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Optical Communications

An appraisal of the many techniques and the steps to be taken before practical systems are achieved.

R. Kompfner

The history of the art of electrical communication is dominated by a trend toward ever-larger bandwidths and higher frequencies. Telegraphy started with signaling rates of a few bits per second—a bit being defined loosely as the basic unit of information, a choice between a yes or a no, a dot or a dash. Telephony—the instant and faithful transmission of the human voice—needs a frequency band of some thousands of cycles per second, something which a single pair of copper wires, connecting a carbon microphone and an earphone, can provide over a distance of a few tens of kilometers.

The invention of the vacuum-tube amplifier made telephonic transmission over wires between stations thousands of kilometers apart possible, while the invention of electrical frequency filters and modulation methods led to "carrier" telephony, where many separate telephone conversations are modulated upon separate carrier frequencies, suitably spaced, just as radio programs are distributed over various frequencies without interfering with each other. It was found that the more telephone channels one could assemble and the more conversations one could transmit over a single transmission medium, such as a pair of wires or a coaxial cable, the lower the cost of a single channel turned out to be—provided, of course, the distance over which transmission was to be achieved was large enough. Naturally, if one places many, many channels, each having a bandwidth of a few thousand cycles, next to each other without overlapping and therefore without interference (a process called multiplexing), one ends up with a large overall bandwidth, hence with high frequencies.

A similar process of reasoning and invention led to the exploitation of higher and higher frequencies in radio broadcasting—a related form of communication, although rather a one-sided one.

As mastery of ever-higher frequencies and ever-wider frequency bands was achieved it became possible to apply the new technology to the broadcast transmission of television; there one needs a band of several million cycles (or megacycles) to transmit live, high-definition television pictures. It is, then, convenient to use carrier frequencies of tens of megacycles, and this is why the television channels occupy the frequency bands they do.

Microwaves. World War II was fought with radar, a means of "communicating" with unresponsive objects by reflecting radio waves off them. Because the return signals were so feeble, and because it was desirable to pinpoint the direction in space from which the reflected signal came, it became necessary to concentrate the radio waves into beams, rather like searchlights. With antennas of practical size this required the exploitation of radiation of very short wavelengths, or very high frequencies, and led to the opening up on a massive scale of the region of the so-called microwaves—loosely defined as the region between 1000 and 30,000 megacycles. Perhaps the crucial elements in the technological frontal attack were the inventions of the multicavity magnetron and of the klystron tube (*1*).

Before the war considerable progress had been made toward solving the problems connected with the use of microwaves for long-distance transmission, and many essential building blocks—such as antennas, waveguides, filters and junctions, detectors, modulators, and frequency converters—had been conceived and tested in the laboratory. It can be argued that the war interfered with the progress of this work because it diverted all the available talent from the problems of communication to the problems of radar; although there is a considerable area of overlap, they are different. On the other hand, practical tubes for the generation and amplification of microwave signals did not exist before the war.

Be that as it may, the world witnessed, after the war, an exploitation of the microwave region for long-distance, wide-band transmission of thousands of telephone conversations and dozens of television programs. This was accomplished by means of a network of microwave radio links (*2*), consisting of beams of microwave radiation, mainly in the 4000-megacycle band, sent through the air between towers supporting the necessary antennas, amplifiers, and other devices. Because of the curvature of the earth's surface, these towers are usually spaced about 50 kilometers apart. Everybody, presumably, has seen such repeater towers at various places in the American landscape (and in Europe also),

The author is affiliated with the Crawford Hill Laboratory of the Bell Telephone Laboratories, Holmdel, New Jersey.

but few people are aware that, in addition, a network of coaxial cables, having almost the same capacity to carry communications and connecting as many cities as the microwave network, lies buried a meter or so underground.

Still, as the need for communication channels grows—and it does grow much faster than our population does—we shall eventually run into difficulties if we try to satisfy the need merely with more microwave systems, and with more cables, at higher frequencies. Systems which rely on propagation of electromagnetic waves through the atmosphere have to contend with diffraction, or beam-spreading, which sets a limit on how close together the systems may be put geographically, and exploitation of the higher frequencies is limited by the nature of the earth's atmosphere. The atmosphere gives rise to large attenuation in certain frequency regions and rain and other atmospheric inhomogeneities scatter and absorb radiation more severely at the higher frequencies (*3*). Propagation by cables, on the other hand, is characterized by an attenuation that rises with frequency, and while the recent introduction of the transistor repeater has made cables again seem economically relatively attractive, a limit can be seen below which the cost of communications per channel-kilometer in a cable is never likely to drop.

