Some Potentialities of Optical Masers*

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Summary—**This paper, originally presented at the 1961 WESCON Convention, is intended as an introduction to the principles and possible applications of the optical maser. Very little prior knowledge on the part of the reader is assumed. The intent is to acquaint him with these exciting new devices with the hope that he, in turn, will discover applications not foreseen by the author. The methods of generating coherent radiation, of focussing it, and of collimating it into tight beams are described. The use of lasers for communication is explored, and certain medical and other applications are suggested.**

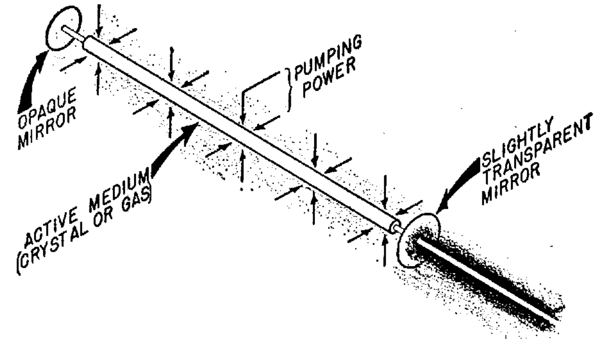

Fig. 1—Elements of an optical maser.

INTRODUCTION

NOT LONG AFTER the development of the microwave maser by Townes, Bloembergen and others, it became apparent that the same principles could be applied to the generation of radiation of far higher frequency. In a historic paper in the *Physical Review*[1] Schawlow and Townes predicted the possibility of extending maser principles into the optical region, described general types of structures which would be required, and speculated upon the performance possible. Very few developments in recent years have excited the imaginations of so many scientists and engineers as has the optical maser, or "laser." The reason, of course, is that this device offers for the first time a means for producing and amplifying coherent light and therefore opens up the optical spectrum for exploitation by all of the techniques currently used in the radio spectrum.

In July, 1960, Maiman [1] of Hughes Laboratories announced the first successful production of coherent light on a pulse basis using optically pumped ruby. Early in 1961 Javan, Bennett and Herriott of Bell Laboratories announced the successful CW operation of a gaseous optical maser [2]. In addition, there has been a great deal of activity in this field at many other laboratories, and the effort is increasing.

The basic principles of the optical maser are the same as those of the microwave maser. Fig. 1 illustrates in schematic form the essential ingredients. First of all, there must be a resonant cavity. In an optical maser this is formed by two precisely oriented mirrors, one of which is slightly transparent. It can be shown that resonant modes will exist between these mirrors at frequencies for which the spacing is an integral number of half wavelengths. In this space between the mirrors is placed an active medium which may be either a gas or a crystal doped by certain atoms (such as chromium in the case of ruby). The medium must possess two atomic states separated in energy by an amount corresponding to the frequency desired, and it must be possible to overpopulate the upper of these states with respect to the lower. This is done by "pumping" the atoms from a ground state to a higher energy state either electrically or optically. From this higher energy state the atoms usually decay nonradiatively to the upper of the two energy states involved in the desired transition. From this upper state some atoms will decay spontaneously to the lower state and emit light just as occurs in any neon sign. The light caused by such spontaneous emission is incoherent and is radiated in all directions at random. However, in the presence of the resonant cavity some of this spontaneous emission will excite one of the resonant modes of the cavity, and the field associated with the resonance will induce emission in the medium. This induced emission is phase coherent with the field which induces it and as a result, if the interaction is strong enough, a coherent electromagnetic wave will build up corresponding to one of the modes of the resonant cavity. Some of this energy will leak through the partially transparent mirror forming one end of the cavity and emerge as a sharply defined beam of coherent light. The significant thing is that this beam of light is a plane coherent electromagnetic wave just as would be produced by a radio transmitter, but of vastly higher frequency.

There are two aspects to wave coherence: spatial and temporal. A wave is *spatially* coherent if there exist surfaces over which the wave amplitude as a function of time is highly correlated. If the coherence is complete, the correlation will be unity, and the voltage at the one point will be proportional to the voltage at other points on the surface. As an example of spatial coherence, consider the amplitude at any two points on an equiphase front in the light from a distant star. The amplitude at two points is the same function of time, and similarly at a given time, the amplitude along different rays is the same function of distance.

A wave exhibits *time* coherence to the degree that there is correlation between the amplitude of the wave

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[1] A. L. Schawlow and C. H. Townes, "Infrared and optical masers," *Phys. Rev.*, vol. 112, pp. 1940–1949; December 15, 1958.

at a given point at one time and at some later time. A single frequency represents the extreme of time coherence; so does any combination of single frequencies, harmonically related. If the line components of the spectrum are broadened due to random modulation, the time coherence is lessened and in the extreme, when the spectrum of the wave consists of a smooth distribution of frequencies, as is true of black body radiation, for example, time coherence virtually disappears. Spectral purity (*i.e.*, the degree to which the spectrum approaches a line spectrum) is thus a measure of time coherence.

