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The recent development of the laser has made possible communications with a beam of coherent light. Since coherent light offers great advantages over radio in the areas of beam directivity and information capacity, optical communication systems have been proposed for many uses.

The first section of this thesis gives a phenomological description of laser operation. A short summary is then given of the characteristics of presently available lasers. The third section includes an extensive discussion of the requirements of optical communication systems using both laser and conventional sources. Using the information contained in the first section of the thesis, calculations are made concerning the required transmitter power to maintain communications

with both radio and optical systems. Where possible, the proposed optical systems are compared with existing radio systems.

It is found that, in general, the laser systems offer no significant power advantage over radio systems despite the higher directivity of the optical antennas. Consequently, the largest demand for laser communication systems will occur when it is necessary to transmit extremely large information rates.

TRANSMITTER POWER REQUIREMENTS OF OPTICAL AND RADIO COMMUNICATION SYSTEMS

by

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INTRODUCTION

The unique characteristics of the laser make it applicable to a wide variety of problems. Proposed uses for the laser range from million-voice communication systems to microwelding; from delicate eye surgery to the long-imagined death ray. Often the proposed use sounds so promising that it seems the laser would soon replace presently used devices. Often, however, it is found that such a new device will not replace presently used methods; rather, it will be used to accomplish a task which is difficult or impossible to perform using present methods.

One of the most promising uses for the laser is in the field of communications. This paper will discuss the transmitter power requirements of optical communication systems using both laser and conventional sources and will compare that to the power required by a radio system performing the same function.

Since the laser is such an important part of a possible optical communication system, the operation of the laser itself is discussed. In addition, the characteristics of the various types of lasers are described.

It is assumed that the reader is familiar with the general processes involved in a radio communication system. Optical counterparts of these processes are being developed rapidly. An extensive discussion is made of the state of the art in optical communication systems with some comments concerning developments which may be reasonably expected within the next few years.

Based on the information compiled in the first three sections of this paper, calculations are made which show how the transmitter power requirements of an optical communication system would compare with that of a radio system. Where possible, the comparison is made with existing radio systems.

The results of the study are quite indicative of the possible uses of lasers in the field of communications.

DESCRIPTION OF LASER OPERATION

While the process of stimulated emission is a purely quantum effect, the conditions under which it occurs can be described classically. Stimulated emission is the effect which produced the laser output. In order to understand the principles of laser operation, all three modes by which electrons can change energy levels must be considered. These will be discussed briefly. Based on the discussion of electron energy transitions, a phenomenological description of laser operation will be made.

Electron Energy Transitions

The three modes by which change in electron energy can occur are:

1. Energy exchange between electron and crystal lattice.

2. Random emission of a photon.

3. Induced transitions.

Electrons in a material are continuously changing energy levels, even when the material is in thermal equilibrium. The energy required to raise the energy of the electron may come from crystal lattice vibrations or some similar mechanism. Similarly, an electron can return to its lower energy state by giving up energy to the host material. In solids, this type of energy exchange process tends to occur more frequently at dislocations or other crystal discontinuities.

To determine the population density (number of electrons per unit thickness of energy level, Boltzman statistics can be applied as follows:

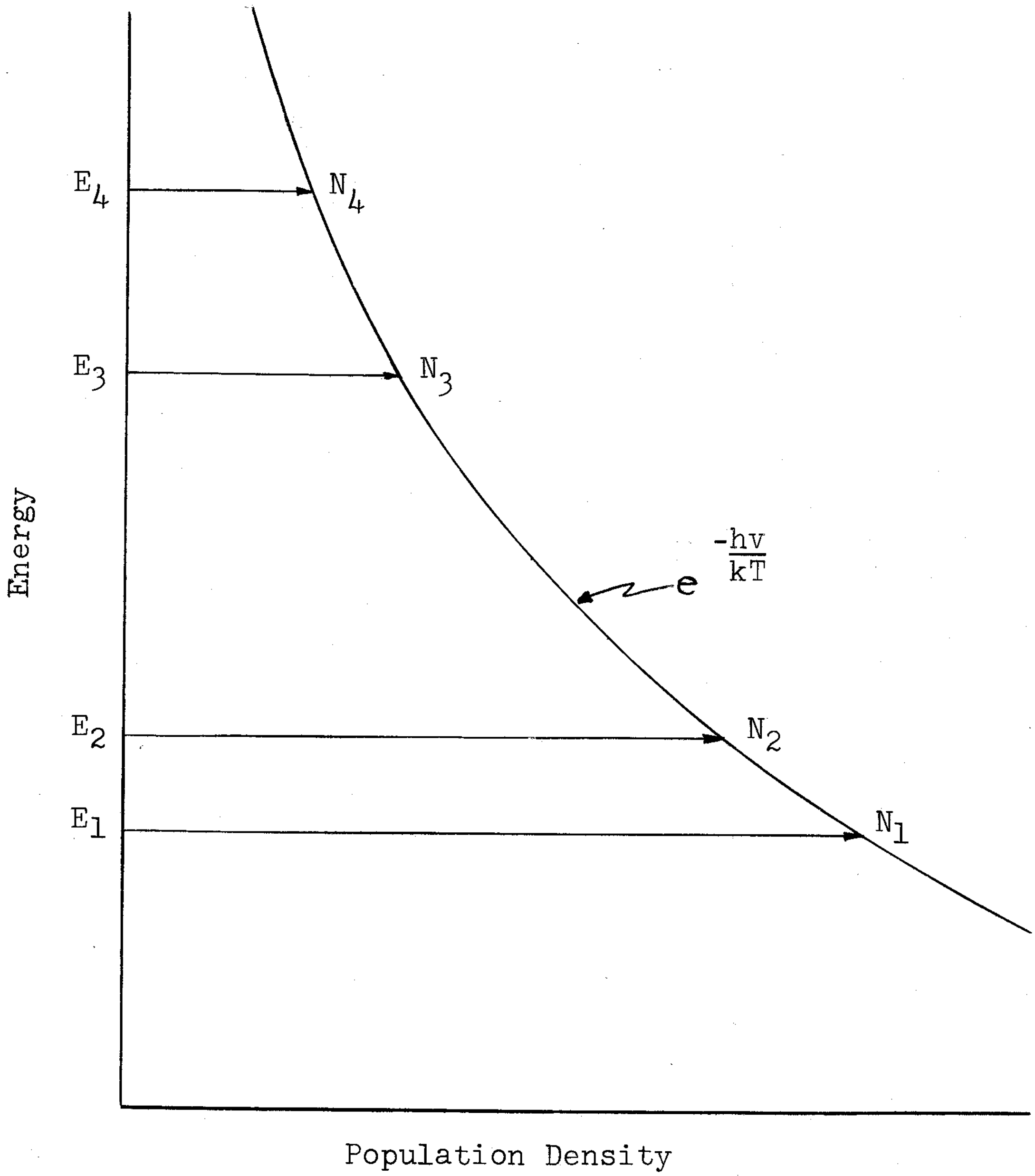
$$N = N_o e^{\frac{-\Delta E}{kT}} \qquad \text{eq (1)}$$

where: N_o is the population density of electrons at a given energy level, ΔE is the difference in energy between the considered level and another level with a population density N , k is the Boltzmann constant, and T is the absolute temperature, (25, p. 6). The electron population density in a material in thermal equilibrium is shown in Figure 1.

The second way in which an electron can change energy levels is for an excited electron to return to a lower energy level and emit a photon equal in energy to the energy loss of the electron. There must be an energy level or band available for the electron and the transition must not be "forbidden" by quantum considerations. This type of electron transition is a completely random phenomenon. The reduction of electron energy with the emission of a photon is the mechanism which produces fluorescence. For any excited electron there is a certain probability that it will fall to a lower level

Figure 1

Electron Population Density of Energy Levels in Thermal Equilibrium



is a given length of time. This probability is determined by the two energy levels involved and can vary widely between energy level pairs (3, p. 398).

The last type of transition (mode 3) is the induced transition of an electron and stimulates it to change energy levels. The electron may absorb the energy of the photon and move to a higher energy level. Or, the photon may stimulate the electron to fall to a lower energy level. The energy loss of the electron is converted to a photon which is in phase with the stimulating radiation (12, p. 81).

When a monochromatic light (pumping source) is incident on a material having an energy gap equal to the photon energy of the pumping light, the following situation develops. First, electrons are excited to the upper energy level, according to process (3). Some of these will fall randomly back to the lower level, emitting a photon according to process (2). Some will, by process (1), give up their energy to the host material and will make a nonradiative transition to the lower state. Others will be stimulated by the pumping light to return to the lower band and these will produce another photon by process (3). The probability that an electron will be pumped up by a photon is equal to the probability that an excited electron will be stimulated to fall to a lower energy by the photon; thus, if only these two mechanisms had effect, the population of the two levels would be equal. If the pump source has a very high intensity, the stimulated relaxations will far exceed the random radiative and nonradiative relaxations and the population of the two levels will, indeed be very nearly equal.