The growth in the volume of communications depends, of course, on increase in the number of users as well as increase in the number of uses. Both, in turn, depend on the availability, reliability, convenience, and cost of communication channels. The cost goes down as the use goes up, so we have here a kind of "beneficial circle" (the opposite of a "vicious circle").

Thus we may expect to see a continuing search for means of efficiently transmitting extremely wide bands of frequencies over long distances—a search made in the certain knowledge that the day will come when such means, however wide-band they may be, will be essential.

Millimeter waves. Before turning to a consideration of the use of light for communication, let us dwell briefly on the subject of millimeter waves for communication. The millimeter-wave range of the electromagnetic spectrum covers the interval from 30,000 to 300,000 megacycles; that is to say, the available bandwidth is of the order of hundreds of thousands of megacycles. What an opportunity for communications! (not through the atmosphere, though, except for very limited and special purposes). It has been known for many years that a metallic tube of perfectly circular cross section, the so-called circular waveguide, has a remarkable property: it transmits electromagnetic radiation of a particular type of mode (the "circular" electric modes) with ever-decreasing attenuation as the frequency increases (*4*). Extensive research has shown that this property makes possible a system of long-distance wideband communication with an overall bandwidth of the order of 50,000 megacycles, carried in a waveguide of 5-centimeter diameter having a loss between repeaters (spaced somewhere between 15 and 30 kilometers apart) of the order of 2 decibels per kilometer. Construction of such a waveguide is technically feasible, though whether such an installation is economical now is not yet clear. This situation, however, will change if and when the demand for more and broader channels of communication catches up with the supply.

Masers and lasers, a debt repaid by microwave spectroscopy. Pure and applied research in physics, and particularly in spectroscopy, profited greatly from the introduction of microwave techniques, hence it was only fair that microwave technique should, in return, benefit from research in spectroscopy. I am, of course, referring to the invention of the maser by C. H. Townes and his associates (*5*). With this invention spectroscopy can be said to have repaid its debt to microwave technology.

The maser exploits an entirely new principle in the history of devices for amplifying and generating radiation of high frequencies. It is based on the existence of resonances in molecules and atoms at such frequencies in consequence of the quantum nature of the interaction between radiation and matter (*6*).

The principal uses of the maser in microwave technology have been its use as a sensitive amplifier (in radio astronomy and radar, and in satellite communications) and its use as a highly stable clock. Though they are important, these uses have not revolutionized microwave technology; the real importance of the invention of the maser principle lies in the fact that it led to the invention of the laser (*7*) [or the "optical maser," as it was originally called by its inventors, A. Schawlow and C. H. Townes] and to its first experimental demonstration by T. Maiman (*8*) and A. Javan (*9*).

Communications engineers have dreamed for many years of using light for communication because of certain of its properties: (i) the frequencies lie in the range of 10^{11} to 10^{15} cycles per second, hence the bandwidth potentially available is larger by many orders of magnitude than anything in the microwave range, or even in the millimeter range; and (ii) since the wavelengths are so much smaller than the linear dimensions of any instrument component (such as a lens or reflector) used to direct beams of light radiation, diffraction effects would be small and one could therefore make beams of extreme sharpness.

Light not derived from an optical maser, such as light from an incandescent filament or an arc lamp, is of very limited utility for communication. Such radiation behaves as if it were generated by a multitude of independent little oscillators, each occupying an area of the order of one wavelength squared, oscillating with random phases in a range of frequencies determined by the sharpness of the filter in the path of the light. Any attempt to make the light more monochromatic merely reduces the amount of light available; any attempt to make a beam of light deriving from such a source more directive merely reduces its effective emitting area and thus also reduces the amount of light.