The following analogy may be helpful in visualizing the difference between coherent and incoherent radiation. Incoherent radiation may be thought of as the three dimensional analog of the pattern of waves on the surface of a swimming pool in its usual state just after the swimmers have left. Waves of all different wavelengths are racing every which way at random, and there is little correlation between the time functions representing the amplitudes at two widely separated points. If the pool were surrounded by quiet water at the same level and the walls suddenly removed, the agitation would spread out in all directions in a way which resembles the radiation of incoherent light. By contrast, if the surface of an otherwise quiet swimming pool were set in motion by the up and down oscillation of a float extending clear across one end, a series of plane waves would be produced. These would exhibit high spatial coherence, because the wave amplitudes as a function of time at different points would be highly correlated. And if the motion of the float were periodic, the waves would exhibit time coherence as well. If the walls were again removed the wave pattern would propagate out in a beam normal to the float, and if the wavelength were short compared with the length of the float, the beam would exhibit very little spread with distance.

Ruby lasers operate on a pulse basis and give quite high peak power output. Characteristically, pulses on the order of 10 kw output power and pulse durations of the order of 1 msec are obtained. The total energy per pulse is therefore on the order of 10 joules. Although the spectral line is clearly narrowed by the maser action, the time coherence is still relatively poor in the ruby laser. The ruby rods tend to oscillate in several modes simultaneously and to produce a series of short spikes instead of a single pulse. The line width of each mode is on the order of 10 Mc as a result of the spike amplitude modulation. The spatial coherence also is far from perfect and is thought to be limited by optical imperfections in the ruby crystals themselves. Hopefully, these are defects which will be eliminated with further research, and in our discussion to follow we will assume ideal coherent operation to be possible. The CW gaseous masers operate at relatively low power levels—on the order of 20 milliwatts—and exhibit excellent coherence. Line widths of approximately 1 cps have been reported, and the spatial coherence seems to agree with what would be expected theoretically. There is every reason to believe that the power output of the gaseous laser can be increased, and these devices look very promising for communication applications.

COHERENT OPTICS

The availability of coherent light greatly increases the scope of things that can be done with optical systems. In particular, the spreading of beams of light becomes limited only by diffraction. In an ordinary searchlight the beam spread is principally due to the finite size of the source of light. A point of the source lying on the optical axis produces a beam parallel to the optical axis, while various points of the source lying off the optical axis produce beams at various angles with respect to the axis. The totality of all these beams thus spreads at a rate determined by the greatest extension of the source and by the focal length of the objective. By contrast, plane waves radiated by an optical maser spread in the same fashion as would the beam from an antenna having the same size measured in wavelengths. Having coherent light is tantamount to having a point source.

When the light from a star is imaged by a small telescope objective under ideal seeing conditions, a diffraction pattern called an Airy disk is formed. It consists of a central patch of light surrounded by a series of rings, the intensity as a function of radius, r, being given by

$$I(r) = I_0 \left[\frac{2J_1\left(\frac{\pi d}{\lambda f} r\right)}{\left(\frac{\pi d}{\lambda f} r\right)} \right]^2, \tag{1}$$

where

d = diameter of the objective,
f = focal length of the objective,
λ = wavelength,

and J_1 is the first order Bessel function. This same diffraction pattern is formed when the light from an optical maser is brought to focus with an ideal lens, assuming the beam illuminates the lens uniformly as shown in Fig. 2. In general, the diffraction pattern is the (two-dimensional) Fourier transform of the aperture illumination. In this case the intensity at the center of the spot is

$$I_0 = \frac{A}{\lambda^2 f^2} P \tag{2}$$

where A = area of objective, and P = power in light beam.[2] Taking a value of 10 kw for the power output of the ruby laser at a wavelength of 0.7 μ, we find the power density at the center of the image to be about 10^{16} watts per square meter. This is a power density far in excess of anything normally obtained in the laboratory. As a comparison, the power density at the surface of the sun is less than 10^8 watts per square meter. Thus, the ruby laser is theoretically capable of producing a power

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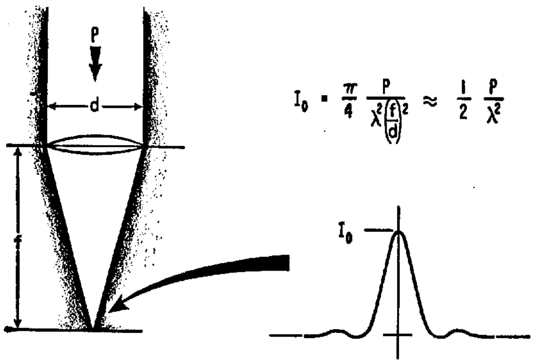
[2] This relation can be derived directly from the radio transmission expression, (5), by setting $D=f$, $A_T=A$, $P_T=P$ and $I_0=P_R/A_R$. Again it assumes a uniformly illuminated aperture.



