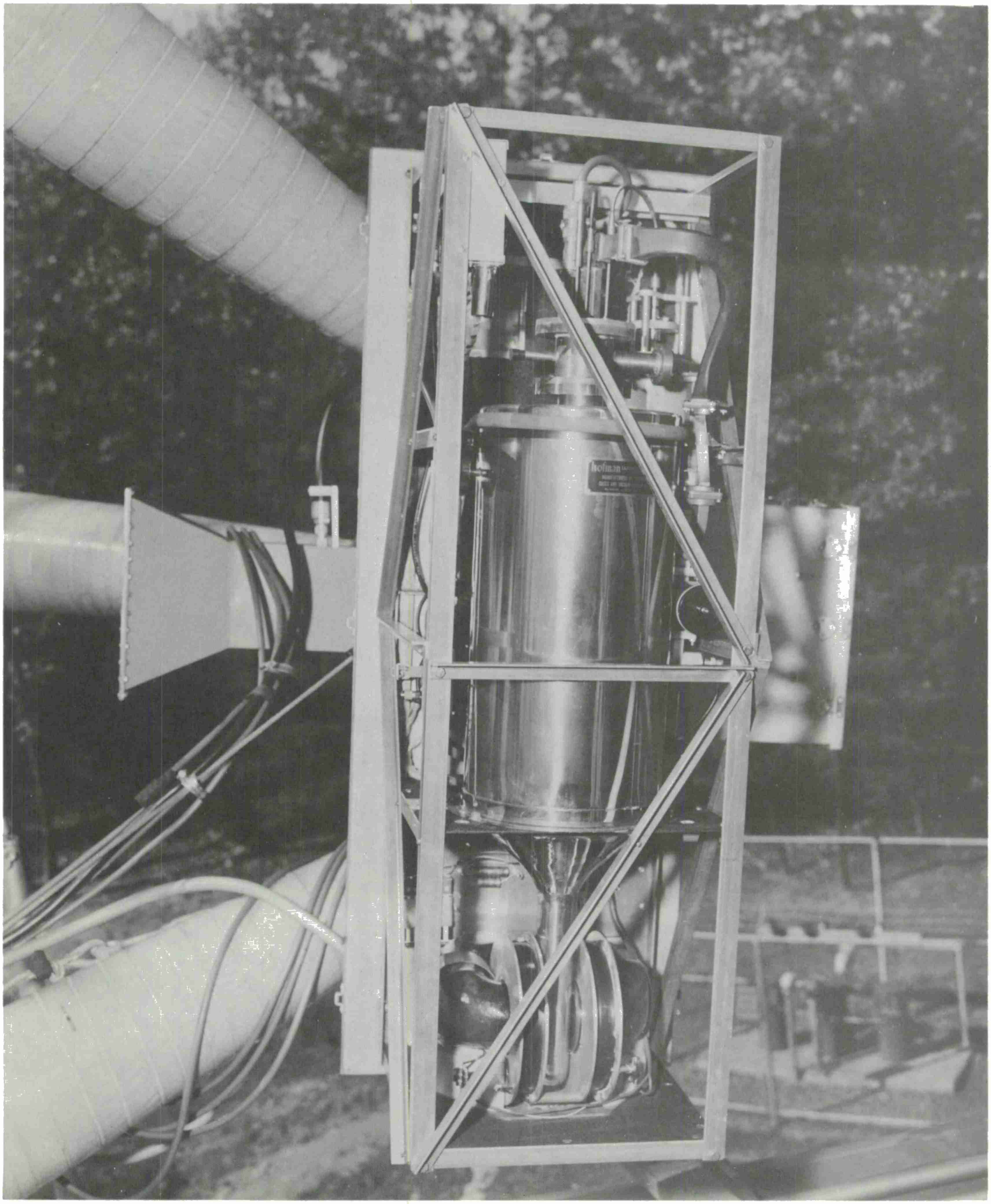

Figure 10. The Hydrogen Line Maser Installed on the Harvard Observatory Radio Telescope

temperature Dewar and the permanent magnet equipped with trimming coils employed to provide the maser's magnetic field can be seen in the mounting structure.

By early February of this year, workers at the University of Michigan[12] were using a X-band maser on their 85-foot radio astronomy antenna. The features of this installation are shown in Table 6.