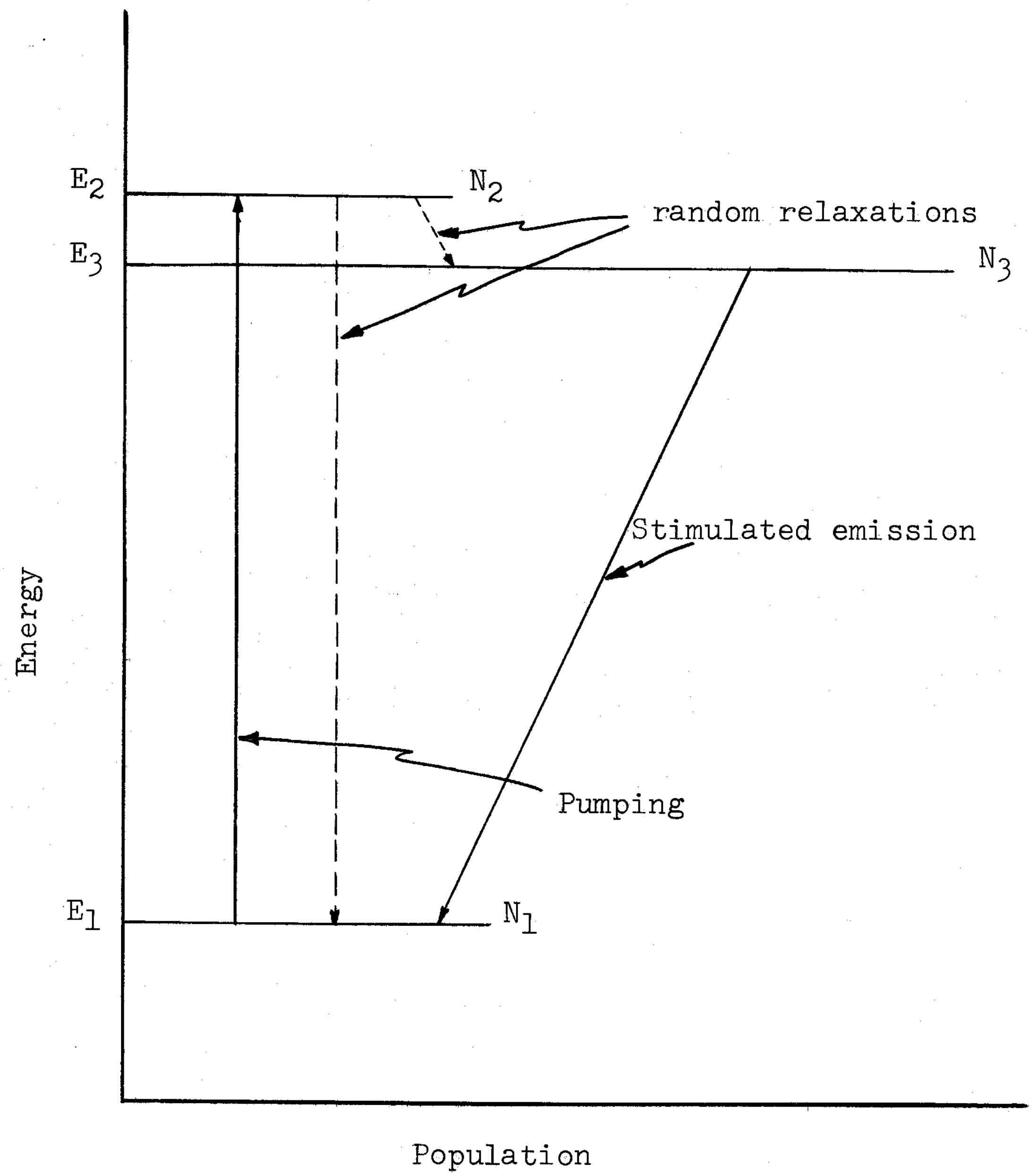
Electron Transitions in a Laser Material

All three modes of electron transitions occur in a laser material. It is the third mode that gives rise to the laser output.

Assume a material is found with three energy levels, two of which, E_1 and E_2, are separated by an energy $E = h\nu_{12}$, and the third, E_3, located slightly below the higher. Further assume the probability for transition between the upper levels is quite high but is quite low for transitions between the lower two levels. Then if an intense monochromatic light of frequency ν_{12} is incident on the material, the population of the levels will be as shown in Figure 2. Because of the intense pumping, N_1=N_2. The relation between N_2 and N_3 is

Figure 2

Electron Population of Energy Levels in an
Operating Three-Level Laser



determined by the Boltzmann formula if the probability of transition between levels two and three is sufficiently high to maintain a thermal equilibrium between these two levels. This condition is shown in Figure 2.

Now a population inversion exists between levels three and one. A photon with an energy equal to $E_3 - E_1$ is more likely to stimulate an electron to fall from level three to one than it is to pump an electron from level one to three. By keeping the stimulated light within the laser material for a long period of time, most of the photons will be in a phase with each other. This is laser action. Since the laser action tends to decrease N_3 rapidly, very high pump powers and very fast relaxation between levels two and three are necessary to maintain the population inversion (12, p. 78-81).

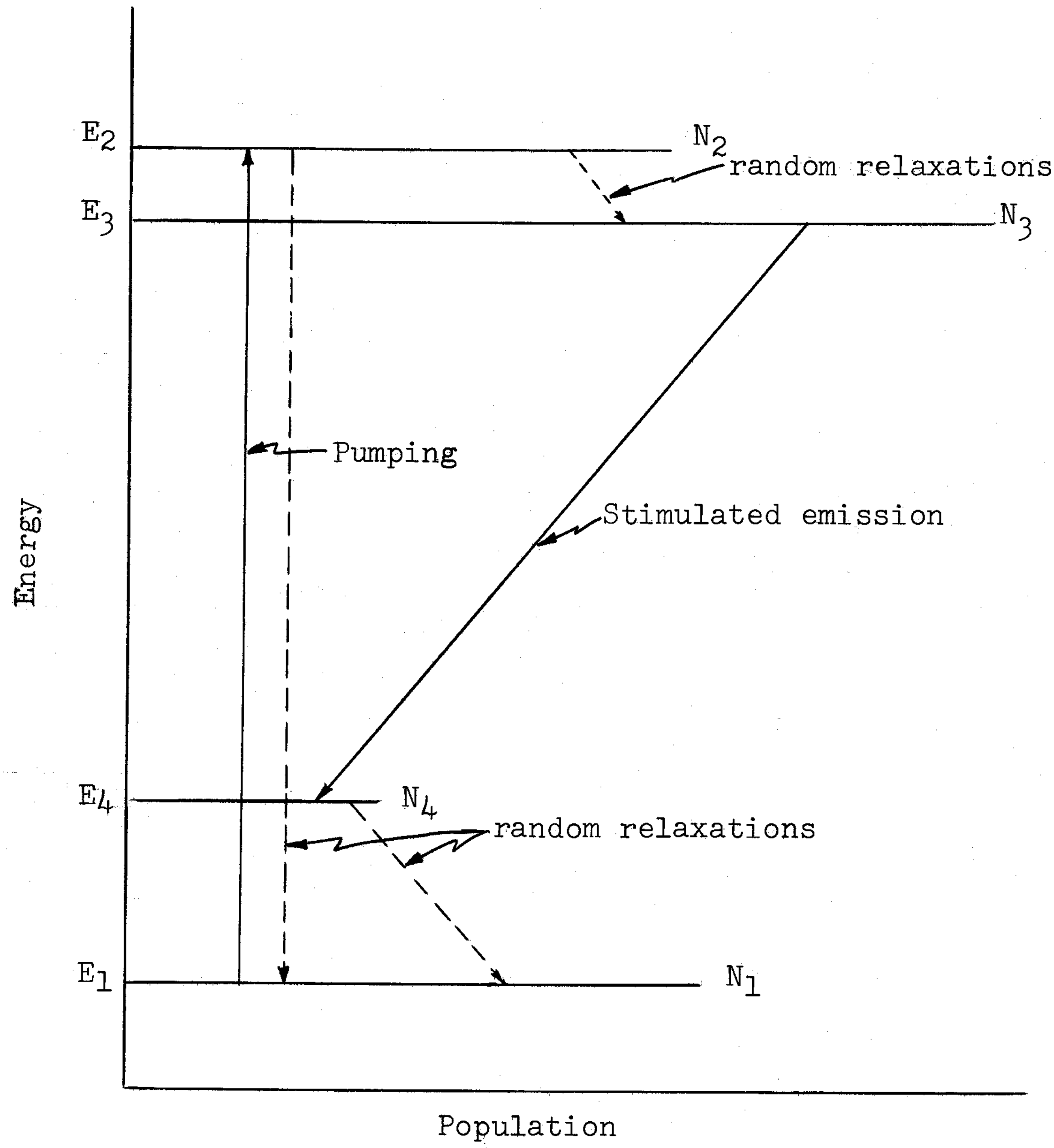
If the Boltzmann equation (eq 1) is solved for T, the result is:

$$T = -\frac{\Delta E}{k \ln \frac{N}{N_o}} \qquad \text{eq (2).}$$

In the case of a population inversion, ΔE is positive and $N > N_o$ making the logarithm of the quotient positive. The resulting temperature is negative. Therefore, the

Figure 3

Electron Population of Energy Levels in an Operating Four-Level Laser



condition of a population inversion is also referred to as a negative temperature.