$$I_0 = \frac{\pi}{4}\frac{P}{\lambda^2\left(\frac{f}{d}\right)^2} \approx \frac{1}{2}\frac{P}{\lambda^2}$$

Fig. 2—Focusing of coherent light.

density one hundred million times that of the surface of the sun! This high-power density is accompanied by a correspondingly high-electrical field strength given by

$$E = \sqrt{\eta I_0} \tag{3}$$

where

$\eta = 120\pi =$ impedance of free space.

For the above case we find

$$\begin{aligned} E &= \sqrt{120\pi \times 10^{16}} \\ &= 2 \times 10^9 \text{ volts per meter} \\ &= 2 \text{ million volts per millimeter.} \end{aligned}$$

At such fields it should be possible to produce many effects heretofore unobservable. Such possibilities as the alteration of the construction of molecules, the disruption of chemical bonds in small regions inside homogeneous substances, etc., suggest themselves.

If, after having been brought to a focus by an initial lens, the light from the diffraction pattern is allowed to propagate further, it can illuminate a much larger lens which can in turn recollimate the light as shown in Fig. 3. Such an arrangement will be recognized as the simple astronomical telescope used in reverse. Just as the resolving power of a telescope is increased in proportion to the diameter of its objective, so the beam spread of the emerging beam from this "optical antenna" is inversely proportional to the diameter of its objective. In fact, the width of the major lobe from the peak to the first null is found from (1) by setting $J_1 = 0$, and is the usual formula for the resolving power of a telescope

$$\frac{\pi d}{\lambda}\frac{r}{f} = \frac{\pi d}{\lambda}\theta = 3.8317 \cdots$$

$$\theta = 1.22\frac{\lambda}{d}\,. \tag{4}$$

As a result of the decreased beam spread, distant points will be illuminated more intensely, and the antenna will exhibit a power gain equal to the square of the normal magnification of the device as a telescope. Used as a searchlight, a laser followed by a telescope can produce a remarkably small spot of light at great distances. For example, a 12-inch diameter telescope on the earth would produce a central spot of light only 8800 feet in diameter on the moon. The illuminated patch, of course, corresponds to the figure of confusion of the same objective when used as a telescope.

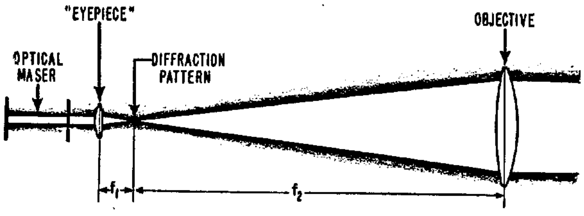


Fig. 3—Optical "antenna" with power gain of $(f_2/f_1)^2$.

$\frac{a^2}{b\lambda}$	% LOSS
0.5	10
0.7	1.2
1.0	0.05

EXAMPLE: $\begin{cases} \lambda = 0.7\mu \\ 2a = 12'' \end{cases}$

.05% LOSS IF: $b = \frac{a^2}{\lambda} = 20$ MILES

Fig. 4—Transmission between apertures.

The extremely small beam spread possible at optical frequencies with coherent light suggests that it should be possible to transmit power over considerable distances with relatively little loss. This turns out to be the case. For a given maximum size of antenna (considering both the receiving and transmitting antenna) the least power loss will occur if the beam intensity as a function of radius off axis is properly shaped. This shape is approximately Gaussian and is, in fact, the distribution which arises naturally when the resonator of the laser consists of two confocal concave mirrors as described by Fox and Li [3]. The beam from a laser employing such a resonator one meter in length is only about a millimeter in diameter: a fine thread of light. However, its radial intensity distribution will be preserved after passing through an antenna of the type shown in Fig. 3, and so it is simple to create a beam of large cross section having this Gaussian distribution. If the diameter of the transmitting aperture and receiving aperture are both $2a$ and if the distance between them is b, as shown in Fig. 4, then, with such a beam, the power loss will be as given by the table and example in that figure. A loss of one twentieth of one per cent of the power in a twenty mile hop is less than occurs with the average transmission line. However, this low loss can only be achieved if scattering and refraction in the medium are absent, and hence can be realized only in free space or if a controlled atmosphere is provided in a pipe connecting the two apertures. The possibility of transmitting power by optical means from earth to a satellite or from one space vehicle to another is a very real one.