Frequency: 8500 Mcps
Cavity Maser Mounted at Focus
$T_e = 100^\circ K$ (overall)
BW = 8 Mcps

Table 6. University of Michigan - X-Band on 85' Reflector

These illustrations have shown us what has already been done with masers. In every case a significant improvement in operation has been achieved. In some cases this improvement could be achieved in no other way than by using a maser. With this kind of past and present to point to, there is every indication that maser applications have a bright future.

The Frequency Spectrum Covered by Operating Masers

Masers have been operated at many points in the frequency spectrum from 300 to 40,000 Mcs.[13] At the lower frequencies there are a number of devices that compete adequately with masers as low-noise amplifiers. As is clear from the expressions for the gain of masers, as one goes up in frequency they become easier to build. This is not the case with a number of the maser's competitors. The exploitation of the higher frequencies where the advantage of the maser is so clearly apparent will require special attention to the discovery of new materials and the development of adequate sources of high frequency pump power.

Problem Areas

As is the case for most devices, a problem area in maser development is the development of adequate materials. The properties of paramagnetic materials strongly affects the following operating characteristics of the maser; the gain, and temperature, at which they must be operated, the bandwidth, and frequency of operation.

Another problem area is that of circuits. It is through intelligent circuit design that we get maser bandwidth, gain stability, and efficiency.

A third problem area is the future development of auxiliary apparatus.

A fourth is the development of simple, reliable, cryogenic equipment.

Finally, we have the problem of the provision of sources of pump power adequate both in frequency and power output.

Auxiliary Apparatus

The maser cannot perform alone. Like many other electronic components, it has a retinue of associated equipments. Indeed, in the final analysis, the performance of a maser system is often limited by the performance of the auxiliary apparatus. Therefore, to exploit fully the low noise feature of the maser, the auxiliary apparatus must be carefully engineered.

Antennas for masers should have small back lobes to avoid interception of the relatively hot ground when pointed well above the horizon. Small side lobes are desirable to avoid intercepting other hot spots and raising the effective temperature of the antenna. Very small back lobes have been achieved at Bell Telephone Laboratories with the horn antenna mentioned previously. If a large area on the ground around the antenna is covered by a reflecting material, the noise entering the antenna through the side and back lobes will then be the relatively cool sky noise. The transmission lines employed with masers must be designed either to have very low loss or some provision must be made for cooling them.

The achievement of directional and stable gain in masers usually requires the use of isolators or circulators. Ferrite isolators operating at low temperatures have been made an integral part of traveling wave masers. Low-loss circulators have been made, and circulators operating at liquid helium temperatures have also been used.

Because of their inherent extreme sensitivity, masers are very subject to saturation of the gain by excessive signal power. This places stringent requirements on switches used to protect masers when employed with radars. Two approaches have been used for solving the switch or duplexer problems for masers; (1) a polarization twist technique in ferrites and (2) the avalanche breakdown in a semiconductor. Using these devices in the systems for additional protection over that provided by the normal radar duplexer has adequately protected the maser.

Provision of a magnetic field is essential for operation of most masers. The magnetic field required varies greatly with the application and the material employed as the paramagnetic substance. While early masers were operated with large, unwieldy, research-type electromagnets, more recent designs for applications have employed small permanent magnets equipped with auxiliary trimming coils, or in those cases where not much field was required, small air core solenoids. It has been found possible to establish adequate magnetic fields for many maser applications by superconducting solenoids and iron-core magnets which require no further power source once the desired field is established. These magnets operating at liquid helium temperatures in the same bath as the maser, maintain the establish fields by the circulating current in superconducting coils. Niobium, with its high transition temperature, has been found very satisfactory for this purpose.

Another important auxiliary device is the pump power source, i.e., the microwave power supply. Normally one needs high frequency sources with reasonable amounts of power output in order to adequately saturate resonances in paramagnetic materials. As the frequency range of masers is pushed up into the millimeter wave region, we will need pump power sources there or at higher frequencies.