Two other energy level configurations are commonly available for laser action. Another three-level device can be devised in which level three is quite close to level one. This condition produces laser action between levels two and three with a very fast relaxation from three to one. The same consideration concerning fast and slow relaxations and high pump powers apply to both three-level laser configurations.

The last type of laser is the four-level laser. During operation, the energy levels are populated as shown in Figure 3. This type of laser places more severe requirements on the material. First, it needs the additional intermediate level. Second, it has two pairs of levels between which the relaxation must be very fast. The four level laser has the advantage that the pump power need not be as high to maintain the population inversion (25, p. 9).

Additional Requirements for Laser Operation

The laser material, with properly located energy bands, must be mounted in an optical cavity in order to operate as an oscillator. In addition, the energy bands must be made very narrow.

Since the stimulated emission is produced by radiation within the material, causing an increase of the radiation intensity, the radiation must be kept within the laser material as long as possible so that the maximum number of electrons may be stimulated to fall to the lower energy level. This process is similar to any other oscillator process in which the amount of energy contained within the oscillating element must far exceed the amount of energy being taken out. In the case of the laser, the radiation is kept inside the laser by means of two very accurate mirrors located at each end of the laser. These may be plane, parallel mirrors or any of several configurations of spherical mirrors. One of the mirrors transmits about 2% of the radiation incident on it. The other portion of the radiation is reflected by the mirrors and remains in the laser material to stimulate more electrons to fall to a lower energy level, (25, p. 23).

An important requirement of all laser material is that the active laser atoms must be sufficiently separated so that there is no interaction between atoms. In solid laser materials this is accomplished by introducing the active atoms as impurities at concentrations of less than 1%. In gas lasers the gas pressure is about 1 mm Hg. This low concentration of active atoms is required in order to make the energy bands very narrow. The narrowing of the energy bands with decreasing concentration is described by the Pauli exclusion principle. Some materials are cooled to liquid N_2 temperatures ($77^{\circ}K$) or below to make the bands still narrower. The narrow bands make the output more monochromatic, allow fewer modes of operation, and produce a more stable output. If the energy bands become wide, the laser action is impaired or may cease completely.

TYPES OF LASERS

There are five basic types of lasers which have been operated to date. These are:

1. Solid, crystalline, optically pumped.
2. Solid, noncrystalline, optically pumped.
3. Solid, semiconductor, electrically pumped.
4. Liquid, optically pumped.
5. Gaseous, electrically pumped.

The first, and most studied, laser was the ruby ($Al_2O_3:Cr^{+++}$). It is a three level laser which operates exactly as described in the previous section. Many other materials in this category have shown laser action. Generally the output is in the form of pulses in the order of 1 msec duration (25, p. 13). CW (continuous wave) operation has been produced in several crystalline materials but at very low efficiencies, even by laser standards.

The solid noncrystalline, optically pumped lasers are made of glass doped with any of a small group of rare earth elements. Due to poorly defined energy levels in the noncrystalline structure, the emission lines are somewhat broader than those of crystalline lasers and the glass lasers require higher pump powers (F, P. 12). One desirable feature of the glass laser is that it can be made into many shapes. One proposed design is a bundle of small fibers with liquid N_2 circulated among them for cooling. This form would allow very high powers to be produced (6 , p. 104).

The most recent addition to the family of lasers is the semiconductor laser. The only material yet successful in this category is degenerately doped GaAs. The laser action takes place in the vicinity of the junction of a heavily (8500 Amp/cm^2) forward-biased diode. The electrons crossing the junction to the P-type region are very likely to recombine with one of the large number of holes in the region giving up a photon of energy just slightly in excess of the energy gap. Holes crossing to the N-type region will also recombine. The photon efficiency (photons per carrier crossing the junction) of the semiconductor laser is nearly unity. Because the energy levels just above the energy gap on the N side are full of electrons, no electron on the N side of the junction could absorb the photon to make a transition across the gap. A similar situation exists for holes in the P-type material. A high current density provides a sufficiently high optical intensity within the crystal to produce laser action. When the external circuit is considered, the equivalent of four-level operation exists. The diode must be cooled to liquid N_2 temperature (77°K). Even so, the high current densities limit the laser to pulse operation with pulse widths up to 20 μsec (25, p. 12).

Only one liquid laser has been announced. It is composed of a terbium compound in a liquid, the nature of which has not been disclosed by the manufacturer. The main difficulty with the liquid laser is that the liquid absorbs much of the laser output (14, p. 59).

A laser of the gaseous type was the first cw laser produced. The original gas was a mixture of Ne and He in a glass tube with partially silvered ends. The helium atoms are excited by a plasma discharge. The upper helium level is quite broad and accepts many electrons. Neon has a narrow excited band slightly below the energy of the helium band. During a collision between an excited helium atom and an unexcited neon atom, there is a high probability that the helium atom will lose its energy to excite the neon atom. With the proper concentrations of Ne and He, a population inversion will exist. The radiation contained within the plasma will then stimulate the neon atom to decay back to its lower energy level. This again is the equivalent of a four-level system (25 p. 14). More recent gas lasers using only one gas have been announced. Wave lengths from the visible to 13 μ have been obtained with gas lasers (25, p. 16). Typical operation provides outputs between one and ten milliwatts with a pump power of 40 watts.

GENERAL CONSIDERATION OF OPTICAL COMMUNICATION SYSTEMS

An optical communication system must have a carrier source, a means of modulating the carrier radiation, a transmitting and a receiving antenna, a detector and a demodulator. Each facet of an optical communication system will be briefly discussed.

The Carrier Generator

The carrier may be generated by any of a large number of devices producing visible or infrared radiation. For a practical system, it is desirable to have a source which produces a high radiation energy density. The laser acts as nearly a point source of radiation by virtue of the fact that the radiation it produces is coherent.* Its effective radiation density is, therefore,

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* The word "coherent" has been given specific definitions consistent with its older meaning: "being logically connected and developed". In the case of an electromagnetic wave, coherent refers simply to the fact that one part of the wave is connected logically to another.

In this case, two types of coherence are defined. First, time coherence exists if, by measuring the characteristics of the wave at one point in time and space one can predict what its characteristics will be later in time at the same point in space. Second, spatial coherence exists if, by measuring the wave at one point in time and space one can predict the characteristics of the wave at that time somewhere else in space. If the predictions can be made exactly, then coherence is complete. If partial coherence exists, the predictions can be made only with a certain degree of accuracy.

very high. The brightness temperature of the laser is in the order of 10^{10} °K (12, p. 83).

Since present lasers are so inefficient, a question may arise as to whether they would require less power than conventional optical sources. Many practical sources use the radiation from a hot solid. Although equivalent temperatures in gaseous arcs may be higher (8, p. 424), the energy density is lower because of the low emissivity of the gas. Of the available hot solid sources (5, p. 30-33), the zirconium arc would probably be the most useful as an optical source for communication. This conclusion is based on the fact that although some other sources operate at higher temperatures (4000°C for a carbon arc compared to 2700° for a zirconium arc), their lifetime is quite limited by the burning away of the electrodes.

The emissivities of metals, although low at room temperature, increase in proportion to temperature. If it is assumed that, at 3000°K, zirconium acts as a black body, the Stefan-Boltzmann law can be applied.

$$W = \frac{\sigma T^4}{\pi} \qquad \text{eq (3)}$$

where W = power emitted into one steradian per cm^2 of source

$\sigma = 5.669 X 10^{-12}$ watts cm^{-2} $^{o}K^{-4}$

At $3000^{o}K$, $W = 146$ watts cm^{-2} $ster^{-1}$. A typical source might have 10^{-2} cm^{2} area and a total radiant efficiency approaching $1/\pi$. By virtue of the mechanical structure of the arc (8, p. 423), it would be difficult to use more than an f/2 cone of light from the lamp.

The Modulator

Any optical radiation can be modulated in amplitude or polarization. If the radiation is sufficiently monochromatic, it may be modulated in frequency. Coherent radiation may be phase modulated. If the radiation can be collimated and focused with precision, it is possible to modulate the bean spatially.

Spatial modulation occurs when the intensity of one part of the beam is made to be different from other parts of the beam as occurs in a standard slide projector. No source other than the laser is sufficiently monochromatic to make frequency modulation practical. The laser output is the only optical radiation which may be phase modulated.

Modulation methods can be classified in three broad categories. These are: (1) modulating the radiation beam itself, (2) modulating the energy supplied to the radiation source, and (3), in the case of lasers, operating on the laser crystal itself to change the frequency of operation.

Several mechanical methods have been proposed for modulating light beams. These include vibrating mirrors and mechanical shutters. Mechanical methods are restricted to frequencies below a few megacycles by the limitation of frequency response of moving parts, and would, consequently, be suitable for only a few voice channels of information on any one light beam, (6, p. 104).

Electrical modulation of a beam has been accomplished using any of three physical principles. These are the Faraday, Kerr, and Pockel effects.