What the klystron tube has been to microwave technology, the optical maser is to optical technology: it is the absolutely essential active element. The opening up of the microwave spectrum was paced by the invention and development of tubes capable of amplifying and generating radiation in that spectrum. A similar development is about to take place relative to the infrared and optical parts of the electromagnetic spectrum, now that the optical maser has been invented. One may indeed ask how it was possible that those parts of the spectrum have been studied and exploited to the extent they have been without the benefits of active elements. (If only thermal sources had been available and used in the microwave region, almost nothing could have been accomplished: no waveguides, no microwave beams, no radar, no microwave spectroscopy.) The answer is that optical spectroscopy has advanced as far as it has partly because thermal sources at very high temperature are powerful radiators in the optical region and partly because the human eye is a sensitive detector there. Both facts are consequences of the quantum nature of light. (As we shall see later, the quantum nature of light does, however, reduce to some extent the usefulness of light as a means of communication.)

Now that the optical maser is an accomplished fact, communications engineers have been given the powerful tool they need. This, in conjunction with all the sophistication of the already developed microwave and millimeter technology and of electronics in general, will now be applied to the problem of long-distance and wide-band communication. Furthermore, from the marriage of the long-established optical technology and the new field of masers and optical masers, now called "quantum electronics," one can confidently expect that a new technology will emerge which will have an impact on many fields of human endeavor, comparable perhaps to that of nuclear energy.

In this article I shall try to outline what optical masers may mean to the field of communications.

Elements of a Laser Communication System

Any communication system consists of terminals separated by a transmission medium. In the terminals the information (telephone conversation, television picture, data) is transformed into a signal, or the signal is turned into information, suitable for the transmission medium in question. The transmission medium itself may contain repeaters which boost the strength of the signal should it be weakened or which reshape the signal should it be distorted in the process of transmission. Every known method of boosting, or amplification, introduces spurious signals, or noise; the ratio of the power of the signal to the power of the noise is called the signal-to-noise ratio—a quantity important in describing a communication channel. Another important quantity, discussed earlier, is the bandwidth of the channel; the whole transmission medium may, of course, contain many channels occupying adjacent bands of frequencies.

Shannon (*10*) has given an equation relating C, the amount of information (in bits per second) which can be sent over a communication channel to its bandwidth B and to its (worst) signal-to-noise ratio S/N:

$$C = B \log_2 \left(1 + \frac{S}{N} \right)$$

This equation describes an ultimate upper limit (which has never been reached) in the classical case—that is, in the absence of quantum effects.

One of the first questions asked when it appeared that use of coherent light for communication might be a practical possibility was: Is there a formula like Shannon's which takes into account the fact that radiation—any radiation—is quantized [that is, transmitted and received only in finite bundles of energy, hf, where h is Planck's constant (6.63×10^{34} joule sec) and f is the frequency]?

The answer is that there *is* a formula like Shannon's. His formula does indeed have to be modified, but not much. An approximate expression, when the noise power N is small compared with the product hfB, has been given by Gordon (*11*):

$$C = B \log_2 \left(1 + \frac{S}{N + hfB} \right)$$

It may be seen that the quantum nature of radiation gives rise to something like an equivalent additional noise power hfB; if one compares it with the classical thermal noise power kTB in a single channel, where k is Boltzmann's constant (1.38×10^{-23} joules per degree Kelvin) and T, the absolute temperature, is, say, 300°K, we find that at a frequency of 3.10^{14} cycles per second, corresponding to a light wavelength of 1 micron, the quantum noise power is about 50 times the classical thermal noise power emanating from a resistive load at 300°K.

The actual noise at the input of a typical microwave communication channel is usually about 10 times the pure thermal noise; we therefore conclude that optical communication channels need not have greatly inferior information capacities. Any inferiority can, in principle, be easily made up for by the vastly large available bandwidths, in view of the fact that the signal-to-noise ratio appears as the argument of the logarithm and the bandwidth appears as a factor.

Transmission media. The first and obvious transmission medium to be considered is air—the earth's atmosphere—because it is a fact in everybody's experience that light is transmitted through it over large distances without noticeable loss—some of the time.

This fact is, however, something of a lucky coincidence, as a glance at Fig. 1 will show, in which the transmission loss, or transparency, of our atmosphere is plotted over a wavelength range of from 3 centimeters to 0.3 micron, or a frequency range of from 10^{10} to 10^{15} cycles. It is perhaps more meaningful to say that mankind evidently possesses sensitive and sophisticated radiation detectors (namely, eyes) in a frequency range where the bulk of the sun's radiation can penetrate the atmosphere. To vast portions of the spectrum in the ultraviolet and infrared ranges the atmosphere is opaque; communication through the atmosphere with radiation in those regions will be difficult.