COMMUNICATION BY COHERENT LIGHT

The use of coherent light for communication purposes is an obvious application, and in this section we will consider the potentialities of lasers in this service. The factors which must be considered are the bandwidths afforded by the new type of channel, the transmission loss, the inherent noise, and the cost. Let us look at these in turn.

In the red end of the spectrum the frequency of light is approximately 4×10^{14} cps. A 1 per cent band in this portion of the spectrum has a width of 4 million Mc, enough for a billion simultaneous telephone conversations. Thus, it should be possible in theory to transmit all of the conversations going on anywhere in the world simultaneously over a single thread of light one millimeter in diameter. Apparently we have bandwidth to burn. This is especially true when one considers the fact that because of the extremely directional beams that can be produced, many simultaneous channels can exist in the same frequency band without mutual interference. The problem is not one of lack of spectrum space, but of how to make use of it: of how to modulate the optical maser or its output so as to fill up the spectrum. Work in this direction is going on at the present time, and beams from lasers have been modulated at frequencies up to X band, so that channels 10,000 Mc wide have been achieved but at the cost of large modulating powers. There seems little doubt that ways will be found to produce extremely wide-band modulation and thus utilize the bandwidth capabilities of optical channels, but even on a less ambitious bandwidth basis; these channels are still attractive, as we shall see.

The transmission loss in an optical channel is small because of the very directional beams easily achieved, as illustrated by the example of power transmission. The basic formula of transmission loss in the optical region is the same as in the radio region, namely,[3]

$$\frac{P_R}{P_T}=\frac{A_TA_R}{\lambda^2D^2} \tag{5}$$

where

P_T = transmitted power,
P_R = received power,
A_T = area of the transmitting antenna,
A_R = area of the receiving antenna,
λ = the wavelength,
D = the distance between the antennas.

This formula assumes uniform illumination of the transmitter aperture, which indeed gives the least power loss on axis. The λ^2 in the denominator shows that the power received is proportional to the square of frequency and this reflects the increasing concentration of energy by the transmitting antenna as frequency is increased. It is important to remember that with fixed antenna sizes any improvement in transmission with increased frequency comes about from this cause alone.

There are practical limits to the directivity of beams which can be achieved even in the optical region. In order for the theoretical beam spread to be attained, an objective mirror must be well within a quarter wavelength of the true figure over its entire surface. While the surfaces of a lens are less critical, there are more of them. As the size is increased this accuracy requirement becomes increasingly difficult to meet. The 200-inch telescope, for example, is far from accurate enough to realize its full resolving power.

Even if the optical surfaces were perfect, the turbulence of the atmosphere would limit the usable beam sharpness. It is very seldom that seeing conditions are good enough to permit the resolution of points separated by less than one half second of arc, so that beams sharper than this would not be suitable for communicating from the earth's surface to space. Along the earth's surface the situation is even worse because of the greater length of high density airpath, so that unless a controlled atmosphere or vacuum is provided, beams of angular spread of at least a few seconds must be used.

If we now further assume that atmopsheric refraction effects are absent, as in an evacuated pipe or free space, there still remains the problem of pointing an exceedingly sharp beam in the right direction. Vibration of mounting structures, bending of supports by thermal expansion and, in the case of free bodies, changes in the moments of inertia due to motions of the parts will all introduce pointing errors difficult to reduce below one second of arc.

In addition to turbulence troubles in the medium, a great deal of power can be lost over a long path through molecular scattering and scattering due to suspended particles. Again the use of vacuum or perhaps a filtered helium atmosphere would reduce this loss. Further, any terrestrial path must be bent to conform to accessible routes and to the earth's surface. This can be done through mirrors or prisms or lenses disposed along the path at frequent intervals. It is difficult to make such a beam bender with less than 1 per cent loss, so that an attenuation on the order of one or more nepers per 100 bends is to be expected.

Quantum mechanical analyses [5] have shown that even an ideal amplifier has a noise power spectral density referred to the input which is given by

$$\psi(\nu)=\frac{h\nu}{\exp\left(\dfrac{h\nu}{kT}\right)-1}+h\nu, \tag{6}$$

where T is the absolute temperature of the source (resistance for circuits, weighted average of the field of view for antennas). The first term in this equation represents thermal noise and at low frequencies (for which $h\nu\ll kT$) this term approaches the familiar kT watts per

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[3] Eqs. (1), (2) and (5) may all be derived from Huyghens' principle. Eq. (5) also follows from the fact that the aperture of an isotropic antenna is $\lambda^2/4\pi$, as may be proved thermodynamically.

cps while the second term is negligible by comparison. At high frequencies (such that $h\nu \gg kT$) thermal noise disappears, but by then the second term alone produces more noise than the total at low frequencies. Thus, at high frequencies more signal power must be received to achieve a given SNR. This is true regardless of whether coherent or incoherent detection is used, and basically stems from the fact that the energy per quantum increases with increase in frequency. At optical frequencies the SNR is given by

$$\frac{S}{N} = \frac{P_R}{h\nu B} = \frac{W_R}{\frac{h\nu}{2}} = 2\bar{n}, \tag{7}$$

where

W_R = average energy received per pulse or per Nyquist interval, $1/2B$.
$\bar{n}$ = average number of quanta per pulse or per Nyquist interval.