When a polarized light beam is passing through certain substances an applied magnetic field will change the plane of polarization. This is the Faraday effect. Other materials will rotate the plane of polarization as a function of an applied electric field. This is the Kerr effect. The Pockel effect occurs in piezoelectric crystals. When a light beam travels along a certain crystal axis, its plane of polarization will be rotated. The amount of rotation can be varied by crystal deformation. A piezoelectric crystal can be deformed by an applied electric field so modulation can be accomplished by using an electric field, (16, p. 105).

All three of these effects generally give rise directly to polarization modulation. If the polarization modulated beam is passed through a properly oriented analyser (a polarized element through which polarized light is passing), the beam passing the analyser will be amplitude modulated.

Both the Kerr and Faraday effects are practical for modulation frequencies of a few megacycles. Above that frequency, the power required by the modulator becomes prohibitive because of the losses involved in varying the large required fields at high frequencies. A Pockel effect modulator mounted in a microwave cavity works well at microwave frequencies, the power required being a function of modulation bandwidth rather than modulation frequency. Still, the power requirements are high, (6, p. 105).

A recent breakthrough has been made in the field of wideband modulators. The new system utilizes a traveling wave Pockel effect modulator to produce a phase modulated signal. Previous Pockel effect modulators, with the crystal mounted in a microwave cavity, produced polarization or amplitude modulation. The new modulator has a bandwidth of at least 1 gc. The supporting equipment used in the experiment could not handle more bandwidth. Peak required power was 12 watts independent of bandwidth. Previous modulators have required kilowatts to modulate a bandwidth of 30 mc (17, p. 147).

Modulating the source energy will, in the case of lasers, produce pulse modulation, (22, p. 105). An incandescent lamp could be amplitude modulated by varying the driving power although the thermal time constant of the filament would severly limit the bandwidth.

An extension of varying the source power would be to vary the Q of the cavity in which a laser is being operated. This can be accomplished by moving one of the end mirrors. Doing so changes the efficiency with which the radiation is coupled to the laser to stimulate emission, (6, p. 104).

The third modulation method, which applies only to lasers, utilizes the possibility of changing the energy level positions within the laser material and thus changing the frequency of the output. The energy level positions may be changed by applying a strong electric field, (Stark effect), or a strong magnetic field (Zeeman effect). Both of these modulation methods require high powers from the modulating source, (6, p. 104). The frequency limitation on this type of modulation is a result of the characteristics of the laser itself, as will be shown.

Assume a crystal laser is 5 cm long and has end mirrors which are 95% reflective. Neglecting losses within the crystal, the average photon will traverse the crystal 20 times, or travel 100 cm within the crystal. If the index of refraction is 1.5, then a photon will remain within the crystal for an average of 5×10^{-9} seconds. If the energy level positions are changed, so the photon can no longer stimulate emission, in less than 5×10^{-9} seconds, the laser action will be impaired or will cease. In an FM communication system, the peak frequency deviations must be many times the width of the frequency band in which any one photon can stimulate emission; consequently, the time between peak frequency deviations must be much longer than 5×10^{-9} seconds. The highest modulation frequency for energy level modulation appears to be in the order of 10 mc.

An ideal modulator would produce wide modulation bandwidths at any modulating frequency with no power being required from the modulator. However, any modulator yet proposed is far from meeting these specifications. The modulators in the group operating on the radiation beam have given the best results to date. Of these, the modulators using the Pockel effect work at the highest modulating frequency and bandwidth but the power required by the modulator is appreciable. Some mechanical methods require less power but are severely limited in frequency.

The Detector and Demodulator

Detection and demodulation of optical frequencies are generally accomplished in one element of the system. Therefore, the two functions will be discussed together.

In some ways the problems of detection and demodulation are more severe than in modulation. The optical equivalent of the rf amplifier and the heterodyne demodulator have not yet been developed to the point of being practical. The state of the art in receiving optical communication is similar to that of radio when crystal detectors were being used.

Laser amplifiers are being developed and limited success has been reported. The Bell Telephone Laboratories have obtained a gain of 13 db (16, p. 302). The amplifier requires the same active material and pumping source as the laser oscillator; the end mirrors are reduced or removed, thus reducing the internal feedback. The requirements of the physical arrangement are that the radiation must not be sufficiently coupled to the laser to produce oscillations, but must be coupled strongly enough to produce amplification. This seems at first to be an unstable condition; but the maser, a very successful microwave amplifier, operates with the same requirements.

Several heterodyne receivers have been proposed and built. These have met with only limited success. One problem at present is that the laser frequencies are not sufficiently stable to maintain a difference frequency within the IF pass band (6, p. 106). Even though the laser frequency is very stable by optical standards, when it is demodulated to an IF of about six decades below the optical frequency, the resulting stability in the IF will also be reduced by six decades. Laser stability will improve as better lasers are developed.

Detectors presently available are of the quantum and thermal types. Because of slow response, thermal detectors would be of little use in communications, (6 p. 105).

The quantum detectors fall into four groups. These are photoconductive, (PC), photovoltaic, (PV), photoemissive, (PE), and photoelectromagnetic, (PEM). They operate as follows: The PC detector is a substance whose resistance is inversely proportional to the radiation intensity striking it. A PV detector produces a voltage which is proportional to the radiation intensity striking the detector. A PE detector emits a number of electrons proportional to the intensity of the radiation falling on the emissive surface. The PEM detector in a strong magnetic field produces a voltage proportional to the intensity of the radiation falling on it. These four types of detectors are also AM demodulators in as much as they respond to radiation intensity.

The PC detector has a high quantum efficiency; that is, most of the quanta of absorbed radiation produce free charge carriers. PC detectors respond to intensity variation frequencies no higher than a few megacycles, (19, p. 1478). There are many materials available in this category. Any one material will respond to a radiation spectrum covering more than an octave of frequency, (9, p. 1502). By selecting the proper materials, this type of detector can detect radiation through the visible spectrum and into the infrared to about 40 μ, (13, p. 1479).

The photovoltaic detector also has a high quantum efficiency. It is capable of detecting intensity variations at gigacycle rates. Since a junction must be built into the detector, the array of available materials for PV detectors is not as great as that for PC detectors. The most common PV material is silicon which has a peak response around 1.0 μ, (12, p. 425).

Photoemissive detectors have a very low noise but a low quantum efficiency. In a photomultiplier tube, the noise is low enough that a flux of one photon per second can be detected by a one cycle per ten minute bandwidth (20, p. 131). In the infrared, typically only one photon in 300 is effective (20, p. 125). There are few good PE materials. These respond to wave lengths in the visible and near infrared to about 1.2 μ (20, p. 131). The three common configurations of photoemissive detectors are photodiodes, photomultiplier tubes, and photocathode traveling wave tubes. The latter two are combination detector and amplifier and are, therefore preferred over photodiodes, especially in low level detection. The standard photomultiplier tube will respond to intensity variation rates of about 100 megacycles (12, p. 281). A recent development in photomultiplier tubes is the "dynamic crossed-field photomultiplier" which will respond to modulation frequencies of 3 gc (4, p. 153). Photocathode traveling wave tubes will demodulate throughout the microwave spectrum.

Radiation striking the surface of a photoelectromagnetic detector will generate charge carriers at that surface. The carriers diffuse through the body of the detector. A strong magnetic field at right angles to the direction of incoming radiation will separate the positive and negative charge carriers and produce a

Hall voltage (or current) in the third orthogonal direction. PEM detectors have found few practical uses, mainly because of the required magnetic field.

As in radio where the crystal detector required little dc power, the PC and PV detectors require small amounts of power. The PE detector-amplifiers require more. If laser amplifiers and heterodyne demodulators are developed, the dc power required to operate the receiver will be greatly increased.

The Antenna System

The directivity of optical antennas is a function of the antenna size, the operating frequency and the source size. When conventional sources are used, the operating frequency is of no consequence. Antennas used with laser sources will have a directivity which does not depend on the size of the laser. In either case, the total received energy depends on the size of both the transmitting and receiving antennas.

In a standard collimating system where the source is large, the divergence of the beam is s/ℓ where s is the source diameter and ℓ is the focal length of the optical system. In order to decrease the divergence, either s should be decreased or ℓ should be increased. For any given type of source, there is a maximum energy density that the source will produce and decreasing s will decrease the energy output of the source. The amount of energy transmitted by the optical system is inversely proportional to the square of the f number where $f = \ell/d$ and d is the diameter of the antenna. If ℓ is increased to improve collimation, then d must be increased proportionally in order to transmit the same amount of energy. The derivation in Appendix I shows that the ratio of received to source power in a large source system is:

$$\frac{P_r}{P_s} = \frac{A_r A_t}{D^2 A_s} \qquad \text{eq (4)}$$

where A_r = receiving antenna area

A_t = transmitting antenna area

D = distance between antennas

A_s = area of source

P_r = received power

P_s = source radiant power per steradian.

If A_s/A_t becomes very small, another phenomenon limits the collimation that can be achieved. Any antenna will form a diffraction pattern. If a point source is used, this diffraction pattern defines the beam divergence. In the case of coherent radio or optical sources, the source has the characteristics of a point source. Lasers are the only optical source which can transmit a reasonable power through a diffraction limit antenna system. If the antenna collimates the beam to the limit of diffraction, the divergence will be:

$$\theta = \lambda/d \qquad \text{eq (5)}$$

where θ = beam divergence to the six db points in radians.