If one requires a communication system which is operating all the time (the telephone system is an example of such a one), rain, fog, and snow pose severe problems even if the beams of radiation have frequencies in the "window" portions of the spectrum. Measurements in the visible and infrared frequency range through dense fog have shown that attenuation as high as 300 decibels per kilometer of path may occasionally be encountered. To ensure continuity under these circumstances would require either an impossibly high transmitter power or impractically close repeater spacings. We therefore conclude that optical communication through the atmosphere may be useful only in special circumstances—if and where the climate is favorable, or when the objective is not uninterrupted service.

For uninterrupted operation one will have to enclose the light beam in order to shield it from atmospheric disturbances such as inhomogeneities in density, caused by temperature gradients, rain, fog, and so on. Thus, one may envisage a pipe, evacuated, or filled with a gas transparent to the radiation to be employed, enclosing the beam or beams of radiation.

One is tempted to consider construction of such a pipe as a waveguide, remembering perhaps that the loss of such a guide is inversely proportional to the square root of the frequency. Unfortunately, the necessary mechanical tolerances are proportional to the wavelength, and the accuracy necessary in making such a pipe for confining and guiding radiation at optical wavelengths is completely out of reach of our present technology. We have to look for other ways of confining the radiation to the pipe. Beams of radiation spread because of diffraction. Lenses, on the other hand, can concentrate beams of radiation. It is therefore natural to think of a sequence of lenses which periodically focuses the beam so that it does not spread too far from the axis and thus prevents eventual interception by the shielding pipe. Such a lens-guide system has indeed been proposed by Goubau (*12*) and analyzed by him and others (*13*).

Losses—in the simplest case, of a straight, regular sequence of lenses—arise from two causes: interception of radiation which has spread because of diffraction beyond the apertures associated with the lenses and loss in the lenses themselves due to absorption and scattering there.

If the distance between lenses is short the beam will be kept close to the axis and little of it will be lost by diffraction spreading, but the loss due to the lenses will be high. If the lenses are few and far between there will be little loss from the lenses but much from diffraction. We can calculate the proportions of a lens-guide which yield the minimum overall loss; we find that the lenses should be placed confocally (that is, so that foci of successive lenses coincide) and that they should have focal lengths and diameters such that the loss due to diffraction is just 1/8 the loss due to absorption and scattering in the lens. If the loss due to absorption and scattering is of the order of 1 to 2 percent per lens, it turns out that the so-called Fresnel number N_F (such that

$$N_F = \frac{a^2}{\lambda d}$$

where a is the lens-aperture radius, λ is the wavelength, and d is the distance between lenses) is optimally of the order of 0.7.

With numbers that one might think not unreasonable, such as a = 2.5 centimeters, $\lambda = 10^{-4}$ centimeter, one finds that d = 900 meters! Suppose the loss in one lens is 1.5 percent, so that the loss per interval is 1.125 × 1.5 (= 1.68) percent. If one can operate with a total signal loss of, say, 10^{-5} between terminals (or between repeaters), this would enable one to place 625 lenses in series, spanning a total distance of 625 times 900 meters, or 560 kilometers! Without repeaters, moreover!

Needless to say, such a system is utterly impractical on this earth, if only for the reason that the surface of the earth is curved and deviates from a straight line in a distance of 900 meters by as much as 6 centimeters, and in a distance of 560 kilometers by as much as 26 kilometers. While it is possible to make the beam of light follow lenses placed on a curved axis by displacing the beam from the lens axis by a certain amount, the difficulties of achieving, and maintaining, the necessary accuracy of alignment would be great. Because of the irregular shape of the earth's surface and of other geographical features one would want to lay a lens-pipe so that it followed the terrain, with finite radii of curvature, perhaps of the order of 1000 meters or less. This would require many more lenses than we envisaged above or redirection devices like reflectors or prisms or a combination of redirection devices and more lenses. Thus we are faced with much higher lens losses per unit distance than we have assumed, and with much shorter distances between repeaters. Just how close repeaters will have to be spaced depends now on the advances in technology, both in making available lenses of lower loss and in providing more output power from, and higher sensitivity in, repeaters.