Thus, the number of quanta received per pulse (or per Nyquist interval) is directly related to the SNR.

The linear increase of noise power density with frequency detracts from the square law increase of received signal power with frequency (with fixed antenna size) so that only a first power improvement in SNR with frequency is obtained.

It appears that optical masers and associated equipment will not be significantly more expensive than other terminal equipment for present-day communication channels. The big question mark in the application of optical masers to telephone communication would seem to be in the expense of the construction and maintenance of the light pipes required. Not enough is known about this at the present time to make even a rough guess as to the cost per mile. Suitable light pipes will probably not be cheap compared with coaxial cable for example, but if very wide-band modulation means can be devised, their cost can probably be cheap per channel of communication.

A TERRESTRIAL EXAMPLE

Using the equations presented in the last section, it is possible to compute the performance of any given channel aside from the unknown of losses in the medium. As a particular example, let us assume that we have a gaseous CW maser with a power output of 80 mw at one micron wavelength. We wish to use transmitting and receiving apertures no bigger than two inches in diameter; we want a 4-Mc channel and a SNR of 40 db at the receiver. It then turns out that the maximum distance over which this can be done is 4000 miles. This figure does not at first seem very surprising since coaxial circuits exist over this distance today, but what is impressive is that this distance is achieved without repeaters. Losses in the medium and in beam benders would reduce this distance perhaps by a factor of 1/10.

SPACE COMMUNICATION

It is interesting to compute the communication capabilities of optical masers over long paths such as are involved in space communication. This subject has been investigated by Schwarz and Townes [6] using somewhat different assumptions from those which follow. Here let us assume a pulse code channel so that we can use devices such as the ruby maser with its higher power output. Using the preceding transmission formulas the curves of Fig. 5 were computed. The ordinate in this chart is the geometric mean of the diameter of the objective at the transmitter and receiver, *i.e.*, $\sqrt{d_T d_R}$. The curves show the value of this mean objective diameter required as a function of distance between transmitter and receiver. The parameter n_1 attached to each curve is the expected number of photons received per joule of radiated energy. Thus if a pulse of energy W joules is radiated, a number of photons $\bar{n} = n_1 W$ will be received on the average. With an ideal receiver (7) shows the SNR in db would be $3 + 10 \log \bar{n}$. Allowing for less than ideal performance in the receiver we may take $(S/N) \approx 10 \log \bar{n}$.

As a first example, let us assume a ruby maser with 10 joules output per pulse. We see that the mean objective diameter required for a 60-db circuit between earth and moon is only 0.3 inch. In other words, the ruby rods themselves without any associated optical system would be sufficient for communication. As a second example, we see that a 3-inch objective is sufficient to provide a 40-db SNR channel between earth and Mars, even when the latter is at superior conjunction (*i.e.*, on the opposite side of the sun from the earth). Finally, we note that 10-inch telescopes would suffice to provide a 30-db SNR clear across the solar system. From these figures it would appear that optical masers are very attractive for interplanetary communication.

What happens if we attempt to use optical masers for interstellar communication? The situation we find here is depicted in Fig. 6. We note that n_1 now ranges from unity to 10^{-6}, so that for points on the lowest curve a million joule pulse is required to receive one photon on the average. Above a 10-inch antenna diameter the curves are shown dotted because it is very doubtful that the sharpness of the beams involved for larger diameters is practical for the reasons stated earlier. It appeared quite practical with lasers of present performance to communicate across the solar system. However, we see from Fig. 6 that the solar system is only a millilight year in diameter. By contrast, the nearest star, Alpha Centauri, is four light years distant. This star is a binary and so probably has no planetary system. In fact, we have to go out to ten light years before we find solar type stars such as Epsilon Eridani, and so it is not until this distance is reached that there is more than an infinitesimal likelihood of encountering other intelligent life. It is obvious from the curves that a tremendous increase in optical maser power output must occur

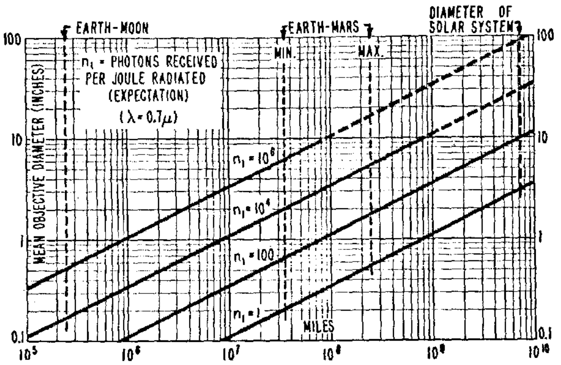

Fig. 5—Coherent optical transmission over interplanetary distance.