λ = radiation wave length

d = antenna diameter (6, p. 101).

The ratio of received to transmitted power in a diffraction limited condition is:

$$\frac{P_r}{P_t} = \frac{A_r A_t}{\lambda^2 D^2} \qquad \text{(15, p. 138) eq (6)}$$

where all symbols are as previously defined. Since the coherent source is highly directional, $P_t = P_s$.

A reflective, diffraction limited antenna cannot deviate from the design dimensions by more than 1/8 wave length of the transmitted energy (6, p. 101). Larger errors in the antenna manufacture will result in a beam divergence significantly in excess of that obtainable with a diffraction limited antenna.

A second problem has arisen in the design of microwave antennas, and will become more critical in optical antennas. It is necessary to equalize the path length from source to receiver independent of which path is followed. This is necessary to prevent destructive interference within the signal. It has been found that the path length should be constant within 1/16 wave length of the highest transmitted frequency (11, p. 449). At optical frequencies the antennas will have to be designed and built so that all path lengths are within a fraction of a micron of being the same optical distance. Designing such an antenna will be difficult. Building one more than 30-50 cm in diameter would be impossible using techniques presently available (6, p. 107).

In general a diffraction limited antenna will not meet the requirement of maintaining equal path lengths and vice versa. Communicating with coherent light and a diffraction limited antenna system will require that both requirements be met simultaneously.

Optical Noise

The noise in radio receivers is determined by thermal noise in the receiver. In optical signals the noise arises from the high photon energy and random distribution of photons in the signal. The complete equation for the spectral noise energy density of an ideal detector is:

$$\psi = \frac{h\nu}{\exp\left(\frac{h\nu}{kT}\right) - 1} + h\nu \qquad (6,\ p.\ 102) \quad \text{eq (7)}$$

where ψ = noise energy per cycle of bandwidth

h = Planck's Constant

ν = frequency of radiation

k = Boltzmann's Constant

T = Absolute temperature.

If $h\nu \ll kT$, eq (7) can be expanded to $\psi = kT$, familiar to radio work; if $h\nu \gg kT$, the equation reduces to $\psi = h\nu$. The two noise components are equal at an equivalent noise temperature of $4^{o}k$ and a frequency of 100 gc. An ideal optical detector would require a received power of $P_r = h\nu B$ to have a signal to noise ratio of unity (6, p. 102). The required received power for S/N = 1 is the noise equivalent power, NEP of the detector.

In practice, ideal detectors do not exist. If a photoemissive detector is used, then only a small fraction of the received photons are effective. This fraction is the photon efficiency, η . In a photomultiplier tube, other noise sources are small, so the

$$NEP = \frac{h\nu B}{\eta} \qquad \text{eq (8)}$$

In photoconductive detectors, the quantum efficiency is generally high, close to 0.5. The major noise is created by random thermal generation of carriers. This type of noise increases in proportion to the square root of the information bandwidth so $NEP \sim (BW)^{\frac{1}{2}}$. For any material, $NEP \sim A^{\frac{1}{2}}$ where A is the area of the detector.

A parameter, D*, is defined as:

$$D^* = \frac{A^{\frac{1}{2}}\ BW^{\frac{1}{2}}}{NEP} \qquad (18,\ p.\ 1503) \quad eq\ (9)$$

and is given at a specified wave length, center frequency, and bandwidth (normally lcps). Detector data comparing different materials is often given in terms of D*. A good PbSe detector operating at 77°K in the 2 μ to 4μ region will have an NEP of 10^{-13} watts.

Photovoltiac detectors produce a noise proportional to the square root of bandwidth at small bandwidths. The noise becomes proportional to bandwidth of wide bandwidths. Practical considerations show that bandwidths large enough so NEP∼BW would be above the frequency to which the detector will respond. The illumination required to give unity signal to noise is:

$$F_1 = \frac{B}{\eta}\left[1 + \left(1 + \frac{2\eta F_s}{B}\right)^{\frac{1}{2}}\right] \qquad (21,\ p.\ 143)\ eq\ (10)$$

where F_1 = the illumination in photons per second

$F_s \approx 10^{16}$ second $^{-1}$ (21, p. 145).

At microwave modulation frequencies eq (10) reduces to

$$NEP = \frac{10^8\ h\nu\ (B)^{\frac{1}{2}}}{\eta} \qquad eq\ (11).$$

If the radiation to be detected is generated by a coherent source, the NEP in a photovoltiac detector may be reduced by mixing the incoming radiation with a local laser output and allowing both to strike the detector.

If strict mechanical and optical requirements are met, the detector output will be the difference frequency between the incoming signal and the local laser frequency. In order to prevent destructive inference between the signal and local oscillator beams, the following condition must be met:

$$\sin \gamma < \frac{\lambda}{2d}$$

where γ is the angle of divergence between the two optical beams and d is the diameter of the receiving antenna (21, p. 144). The number of photons per second, F_{12}, now required for S/N = 1 is:

$$F_{12} = \frac{2B}{\eta}\left(1 + \frac{F_s}{F_2}\right) \quad \text{(21, p. 144)} \quad \text{eq (12)}$$

F_2 = photons per second from local laser

$F_s \approx \eta F_s \approx 10^{16}$ second^{-1}

if $F_2 \gg F_s$ which would be the normal situation, eq (12) leads to:

$$\text{NEP} = \frac{2\,h\nu B}{\eta} \quad \text{eq (13).}$$

In a photovoltiac detector, η is generally close to unity so this heterodyne receiver will theoretically detect signals only slightly more than twice as large as those detectable by an ideal receiver.

As was stated earlier, laser amplifiers for use as the first stage in the optical detector are being developed. The theoretical NEP of a laser amplifer is:

$$NEP = \frac{1}{E} h\nu B \quad (25, p. 29) \quad eq (14)$$

where $E = 1 - N_1/N_2$

N_1 = lower state population

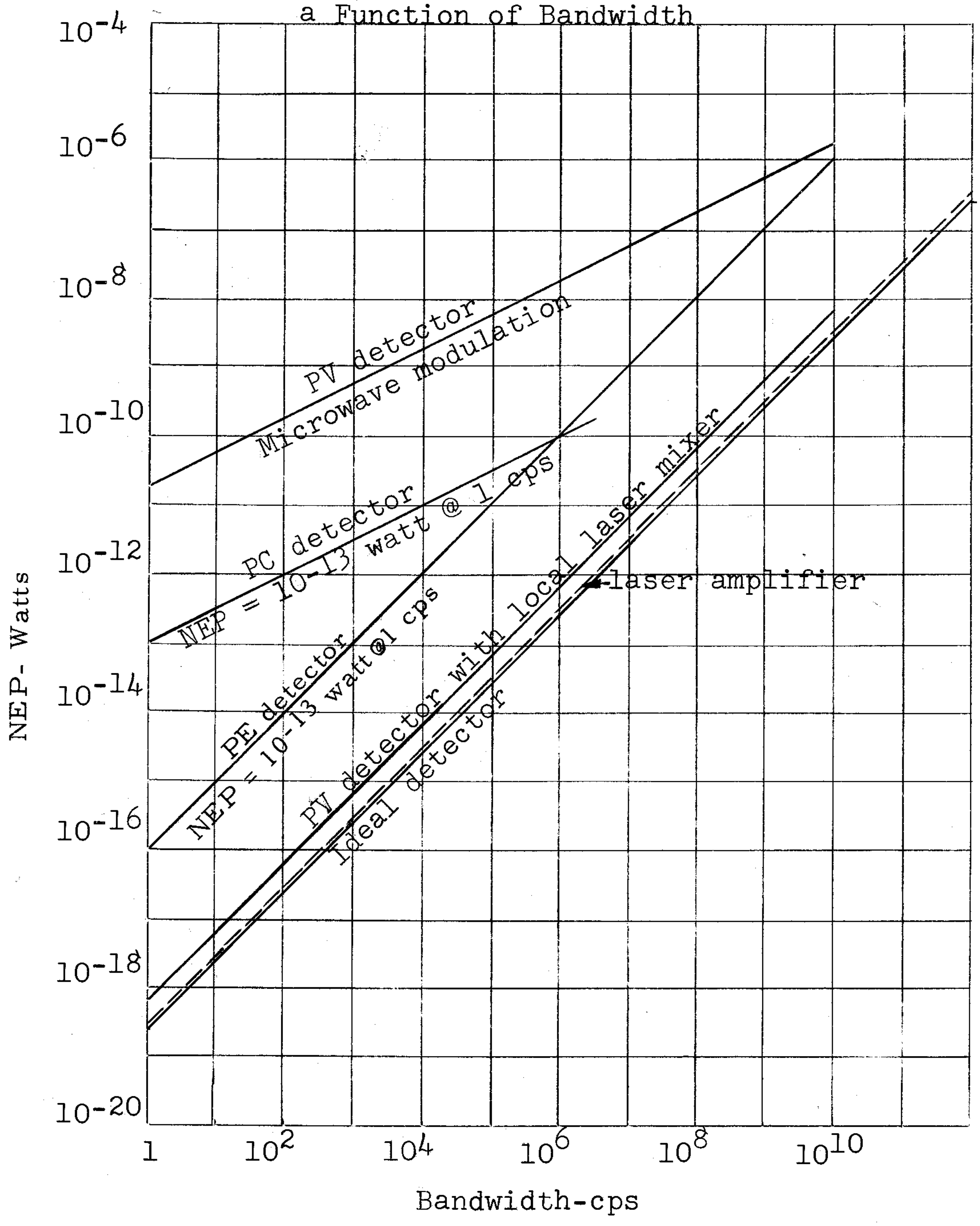
N_2 = upper state population.