A significant step in providing low-loss lenses has been taken recently with the invention of the gas lens, in which the light rays are bent by means of thermal gradients in flowing gases, or density gradients in two mixing gases (*14*). Such a lens has no refracting surfaces, the irregularities of which would cause loss by scattering, and the loss within the lens itself is negligibly small. The design and construction of such lenses and the tolerances necessary to achieve the objectives of long-distance, low-loss transmission are, at present, the subjects of intensive studies.

Other means for confining and guiding a beam of light within a shielding pipe have been proposed, such as a sequence of curved pairs of reflectors arranged like those in a periscope, or thin transparent fibers acting as dielectric waveguides (*15*). It is not clear at this time how the numerous serious problems associated with all of the schemes proposed so far, such as the loss per unit length, the difficulty of dealing with permanent and also with time-varying bends of the pipe, the high mechanical accuracy needed in the construction, and the generation of secondary and ghost beams, can and will be solved.

Terminals and repeaters. Discoveries and inventions, new phenomena, new techniques, and new materials are following each other at such a rapid rate that it is not possible to describe any particular terminal or repeater arrangement without running the risk of being completely out of date in a year or so. The most practical frequency ranges, the achievable bandwidths, the best modulation methods, and other, similar matters are still shrouded in the mists of the future. What can be done depends critically on certain devices, which in many cases do not exist except in principle; progress in the development of devices, in turn, depends greatly on how important a part they may have to play in a system. While much progress has been made in many directions since the invention of the optical maser, no serious definite proposal for any complete long-distance communication system in any particular frequency range has been made up to this time, not only because of problems concerning the transmission media but also because of the lack of devices needed for certain critical functions. Thus, all one can do at this time is to describe the "state of the art." The critical functions are generation, amplification, modulation, and detection or demodulation.

Generators. The pulsed ruby maser (*8*), historically the first maser, is a solid-state generator of coherent red light. It is capable of immense peak powers, but for very short durations only and it is not well suited for communication, at any rate not on this earth. The gas maser, such as the helium-neon laser (*9*), can provide continuous coherent radiation at many wavelengths, the best known being at 0.6328 micron; others are 1.15, 2.02, and 3.39 microns.

When the gas maser is made to operate in a single mode of oscillation (and this is practical, though not very easy) it may be as monochromatic and stable an oscillator as can be found in any other frequency range. Outputs are in the milliwatt range, and a moderate amount of tuning, of the order of a few hundred megacycles, is possible. Gas masers have been found to oscillate at several hundred separate frequencies (*16*), corresponding to wavelengths from below 0.4 micron to 133 microns, which are of course identical with those of the corresponding absorption lines in the particular gases or mixtures of gases.