Thus far, we have been talking about more or less conventional and familiar auxiliary equipment. The maser also requires a low temperature environment. This calls for low-temperature apparatus and cryogenic equipment. These low temperatures can be achieved by immersing the maser in liquefied gas or into the cold reservoir of a cyclic refrigerator. Small cyclic refrigerators for use with field devices and designed to achieve temperatures in the liquid helium region are now under development. The availability of such a device will go far to alleviate the logistic problem associated with providing liquefied gases at some of the remote field sites.

In order to achieve satisfactory gain, bandwidth, and stability of a maser amplifier, a maser designer must address himself to the following problems: (1) He must minimize the magnetic Q ; he does this by combining materials, operating temperature and miceowave circuits in such a way that a maximum amount of stimulated emission is achieved. (2) Because in the final analysis, the bandwidth of the maser is tied to the linewidth of the material, the latter is an important parameter to the maser designer. (3) To insure adequate gain stability and unidirectional gain, the unidirectional properties of the right or left handed circular polarization component existing in many slow wave structures or in microwave transmission lines must be utilized to get large forward to backward gain ratios. It may be desirable or necessary in some cases to equip the maser with a compatible isolator that will attenuate the signal in the reverse direction. The isolator should operate at low temperatures.

The Maser's Future Potential

The maser is intimately concerned with our exploration of space. Antennas probing space are frequently pointed at the relatively cool sky and so oriented have the low-noise temperature that it allows one to get the most from a low-noise maser receiver. We have had an example of a deep space radar probe in the detection of the planet Venus. Further improvement of radar power and antenna aperture and the use of refined solid state masers should put the entire solar system within radar range.

The use of a maser will permit one to reduce the weight of space-borne transmitter without degradation of the quality of information communicable. This important reduction provides extra space and weight for scientific apparatus or provides for a reduction in the required booster power for sending the equipment into space.

The potential of sextants using radio sources is becoming more and more attractive because of their all-weather capability. The use of a maser to increase the sensitivity thereby increases the versatility because it permits fixes being taken on a larger number of radio sources. An increase in receiver sensitivity frequently allows a reduction in the antenna size, an important consideration for portable operation.

In the field of radio astronomy, we expect masers to contribute much to extra galactic investigations. These investigations should reveal much about the nature of our universe.

The realization of world-wide reliable communications by means of satellites is near at hand. The increased sensitivity of receivers will increase the information passing capability of communication systems employing reflections from passive orbiting satellites.

Conclusion

From what has been said, we have seen that the maser has already gone to work. It has been shown to do much more than entertain scientists as a laboratory curiosity. It is evident that significant applications and important improvements lie ahead. Much hard, and somewhat unglamorous work is involved, but this work is essential.

In addition to what it accomplishes directly, the maser has and will continue to serve as a stimulant to the development of competing means of getting low-noise microwave amplification.

JWM/mhd

APPENDIX

Systems Applications
of
Solid State Maser Amplifiers
to
March 1960*

Frequency (Mcps.)	System Noise T_e ($^{\circ}$K)	Aperture Diameter (feet)	Organization	Application	Factor of Improvement with Maser
440	200°	84'	Lincoln Laboratory	Millstone Hill radar - Venus contact- February 1958	3.5X
1420	85°	60'	Harvard College Ovservatory	Hydrogen line radio astronomy - 1959	5X
5650	17.2° min	(7' equiv.)	Bell Telephone Laboratories	TW maser and low-noise horn-1959 Bandwidth 8 Mcps.	
8500	100°	85'	Univ. of Michigan	Radio telescope February 1960 Bandwidth 8 Mcps.	8X
8700-10,000	85°	50'	Columbia Univ. - Naval Research Laboratory	Detection of cosmic noise- April 1958	12X
9300	170°		Hughes Aircraft Co.	Ground test of airborne tracking radar-1959	

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*This table includes all such applications documented in the normally available technical literature

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13. ABSTRACT

Maser development has matured to where we now have examples of applications to a number of systems. The problems associated with these applications are receiving more and more attention. Recently, significant advances have been made, making the application of masers to systems more feasible under more diverse environmental circumstances. Included is a description of the fundamental aspects of masers and a summary of the present state of development. To reveal areas where important contributions can be made to facilitate maser applications, advantages and disadvantages of masers as low-noise amplifiers are reviewed. The results of a number of applications are briefly surveyed to illustrate the maser's potential, and an indication is given of some of the application possibilities of the future.

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solid state
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