Since N_2 generally greatly exceeds N_1, E is close to unity and the laser amplifier approaches the ideal detector.

The NEP of several detectors is shown as a function of information bandwidth in Figure 4.

Figure 4

Noise Equivalent Power of Several Detectors as a Function of Bandwidth



COMPARISON OF RADIO AND OPTICAL COMMUNICATION SYSTEMS

A comparison will be made of optical and radio communication systems operating under three different environmental conditions. These are: (1) communicating between two points on earth's surface, (2) communicating between two points outside earth's atmosphere, and (3) communicating between a point on the earth's surface and a point outside the earth's atmosphere. Three types of radiation sources will be considered. These are: (1) a standard radio transmitter, (2) a laser, and (3) a zirconium arc source.

Earth Based Communication Systems

One of the newest major microwave relay systems is the TH relay network operated by the Bell system. The characteristics of the TH radio system will be compared with those of possible optical systems.

The TH system is a "long haul" system operating in the 5925-6425 mc band. It is an FM system with eight channels in each direction; six channels are working and two are for protection, (10, p. 1459). The frequency shift for any of the eight channels is ±4mc. Each channel will transmit 1860 simultaneous conversations (10, p. 1467). The average spacing between repeators is 30 miles. The antenna gain at 6 gc. is 43 db. The loss between isotropic antennas is 142 db (10, p. 1463). There is an 8 db loss in wave guides making a total loss of 64 db (10, p. 1404). The transmitting tube is a five watt TWT which is flat over the .5 gc band. The receiver noise figure is 10 db. The repeater is an IF repeater, that is, "the modulated radio frequency signal is heterodyned to an intermediate frequency for amplification and equalization and then heterodyned back to the radio frequency without demodulation." (10, p. 1467). Average annual outage time is expected to be less than 0.01% with outage time during the worst month being around 0.03%. Signal fading is expected to be the worst cause of outage (2, p. 52).

A zirconium arc source used for communication over the same distance would transmit a power according to eq 4, of

$$P_r = \frac{P_s}{A_s} \quad \frac{A_r A_t}{D^2}$$

where P_s/A_s = 146 watts cm^{-2} $ster^{-1}$ = 1.46×10^6 watt m^{-2} $ster^{-1}$

$A_r = A_t = 1 m^2$

$D = 50$ km

$P_r = 5.8 \times 10^{-4}$ watt

assuming transmission through a vacuum.

Even with large antennas of 1 meter^2, the signal to noise ratio would be only 30 db for an information bandwidth of 0.5 gc if the signal were received by the PV detector described in Figure 4. Atmospheric absorption will drastically reduce the S/N computed for a vacuum.

Atmospheric transmission measurements made over a 10.1 mile path on a clear day show transmission in excess of 40% in several spectral regions (atmospheric windows).

These are, roughly, 0.8 to 0.9u, 1.0 to 1.1 u, 1.2 to 1.3 u, 1.5 to 1.75 u, 2.1 to 2.3 u, 3.45 to 4.0 u, and 8.15 to 12.4 u (22, p. 225). Even these windows which transmit 40%-50% over a ten mile path would transmit only 6%-12% over a 30 mile, or 50 km, path.

Using the Wien displacement law, $\lambda_m T = 2893$ micron degrees (12, p. 31), eq (14), a 3000°K black body has a peak spectral radiation at 0.96 microns. Comparing the spectral radiation from a 3000°K black body (12, p. 34) with the atmospheric transmission spectrum (22, p. 225) shows that only about half of the black body energy falls in the atmospheric window regions; the rest is completely absorbed by the atmosphere. The total transmission is, consequently, only about 3% under good conditions. Therefore, the signal from a zirconium arc source would be attenuated 15 db by clear atmosphere. The S/N ratio of 30 db computed without considering atmospheric absorption would be reduced to 15 db by clear atmosphere.

A cw gas laser producing 10 mw of radiation at 1μ and used in conjunction with antennas with an area of 0.1 square meter would transmit (using eq 6) over a 50 km path, $P_r = P_t \frac{A_r A_t}{\lambda^2 D^2} = 4 P_t$.

This result indicates that using an 0.1 m^2 transmitting antenna, the radiation could be focused to a spot smaller than 0.1 m^2 at a distance of 50 km and virtually all the transmitted energy, not absorbed in the atmosphere, will be received. If a frequency that is transmitted well by the atmosphere were chosen, about 12% would be transmitted over a 50 km path. The received power would then be 1.2 mw. Transmitting an 0.5 gc bandwidth and receiving the signal with a semiconductor diode, 1.2 mw represents a signal to noise ratio of about 35 db. Another 30 db could be obtained by using a local laser to mix with the signal at the receiver.

So far, only clear atmosphere transmission has been considered. Measurements made in haze and smoke indicate that transmission through hazes of optical density of 2/km or less in the visible becomes almost complete at 10 μ, (1, p. 498). Hazes have optical densities in the order of 0.7/km at 1 micron and 0.2/km at 3 microns

(1, p. 494). Measurements made in fog show an optical density between 5/km and 30/km at 0.55 μ which does not decrease appreciably to 5 μ. At 10 μ the optical density is about half that in the visible, (1, p. 495). The optical density/km is equal to the nepers of attenuation/km. Other measurements of transmission in fog and rain, and measurements made during a snowstorm made over a 3.4 mile path show the following results (22, p. 226).

λ- microns	transmission in fog and rain	equivalent nepers/km	transmission in snowstorm	equivalent nepers/km
0.55	0.04%	1.45	0.004%	1.87
1.26			0.04 %	1.45
3.64	1.2%	0.82		
3.98			0.08 %	1.32
11	5.6%	0.53		

Even in the rainstorm, the least interfering of the three weather conditions, the absorption over a 50 km path would be 40 nepers, or 174 db, at 3.64 μ and considerably worse at one micron. All the above measurements were made with incoherent light sources; there is no guarantee the same will hold true with coherent sources (6, p. 100). However, there is a strong indication that a free air optical communication system would not suffice as a highly reliable, wide band, information transmission system.

In order to eliminate atmospheric effects, it would be possible to transmit the beam through a "light guide" with a controlled, nonabsorptive atmosphere. If such a guide were made with a cross sectional area of 10^{-2} m^2 (13 cm in diameter) and with nonreflective walls, a 10 mw laser using diffraction limited 10^{-2} m^2 transmitting and receiving antennas could transmit 0.4 mw of power over a 50 km path. This would provide a signal to noise ratio with a diode detector of 30 db with an 0.5 gc bandwidth (60 db if a local laser is used at the receiver). If the walls of the guide are made 95% reflective, paths making 13 or fewer reflections are attenuated by 3 db or less. The effective area of the receiving antenna is $A' = (2n + 1)^2 A$, eq (15), where n is the maximum number of reflections. This equation is derived in Appendix II. For $n = 13$, $A'/A = 729$ so again essentially all the transmitted energy is received. The light guide cannot be made straight for a full 50 km. If one bend is made every km, then 50 reflections of the whole beam will be made. If each bend attenuates the signal by 5%, the 50 bends would be made at a cost of 11 db. The total resulting signal to noise ratio using such a light guide would be 35 db at a bandwidth of

0.5 gc with another 30 db again being available by using a local laser at the receiver.

Using a reflective light guide of only 10^{-3} m^2 area ($\sim$4cm diameter) and corresponding antennas would provide a received power of:

$$P_r = 2.9 \text{ milliwatts}$$

if no bends in the guide were made. Assuming 50 bends to be required, such a system would provide a signal to noise ratio of 30 or 60 db with the same considerations as before.

A 10^{-2} m^2 light tube and a zirconium arc lamp would provide $P_r = \frac{P_s}{A_s} \frac{729 A_r A_t}{D^2} = 4.25 \times 10^{-5}$ watt without considering bends. The resulting signal to noise ratio , including reflection losses, is only 10 db and does not offer the possibility of mixing at the receiver.

The foregoing discussion has brought out the following important points: (1) In order to have a highly reliable optical communication system, the communication path must be through a controlled atmosphere. (2) Even with a carefully constructed light guide with highly reflective sides, to provide a circuit with characteristics comparable to the TH microwave radio relay system requires a laser drawing as much power as the TWT transmitter in the TH system.