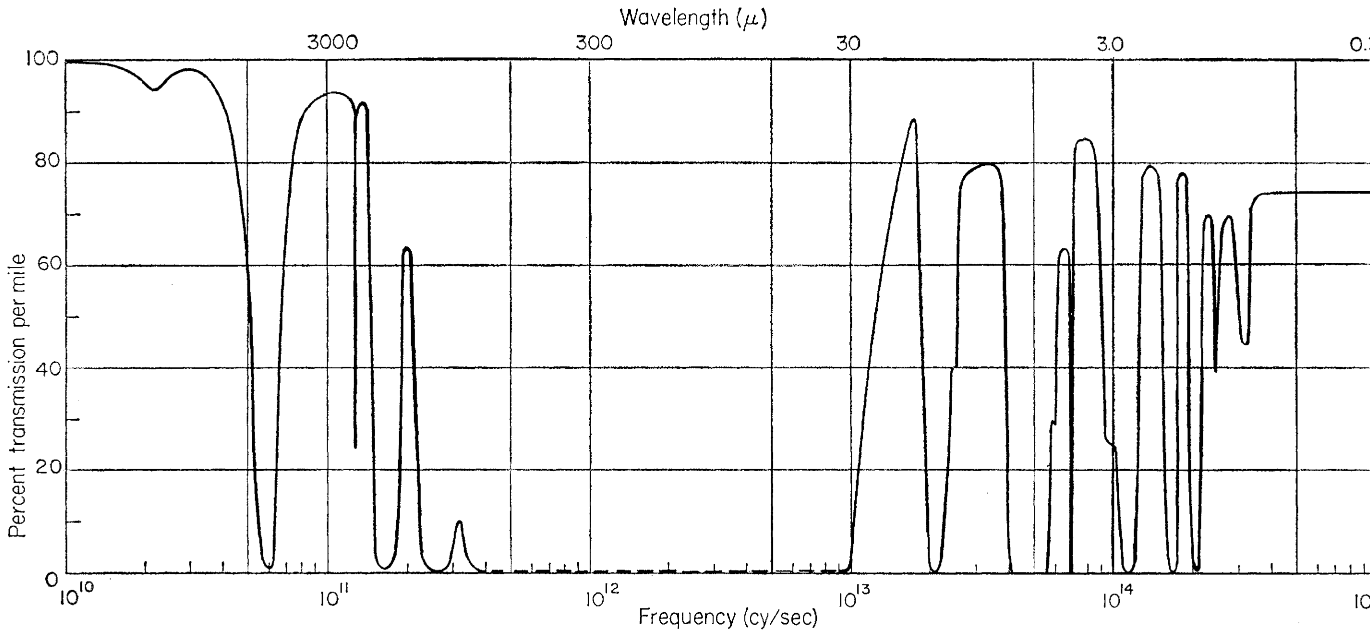

Fig. 1. Electromagnetic wave transmission through air (sea-level pressure).

More oscillating frequencies will no doubt be discovered in the course of time.

Another kind of maser oscillator, called the junction laser (*17*), is a semiconductor device in which a current of electrons across a forward-biased junction causes coherent emission of light. The first such device was made of heavily doped gallium arsenide and was found to oscillate at the 0.84-micron wavelength in the near-infrared. Since then a number of other semiconducting compounds have been observed to oscillate at various frequencies, at wavelengths ranging to about 8 microns, and surely more will be discovered.

The junction laser is a highly efficient device; net efficiencies of 25 percent have been reported, and this, incidentally, is a higher efficiency than that of any other known device for converting electrical energy to light.

Unfortunately, no such laser has yet operated continuously at room temperature. Continuous operation has been achieved at the temperature of liquid helium, but only pulses of short duration are achieved at room temperature. The frequency of oscillation depends strongly on the current flowing through the junction and on the temperature. From one point of view this dependence represents tunability; from another, instability.

When these drawbacks have been overcome the junction laser will undoubtedly assume an important role in communications; as matters now stand, the gas maser is superior in those respects which are important to communications: monochromaticity, stability, continuous operation, and convenience in use.

In spite of the multitude of frequencies of oscillation which are available with gas masers, by far the greater part of the spectrum is outside their tuning range and bandwidths. The recently demonstrated parametric oscillator (*18*) promises, however, to make wide continuous ranges of frequency available in the visible spectrum and the near-infrared. The parametric oscillator is essentially a piece of matter in which the dielectric constant depends strongly on the intensity of the electric field, so that a strong electromagnetic wave at a frequency f_p, the so-called "pump" frequency, gives rise to gain at two frequencies f_1 and f_2 such that $f_1 + f_2 = f_p$; f_1 and f_2 can be varied at will within a relatively large range, hence oscillations in that range can be produced. Much work will have to be done, however, before a practical optical parametric oscillator is available.

Amplifiers. Since, in general, oscillators are but amplifiers with positive feedback, amplifiers can exist wherever we have oscillators—in principle, at least. We find wide variations, though, in respect to some of the important properties on an amplifier—such as net gain, range of power over which it is linear, maximum power level, bandwidth, and noise factor—when we consider the many possible different species.

So far, the optical-maser amplifiers which have been tested have been of the traveling-wave type, with the signal entering the input port and the amplified signal leaving the output port; since there is as much gain in the maser in one direction as in the other, small reflections of power can easily lead to instability or oscillations, and it is therefore necessary to provide a nonreciprocal element near the output, such as a Faraday rotator.

One such amplifier has been demonstrated to operate in a pulsed mode at a wavelength of 0.69 micron with a bandwidth of more than 1000 megacycles and a gain of 12.2 decibels (*19*).

Another type of amplifier, of greater potential value to communications, is a xenon-gas laser operating at a wavelength of 3.5 microns; with this instrument a gain of 400 decibels per meter of length and a bandwidth of about 100 megacycles has been obtained (*20*). A measurement of the noise contributed by the amplifier showed that the instrument behaves essentially like an ideal amplifier, in which the noise arises mainly from the quantum nature of radiation.

At the present stage of the technology, amplifiers are definitely not as important as generators of optical frequencies are, and accordingly less effort is being spent on the former than on the latter. As the art progresses we shall probably see a reversal of this situation.