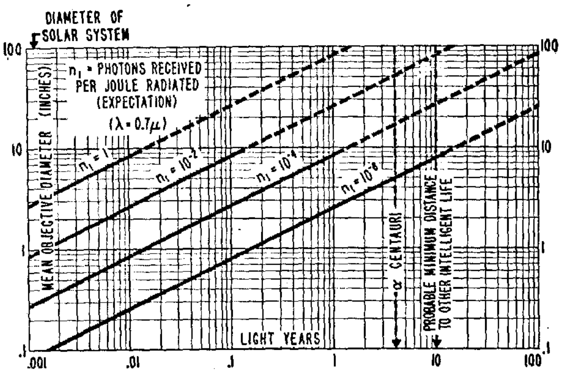

Fig. 6—Coherent optical transmission over interstellar distances.

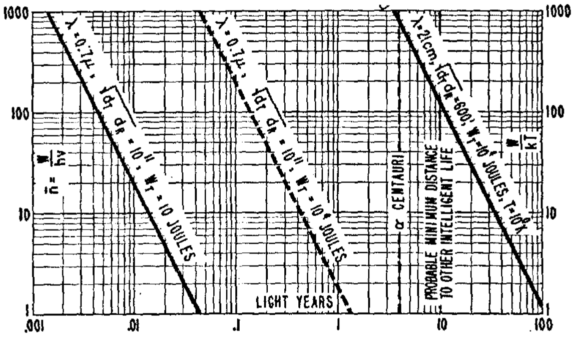

Fig. 7—DX performance—optical maser vs microwave system.

before interstellar communication by this means is feasible. Fig. 7 shows a comparison between the performance of optical masers and a practical, high-power 1420-Mc system at interstellar distances. The ordinate here is the expected number of photons per pulse in the case of the optical system and the quantity W_R/kT which has the same significance for the radio system. The curve at the far left is for the present ruby maser and 10-inch antennas, the middle curve shows the effect of increasing the power per pulse to 10^4 joules, and we see that even here the expectation is far less than one photon per pulse at 10 light years. By contrast, a radio system near the hydrogen line frequency ($\lambda = 21$ cm) using 600-foot antennas such as the one currently under construction at Sugar Grove, a transmitter power of 10^4 joules per pulse (for example, 10 Mw for 1 msec) and a receiver noise temperature of 10°K would have the performance shown by the curve at the far right and would be able to achieve a SNR of over 20 db at 10 light years. The radio system has about 417 times the beam spread of the optical system in Fig. 7. The reason for its superior performance in spite of this poorer directivity is two-fold. First, the assumed receiving antenna has 720 times the diameter and therefore picks up $(720/417)^2 = 3$ times the power. Second, the noise power per cycle is some 2000 times less at the radio frequency and 10°K than at the optical frequency. Thus at a given range the SNR for the radio system is 6000 times that of the optical system. For a given SNR the range is therefore $\sqrt{6000} = 77.5$ times as great.

CONCLUSIONS

Optical masers appear to offer exciting possibilities in several areas. First, they make it possible to achieve tremendous power densities in tiny regions of space. They are thus a research tool for investigating the effects of such densities on physical and chemical processes. There are also undoubtedly hundreds of industrial processes where extremely high energy densities could be used. Examples suggest themselves such as micro-engraving to produce complex semiconductor devices, or ultraminiature circuit components of various sorts. For example, grids for klystron tubes might be formed by evaporating a regular pattern of holes in a thin metal film.

Pulses of parallel light from optical masers may be imaged by the lens of the eye onto the retina where they will produce scar tissue as a result of steam formation and consequent tissue damage. This is attractive as a nonsurgical means of preventing retinal detachment. It also presents the less attractive possibility of blinding enemy troops. There has been much speculation that the development of the optical maser might make possible the proverbial death ray. It is clear that enormous increases in the amount of radiated power would be required before such a ray would be effective, except possibly for retinal damage and incendiary effects produced by focussing the light.

Optical masers can produce far tighter beams of radiation than have heretofore been possible. Such beams will allow efficient communication over great distances. Small antennas suffice even for interplanetary distances, but for interstellar distances the larger antennas required are impractical and optical systems are not competitive with decimeter and microwave radio systems. Highly directive beams make possible optical radar and detection schemes of heretofore unachievable resolving power. For certain space applications where the receiver may be in an inaccessible location such as a satellite, coherent optical beams may be economical for the transmission of power.