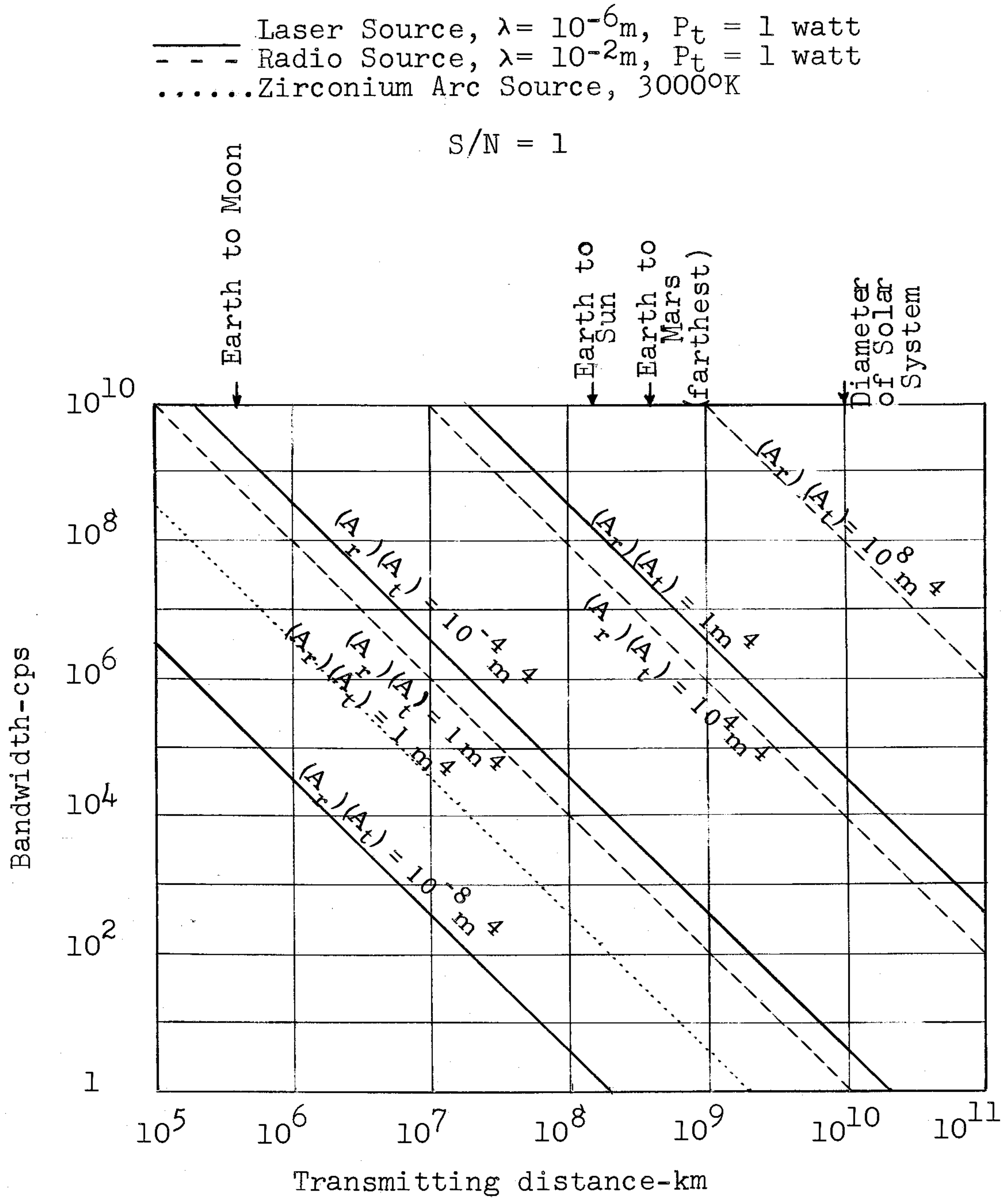
The only way to make the expense of a light guide feasable would be if it would provide a characteristic unobtainable in standard radio communication. With the increasing demands on the radio frequency spectrum, this characteristic may well be increased bandwidth. A one watt cw laser (which does not yet exist) could transmit a 50 gc bandwidth beam through a four cm diameter light guide for 50 kilometers and be received with a photo-diode and local laser mixer at a signal to noise ratio of 60 db. When such bandwidths become necessary, the laser will probably become practical for earth-bound communication systems.

Communication Between Points in Space

The problem of space communication is considerably simplified by the fact that there will be no atmospheric absorption of the signal. It has been shown quite conclusively that communication over interstellar distances, while a formidable problem with radio, would be virtually impossible at optical frequencies, (15, p. 139-140). Interplanetary communication is of more immediate interest and will be discussed further.

Figure 5 shows the maximum bandwidth which could be received at a signal to noise ratio of unity per watt of transmitted power as a fraction of transmitting

Figure 5
Maximum Bandwidth as a Function of Transmitting Distance



distance. Since, from eq (5), the received power is a function of the product of the antenna sizes, the family of curves represent several antenna size products. The optical detector is assumed to be ideal; the radio receiver is assumed to have an equivalent temperature of $10^{o}K$. The optical frequency is 300 tc ($1\ \mu$); the radio frequency is 30 gc (1 cm).

The curves representing a laser system in Figure 5 are constructed from eq (6) and Figure 4. For any transmitting distance and antenna size P_r is computed. Using this P_r, Figure 4 shows the bandwidth which can be received at a S/N of unity. This bandwidth is plotted in Figure 5. A curve similar to Figure 4 could be plotted for a radio receiver with an equivalent temperature of $10^{o}K$. Using such a curve and eq (6) would result in the curves representing a radio system plotted in Figure 5. The curve for the zirconium arc source was derived using Figure 4 and eq (4).

The bandwidth which can be received is proportional to the transmitted power and inversely proportional to the desired S/N in the receiver. To compute the bandwidth which could be received with other parameters specified, find the bandwidth which could be received with the conditions specified for Figure 5. Multiply the bandwidth shown in Figure 5 by the transmitted power in watts and divide by the desired signal to noise ratio in order to determine the unknown bandwidth.

Using the procedure just outlined, it can be determined that a 10 mw laser with an antenna system where the product of the antenna areas is one m^4 could transmit a four mc bandwidth a distance equal to the radius of the moon's orbit at a signal to noise ratio of 50 db but could transmit only 10 kc to the sun at a signal to noise ratio of only 20 db. In order to communicate over the distance from the earth to Mars at superior conjunction (when Mars is on the other side of the sun from the earth) with a four megacycle bandwidth, 40 db S/N, and one m^2 antennas would require a 30 watt laser. Such a laser is still at least several years in the future. Present lasers could transmit information only very slowly over such a distance. B. M. Oliver suggests (15, p. 139) a pulse modulation with a solid state laser. Still, the average power requirement holds for any given bandwidth. Present pulse lasers would have to be pulsed infrequently resulting in small information rates.

For any given antenna size, information bandwidth, and transmitting distance, the radio system would have to transmit 46 db more power than the laser. The zirconium arc would have to produce even more power than the radio assuming an ideal detector. The ideal detector of incoherent radiation has not yet been approached. Therefore the zirconium arc will be considered no further in this section.

The radio transmitter may be 100 times more efficient than the laser. Thus, the dc power required by the radio transmitter would exceed that required by the laser by 26 db. A large, 30 watt, laser may approach the efficiency of the radio transmitter. This would increase the advantage of the laser toward 46 db. The smaller power requirement of the optical system is often pointed out (eg., 15, p. 139).

The apparent power advantage of the optical system is small, if existent, when the antenna systems are considered further. An optical antenna must be made very rigid in order to maintain the critical dimensional tolerances. They are usually made of silvered glass and are very heavy. Radio antennas of the same weight could be made with at least ten times the area of an optical antenna. This alone would reduce the advantage of the optical system by 20 db.

As stated previously, the beam divergence from antenna is $\theta = \lambda/d$. An optical antenna 1m^2 area (1.3 meters diameter) transmitting at $\lambda = 1\mu$ would have a beam divergence of 0.8 μ radians. Even high quality tracking devices have peak tracking errors of ten times that. For this reason, practical optical antennas for space use would be limited to 13 cm diameter (10^{-2} m^2 area) which would produce a beam divergence of about 8 μ radians. A radio antenna transmitting a 1 cm wave length would have to be 1250 meters in diameter to produce a 8 μ radian divergence. Such an antenna would be impractical by reasons of size alone. Therefore, the radio antennas would be much easier to point than the optical antennas.

To summarize, a comparison of optical and radio systems using antennas of equal size shows that the radio system must transmit 46 db more power than the optical system. Due to the inefficiency of present lasers, the radio system would require a dc power of about 25 db more than the laser. The power advantage of the laser system may be increased toward 46 db by the development of more efficient lasers. Comparing systems with equal antenna masses, however, shows that the optical system has less than a 25 db advantage using lasers with an efficiency equal to the radio transmitter and an ideal receiver. Due to the very high directivity of the optical antennas, they will be much more difficult to point. The net result is that an optical system would have little, if any, advantage over a radio system for interplanetary communications.

Earth to Satellite Communication System

Two major types of radio communication satellites have been operated successfully. These are Project Echo and Project Telstar, both operated by the Bell system. Each will be discussed briefly and compared with the optical system which would be required to accomplish the same result.

> On August 12, 1960, a 100-foot-diameter spherical balloon was placed in orbit around the earth by the National Aeronautics and Space Administration. The objective was to demonstrate the feasibility of long distance communication by means of reflection of microwaves from a satellite. It was intended that a two-way coast-to-coast voice circuit be established between the Jet Propultion Laboratories at Goldstone, California, and a station provided for this purpose by Bell Telephone laboratories at Holmdel, New Jersey, (7, p. 975).