Modulators. The simplest way to modulate a beam of light—that is, the simplest way to make it carry a message—is to turn the generator of light on and off. With the junction laser this is indeed possible and has been done at very high speeds; this means that the amount of information carried can be very large, with bandwidth of the order of 1000 megacycles. Other types of generators, however, are too slow or sluggish to respond to this kind of treatment, so a need has arisen for a separate device, called a modulator, in which an unmodulated, steady beam of light enters at one port, the signal to be impressed on the light beam enters at another port, and the modulated light beam emerges at the third port.

The most promising type of modulator depends on the electrooptic effect—that is, the change in refractive index as an electric field is established in some species of crystals *(21)*. Thus an electric field produced by, and proportional to, a signal may cause either a phase shift, a rotation of the plane of polarization, or a change in intensity (of a beam of light traversing the crystal) which is related to the signal in some definite way.

For assessing the performance of a modulator the following quantities are relevant: the frequencies or bandwidth over which information can be impressed on the light beam; the optical bandwidth (the range of the optical spectrum for which the modulator is transparent); the attenuation of the light in the modulator; and the signal power needed to achieve a standard amount of modulation (say, a phase shift of $\pm 90°$).

Typical of what can be achieved in the laboratory at this time are the following quantities reported for a traveling-wave-type modulator *(22)* in which the signal and the light travel together along a two-wire transmission line of the Lecher type with the same velocity, with ammonium dihydrogen phosphate as the electrooptic material between the wires: signal frequency band, from 0 to at least 1000 megacycles; transparency attainable throughout the visible range and up to a wavelength of 1 micron, with a light-loss of 6 decibels; signal power needed, 12 watts; signal power attenuation, 2 decibels; length of modulator, 1 meter.

Another kind of modulator depends on the large electric field across the depletion layer associated with a *p-n* junction in an electrooptically active semiconductor, like gallium phosphide, generated when a reverse bias is applied to the crystal *(23)*. Because of the smallness of the region in which the interaction takes place—namely, the depletion layer—this may turn out to be a very efficient device, giving large optical phase shifts over a large bandwidth for relatively little signal power, but meaningful data on actual performance are not yet available.

It is clear that much improvement is needed in every one of the quantities given above, in order to obtain modulators of sufficient bandwidth, which require little modulating power, and which are transparent and usable in the whole frequency range opened up by the optical maser.

Detectors. Photocells, devices which depend on the emission of electrons when light is absorbed by the requisite material, are ancient and well understood and still very useful in optical communication technology, particularly when they are coupled to electron multipliers in the same vacuum envelope. The speed of response of photoemission is intrinsically so high that so far no accurate measurement of it has been made. This means that the bandwidth of the response to a modulation on the incident light beam is unlimited—in principle. In practice, a bandwidth of 4000 megacycles and a current gain of 10^5 has been achieved *(24)*.

The optical frequency range of such photomultipliers is limited because the photon energy has to exceed the work function of the photosensitive cathode; this limits the response to wavelengths below 1.2 micron. Furthermore, the number of photoelectrons per incident photon is, at best, one in ten, and the number falls off drastically toward the infrared, so that the photocell is a very inefficient detector in that region. However, the huge current-gain achievable (without much extra noise) with an electron multiplier permits the construction of simple and effective receivers of modulated light beams. Combinations of photocathodes and traveling-wave electron-beam structures *(25)* have also been used successfully for demodulating light beams which carry information in the microwave region, where electron multipliers suffer from transit-time dispersion.

It seems that solid-state detectors like the *p-n* junction diode *(26)* will have an important role to play in optical demodulation, not only in the far-infrared region, where photocells do not operate at all, but also in the near-infrared and perhaps even in the visible region. Through choice of a material (silicon, germanium, indium antimonide, and so on) with the proper bandgap and choice of the proper concentration of doping impurities, the detectors can be matched to the desired frequency of operation over very wide bands; the efficiency of internal photoemission can approach unity, while avalanche processes can provide current gain. The modulation bandwidth can be many thousands of megacycles wide *(27)*, adequate for the foreseeable future of optical communication.