Optical masers make available tremendous communication bandwidths both because of the enormous number of cycles in a small percentage of the visible spectrum, and because of the space diversity resulting from the tight beams.

Finally, it should be added that optical masers are so new and so revolutionary that other uses will undoubtedly develop which cannot be foreseen at the present time. Some of these uses may far exceed in importance anything which has been discussed.

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Moisture Exclusion from Encapsulation of Long-Life Transistors*

R. I. B. COOPER†

Summary—**The requirement for long-life transistors places stringent demands on sealing processes. There are empirical reasons for believing that water content is a critical factor and should be preserved at a very low value.**

The first consequent problem is to design the sealing operation so that the encapsulate is sufficiently dry at the beginning of life. A practicable solution demands the use of moisture getters and the properties and usage of these are compared.

The second problem is to reduce later leakage of water vapor into the can to a low level. The radioactive method of leak detection is shown to be the most satisfactory to use for controlling the quality of the high-grade packages required.

INTRODUCTION

PARTICULAR attention has been focused on the reliability of the transistor as it is the only active component which appears to have no intrinsic wear-out mechanism. Its rival as an amplifier and high-speed switch, the thermionic vacuum tube, eventually fails in emission however well sealed it may have been. Its rival as a low-speed switch, the electromagnetic relay, eventually suffers from contact erosion. An ideal transistor, *i.e.*, one whose operation involves no surface processes, should in principle last almost indefinitely if used within its specified ratings.

The only limitation to the life of such a transistor would be the process of bulk diffusion which would gradually soften the boundaries between the active regions. With the possible exceptions of copper or lithium, whose rate of diffusion in the operational temperature range of transistors may be open to doubt, it can safely be said that the diffusion of all other atomic species in germanium and silicon would be too slow to require consideration in a realistic assessment of life. Progressive dissolution of germanium by indium, a separate phenomenon to be distinguished from diffusion, has been known to terminate the life of some devices manufactured in a special way.[1]

In a practical transistor, surface processes inevitably play some part and, consequently, slow changes in the surface structure due to reaction with the environment progressively alter its characteristics. Eventually, the circuit in which it is being used may fail to operate. The purposes of this article are 1), to argue that the water is the most potent agent for such changes, at least in the case of germanium, and 2), to describe the technology employed to reduce this source of trouble to acceptable proportions.

Although the article concerns itself exclusively with the technology of moisture exclusion from transistors, it cannot be doubted that at least some other components, for example, capacitors and quartz crystals, may eventually require similarly rigorous sealing processes. At present, reliable figures for the limits of acceptable moisture content of these components are not available, nor is any reliably accredited correlation of ageing with moisture ingress forthcoming. This is due partly to the difficulty of ensuring the exclusion of other

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[1] J. Roschen and C. G. Thornton, "Solid-state dissolution of germanium by indium in semiconductor devices," *J. Appl. Phys.*, vol. 29, p. 923; June, 1958.

for high-resist[illegible] this assumption is generally valid throughout the microwave region[2] with rare exceptions.[3]

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[2] A. F. Gibson, "Infrared and microwave modulation using free carriers in semiconductors," *J. Sci. Instr.*, vol. 35, p. 274; August, 1958.

[3] A. C. Baynham, A. F. Gibson and J. W. Granville, "On the dielectric constant of germanium at microwave frequencies," *Proc. Phys. Soc.*, vol. 75, pt. 2, pp. 309–311; February, 1960.

Correlation Optical Radar*

Recently, considerable attention has been given to ranging systems which employ optical masers as pulsed oscillators.[1] To date, the devices have used a fluorescent line in ruby of wavelength 6943 Å (in the visible red) which corresponds to a frequency of about 4.3×10^{14} cps. The standard practice has been to pulse the maser in such fashion that the output is a narrow beam which, as measured, radiates one or a few joules of the desired frequency in a period, typically of order 10^{-4} to 10^{-3} seconds. This energy at the red wavelength corresponds to 10^{19} photons. Of course, a millisecond pulse radar is of rather restricted use but could be considered quasi-CW for many tactical situations. In ruby the light output during this rather long quasi-CW pulse actually consists of many random spikes of about 10^{-7} to 10^{-6} seconds duration. This randomness of the spikes evidences the difficulty in designing a coherent radar, since the spike-to-spike uncertainty allows no single value of phase to be remembered for coherent detection unless it is decided to use one or a few individual spikes. Under these circumstances, the only efficient way to achieve coherent data processing is to delay a portion of the transmitted wave and beat it with the echo before integrating; in short, it is desirable to build a correlation optical radar.