Some of the outstanding features of the system are listed below:

East-West channel	60' paraboloid transmitting antenna at B.I.L.
	85' paraboloid transmitting antenna at J.P.L.
	Operating frequency = 960.06 Mc.

West-East channel Another 85' paraboloid transmitting antenna of J.P.L. 20' X 20' horn reflector receiving antenna at B.I.L. Operating frequency = 2390 Mc.

Slant range between Holmdel and the balloon varied between 1000 and 3000 miles (7, p. 977).

Both sites used 10 kw transmitter (7, p. 978).

Using frequency modulation with a modulation index of ten, expected S/N was:

J.P.L. to B.T.L.	57 db	
B.T.L. to J.P.L.	49 db	(7, p. 979).

The expected S/N figures were later verified (7, p. 996).

The transmitters could be operated with frequency modulation, phase modulation, single side band, double side band, or amplitude modulation, (7, p. 983). Frequency modulation was found clearly superior to SSB or narrow band PM, (7, p. 996).

The 60' paraboloid at B.T.L. could be pointed within 0.05° (7, p. 985). Both antennas had a beam width of 1.2° (7, p. 986). Tracking was done primarily by controlling the drive mechanism with tapes of the predicted orbit. This was corrected during transmission by current data from optics, radar, or carrier peaking, (7, p. 988).

Echo provided an excellent circuit for 200 to 3000 cps bandwidth and "any service that could be transmitted in this bandwidth could equally well be handled by the satellite circuit," (7, p. 996).

Now consider the optical system which would be required to accomplish the same task. If a 10^{-2} m^2 transmitting antenna were used, its six db beam width would be 8 X 10^{-6} radians. A 100' balloon would subtend an arc of 10 X 10^{-6} radians at a distance of 2000 miles so virtually all the radiated power will strike the balloon. The pointing accuracy would have to be improved a factor of 100 over the 10^{-3} radian accuracy with which the radio antennas could be pointed. A 10^{-2} m^2 receiving antenna would subtend about .4 X 10^{-6} radian from the balloon 2000 miles away. This is 16 X 10^{-14} steradian or about 2 X 10^{-14} part of a hemisphere. If the receiving antenna views the balloon 90^o away from the line of view of the transmitting antenna, only half the balloon will appear illuminated. If the balloon reflects diffusely, only 10^{-14} part of the transmitted power will reach the receiver. With an ideal receiver a 1000 watt average power lawer would be required to maintain one 40 db S/N voice channel over a path similar to that of the echo project even ignoring atmospheric absorption.

Clear atmosphere would attenuate the signal about 10 db boosting the transmitted power requirement to 10 kw, the same power transmitted in project echo. Inclement conditions would preclude the use of an optical system.

Project Telstar uses much the same type of terminal equipment as Project Echo. B.T.L. used a larger, 60' X 60', horn reflector receiving antenna which tracks within 0.05°, (23, p. 167). The satellite itself transmits about 2.25 watts and is nearly nondirectional, (23, p. 167). Bell Laboratories has established a communication circuit with the satellite using an 850 watt transmitter and an 18" dish transmitting antenna. They used frequency modulation with a peak deviation of 33 kc on a 6384.58 Mc carrier. S/N of the output of the receiver was 44 db, (24, p. 343).

Again, it would take 1000 watts of optical power transmitted from the satellite to maintain one 40 db voice communication circuit. The only advantage an optical communication system can clain is the high directivity of its antennas. In a system where one radiator must be onmidirectional, the optical system cannot compete with radio.

If the satellite is of such a nature that directional antennas can be used, the same considerations derived for an interplanetary system would hold except that the distances are smaller and atmospheric attenuation must be considered. Thus, the optical communication system losses some of the slight power advantage it had over radio in interplanetary communication even with clear atmosphere. Directional antennas on the satellite still would not allow transmission through fog or clouds unless the cloud layer is very thin, in the order of 100 meters or less.

CONCLUSIONS

1. On the basis of power requirements, the laser is superior to other optical sources for the purpose of communication.

2. Optical communication systems cannot be used for reliable communication on the surface of the earth unless the atmosphere between transmitter and receiver can be controlled.

3. If a five cm diameter light guide were built, a laser would have to transmit less power than the radio transmitters used in the TH relay system. However, the power required by the transmitters would be nearly equal. To make the construction of a light guide feasible, the optical system would have to be capable of carrying a larger information bandwidth than is possible with radio.

4. In space communications, a laser system would have a power advantage over a radio system using antennas of equal area. Using antennas of equal weight would greatly reduce the power advantage of the laser system. Considering the greatly increased problems of pointing the optical antennas makes it doubtful that lasers will be used in place of radio for space communication.

5. A laser communication system has no power advantage over radio when a diffuse reflection or a nondirectional transmission is involved in the transmission path.

6. A highly reliable communication link between the earth's surface and an earth satellite could not be maintained by an optical system.

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APPENDICES

APPENDIX I

Derivation of Range Equation for System with Finite Source Size

A. $\theta = s/\ell$

B. $M = \theta D = \dfrac{Ds}{\ell}$

C. $P_r/P_t = \dfrac{4A_r}{M^2} = \dfrac{4A_r \ell^2}{D^2 S^2}$

D. $P_t/P_s = \dfrac{\pi}{4f^2}$

E. $P_r/P_s = \dfrac{4A_r \ell^2}{D^2 S^2} \cdot \dfrac{\pi}{4f^2} = \dfrac{A_r \ell^2}{D^2 S^2 f^2}$

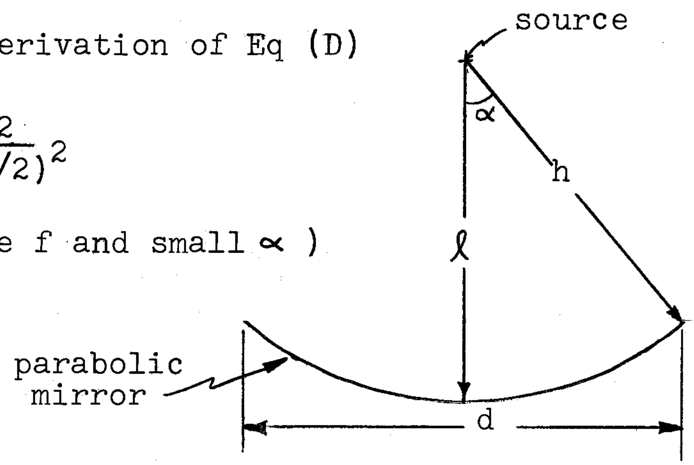
F. $f = \ell/d$

G. $P_r/P_s = \dfrac{A_r d^2}{D^2 S^2}$

H. $P_r/P_s = \dfrac{A_r A_t}{D^2 A_s}$

θ = beam divergence angle
s = source diameter
ℓ = focal length
M = diameter of beam at distance D from source
D = distance from source to receiver
A_r = area of receiving antenna
P_r = received power
P_t = transmitted power
P_s = Power radiated into one steradian by source
f = f/no
d = diameter of transmitting antenna
A_s = area of source
ω = solid angle subtended by the mirror from the source

Derivation of Eq (D)



I. $\alpha = \tan^{-1} \dfrac{d/2}{\ell - (d/2)^2}$

J. $h \approx 1$ (for large f and small α)

K. $\alpha \approx \sin^{-1} \dfrac{d/2}{\ell}$

L. $\alpha \approx \dfrac{d}{2\ell} = \dfrac{1}{2f}$

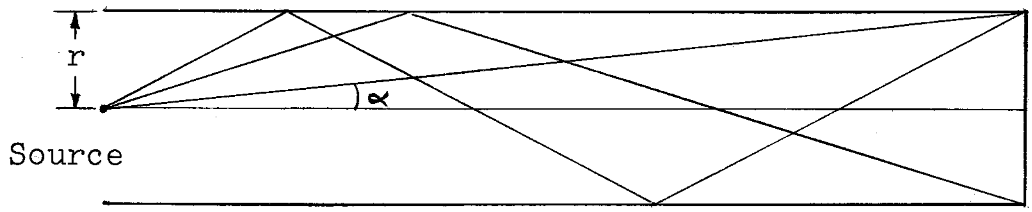
M. $\omega \approx \frac{\pi}{4}(2\alpha)^2 = \pi\alpha^2$

N. $P_t/P_s = \omega = \pi\alpha^2 = \frac{\pi}{4f^2}$

The error incurred by approximating I and L in an f/2 system is about 6%. Approximation M reduces the total error to about 5% in an f/2 system.

APPENDIX II

Derivation of Effective Receiving Antenna Size in Light Guide



It can be seen from the above drawing that for a ray to strike the receiver without reflections, it must travel within a cone of half angle α . For each reflection, the ray may cross the guide once, or moves an additional horizontal distance of $2r$. Thus the effective radius of the antenna is increased by $2r$ for each reflection. With no reflections the effective radius is r. After n reflections the effective radius is:

$$r' = 2nr + r = (2n + 1)r$$

The effective area is:

$$A' = \pi r'^2 = (2n + 1)^2 \pi r^2 + (2n + 1)^2 A.$$