Because the response of all these detectors is in terms of electrons per photons—that is, of current as a function of light intensity—and because the light intensity is proportional to the square of the electric field, they are called "square-law" detectors. This response in terms of current as a function of light intensity permits the mixing or beating of two separate optical signals on a single photo detector, one of them a very strong single frequency locally generated (and therefore called the local oscillator), the other, the incoming feeble signal, which has to be demodulated and amplified. The photocurrent will then contain components at frequencies equal to the difference of frequencies of the signal and local oscillator, which frequencies can be in the microwave range or lower, where efficient broadband amplification is easily obtained. Whether this scheme of detection—called heterodyne in radio technology language—will be used in practice will depend on whether the necessary very precise alignment of two independent light beams can be achieved and maintained.

Assessment and Outlook

The foregoing sections are intended to convey something of the promise of the art of optical communication and, at the same time, an idea of the great and many steps that have yet to be taken before practical and economically competitive optical systems can be achieved.

The atmospheric medium is hostile, and even now, after many years of study of the atmosphere, not enough is known quantitatively, and understood in terms of cause and effect, to permit us to say whether optical communication systems through the atmosphere will be practical.

Development of the shielded medium, such as a sequence of lenses, is an approach which seems full of promises and also of difficulties—a wonderful field for ingenuity and hard work.

Many devices for generating, amplifying, modulating, and detecting optical coherent radiation have been invented and tried, but it must be said that what cannot yet be done, or done well enough, far outweighs what can be done. So here again there is an immense opportunity for ingenuity and systematic hard work. The putting together of all these devices and techniques into systems will have to wait until we have all the parts and the necessary understanding. That time will surely come—how soon, it is impossible to say.

References and Notes

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6. In thermal equilibrium the distribution of atoms in their various possible excited states with energies E_i is governed by the Boltzmann relation $n_i = n_0 e^{-E_i/kT}$. Radiation at a frequency f_{ij} such that $E_i - E_j = hf_{ij}$ interacts with the atoms in causing the lower-level atoms to absorb and the higher-level atoms to emit and is thus attenuated because there are fewer atoms in the j-level than in the i-level. If one succeeds, through any one of a number of possible means, in placing more atoms in the j-level than are in the i-level, radiation at the frequency f_{ij} will experience a net amplification.
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Acoustical Thermometer

An ultrasonic interferometer provides a new method for the precise measurement of low temperature.

Harmon H. Plumb and George Cataland

In the last few decades scientific interest in the area of low-temperature physics has been accelerated and the related field of cryogenic engineering has been developed. While some of the engineering applications have been direct products of previous research efforts, considerable impetus has been provided by ventures into outer space. Accumulated knowledge of the properties of hydrogen (in both the liquid and the gaseous states) has been important for propulsion, but additional interests are steadily developing—for example, cryogenic pumping for a variety of applications, the possible use of superconducting phenomena, and creation of environments which provide low noise levels.

Basic to the extension of fundamental research on phenomena at cryogenic temperatures, as well as to engineering development, is the attainment of a practical temperature scale. To be useful such a scale must be reproducible and must reasonably approximate the thermodynamic, or Kelvin, temperature scale. Additionally, there must be a secondary thermometer possessing a temperature-related parameter that can be relatively simply and reproducibly measured.

In this article we discuss methods of achieving a temperature scale which approximates the thermodynamic scale (below 20°K); sources of difficulty in the methods; a new approach (measurement of the speed of sound in helium gas) to precision low-temperature thermometry; the instrument employed; achievement of a new provisional temperature scale; and the means by which the scale is made available to the scientific and engineering public.

Attainment of Absolute Temperature

The absolute thermodynamic, or Kelvin, temperature scale, which is independent of the properties of any substance, results from basic thermodynamic considerations. It is frequently derived (*1*) by operating a reversible engine in a Carnot cycle between two heat reservoirs, which may be characterized by the temperatures T_1 and T_2. The ratio of the heat absorbed (Q_1) and the heat rejected (Q_2) by the engine is equal to the temperature ratio on the Kelvin scale.

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2} \qquad (1)$$

To fix the size of the degree and thereby complete the definition of the Kelvin scale, an arbitrary number of degrees must be assigned to some temperature interval.

Originally the size of the degree was defined by assigning exactly 100 degrees to the temperature interval between the freezing and the boiling points of water.

In 1954 the Kelvin scale was redefined in terms of a single fixed point —the triple point of water—and the temperature interval between zero of

The authors are affiliated with the Institute for Basic Standards at the National Bureau of Standards, Washington, D.C.