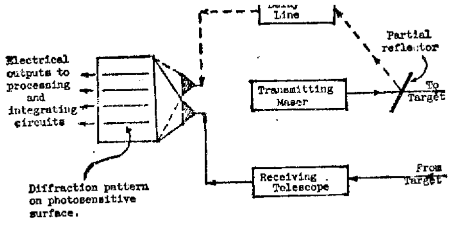

Fig 1.

In a correlation optical radar the mixing may occur at photosensitive surfaces illuminated by the diffraction pattern from two slits. One slit projects a delayed portion of the emitted light, and the other projects light reflected from targets (Fig. 1). The photosensitive surface will be made up of a mosaic of several segments per fringe. It is easily seen that a change in target range of $\lambda/2$ will reverse positions of light and dark fringes. Thus, two segments per light fringe will detect target motion, and four segments per light fringe will provide information as to increase or decrease in range. It should be pointed out that the scheme could suffer from too much information. For example, with a carrier of 4.3×10^{14} cps, the radar Doppler is about 1.3×10^{6} cps for a 1-mph target. Thus, moving target indication will require more involved processing and detection than microwave radars where display of the Doppler output may require no more than a pair of earphones.

An additional problem will be to provide a low-loss delay mechanism for the replica of the transmitted pulse. Losses here will, at least until better systems are achieved, limit the range more severely than beam spreading—the ultimate limit in ranging systems. One possible storage device for such a radar is a fiber optic waveguide of optical path length equal to the round trip target distance. Present fiber optic waveguide is reported to have losses of nearly 10 db in 20 feet,[2] or round trip (radar) losses of about a db/foot for wavelengths in the visible region. This will be somewhat improved by the actual slowing of the light by the waveguide. However, if we assume 10^{19} photons are available for signal processing at the transmitter, and find that 10^4 photons are needed to beat the echo, we obviously have a range limited to not much more than 150 feet. The choice of 10^4 photons is based on the number of quanta required to remove an eightfold uncertainty about the target at the output of the signal processing and integrating circuitry. Thus, a fourfold uncertainty must be resolved to get phase information adequate for velocity determination, that is, to 90°, and a further twofold uncertainty as to the existence of a target must be removed at any given phase. Treating this signal from a wave standpoint requires 8^4 photons.[3] Of these 4×10^3 photons, 2×10^3 are from the target and 2×10^3 are the delayed and attenuated portion of the emitted pulse. Therefore, 10^4 photons should be adequate, assuming photoelectric surfaces of good quantum efficiency and low system noise. Improving the loss factor by one [illegible][4] gives a radar range in the order of 1500 feet, which begins to look interesting tactically. Inserting fiber optic amplifiers[2] or other negative resistances along the delay path will allow for a small increase in range. Our calculations indicate that one or two octaves may be expected if spurious responses produced by reflections in the system are kept to 10 db or more below the desired signal. If the system can be approached from a coded pulse rather than from a quasi-CW basis, the spurious response due to reflections may be reduced by gating the negative resistances. The development of unilateral light amplification will, it is hoped, result in devices limited in range only by the conventional radar range equation.

In summary it is felt that optical maser radars can be built which will accurately measure target velocity as well as range, and which will accomplish this by a coherent radar technique. This method will resemble an interferometer in which one path will be through an optical path in dielectric waveguide of known length. Although the losses in present fiber optics at 6943 Å severely limit range capabilities, it may be possible to develop tactical optical maser radars with ranges of one to a few miles.

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* Received by the IRE, August 28, 1961.

[1] D. A. Budenhagen, *et al.*, "An experimental laser ranging system," 1961 IRE International Convention Record, pt. 5, pp. 185–193.

[2] E. Snitzer, "Proposed fiber cavities for optical masers," *J. Appl. Phys.*, vol. 32, pp. 36–39; January, 1961.

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Unidirectional Lower Sideband Parametric Amplifier Without Circulator*

A method is presented of obtaining the characteristics of a traveling-wave parametric amplifier, *i.e.*, matched input and nonreciprocity of amplification, using a structure containing only two variable reactance units operating in the lower sideband mode.[1] A circulator is not required.

The matched input in a negative conductance traveling-wave device can be attributed to the cancellation of the backward waves excited by successive sections of the line. In a lumped structure this can be achieved simply by using a quarter wave separation of the negative conductance units. Fig. 1 illustrates one section of a ladder network matched to a load of $G-G_n$.

The nonreciprocity of a traveling-wave parametric amplifier is determined by the direction in which the pump power is sup-

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[1] Since this letter was submitted, it has come to the attention of the author that a similar device has been described by L. D. Baldwin, "Nonreciprocal parametric amplifier circuits," Proc. IRE (Correspondence), vol. 49, p. 1075; June, 1961. A somewhat differing layout has also been disclosed independently by K. H. Locherer and R. Mauer, *Electronics*, vol. 34, p. 21; March, 1961.