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## Optical Communications Using Gallium Arsenide Injection Lasers

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## OPTICAL COMMUNICATIONS USING GALLIUM ARSENIDE INJECTION LASERS

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### ABSTRACT

A synthesis is presented which illustrates the applicability of gallium arsenide injection lasers as the source in high data rate optical communication systems. The synthesized system is a data link between two synchronous relay satellites separated by 45,500 statute miles. Requirements of the system were a data rate of 25 megabits per second and an information error rate of less than  $10^{-6}$ . The system is synthesized using the parameters of commercially available injection lasers and photodetectors. A greater information capacity is shown when optimistic parameter values are used.

### INTRODUCTION

The consideration of injection lasers over other types of lasers is motivated by their desirable operational characteristics such as relatively high peak power, high efficiency, small size, ease of modulation, long lifetime, and fast response time. The principal limitations of injection lasers are their non-coherent emission characteristics, relatively large beam patterns, and limited average power. However, the spectral emission of gallium arsenide injection lasers is compatible with commercially available photodetectors. Therefore, direct detection of their emitted radiation is possible. Furthermore, it will be shown that by arraying the laser diodes in a properly designed transmitter optical assembly, the beam pattern and average power limitations can be overcome.

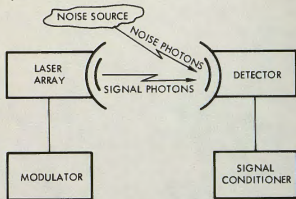
Operating characteristics of commercially available gallium arsenide injection lasers, critical to the performance of an optical communication system, are discussed. Included in this discussion are results of laboratory measurements on the effects of cooling the laser diodes in order to increase the average output power.

To illustrate the applicability of using gallium arsenide injection lasers, an example communication system is synthesized. The example system is a synchronous satellite to synchronous satellite link operating at a data rate of 25 megabits per second over a range of 45,500 miles. A given constraint of the system is a bit error rate of less than  $10^{-6}$ . Thus it will be illustrated that when

properly designed a gallium arsenide communication system can efficiently transfer data at a high rate over long ranges. This example system, which is synthesized with conservatively rated components, is then shown to have still greater potential when optimistic parameter values are used.

### SYSTEM DESCRIPTION

The system that has been synthesized is a unilateral communications link between two earth synchronous satellites. A pictorial of this system is provided in Figure 1.



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FIGURE 1. HARDWARE CONFIGURATION

The transmitting terminal consists of an electronic modulator, an array of gallium arsenide injection diodes, and an optical antenna assembly. As subsequently discussed, a data signal is created by forward biasing the diodes for short periods into a high current conducting state causing them to lase and emit infrared energy. The resulting radiated energy can be modulated with information at a high rate by appropriately formatting the data pulses. For efficient communications, radiation from the lasers must be collimated into a narrow energy beam. This is accomplished with an optical assembly that consists partially of an optical Cassegrain antenna. Design calculations have shown that, when appropriately illuminated by an optical feed, such an antenna will sufficiently collimate the energy from the laser sources. That is, the resulting beam will possess adequate radiant intensity for effective communications.

The receiving terminal consists of an optical antenna, an optical detector, and a signal conditioner. The optical antenna must be large enough to capture sufficient signal energy for minimal error detection. Design of this element of the system is not considered to be critical and may be assumed to consist of reflectors like those in an optical Cassegrain antenna. In addition to signal energy, background noise photons are also collected by the receiving antenna. Calculations have shown that noise photons, which originate from such sources as stars, planets, and the moon, are the significant system noise contributors. Both the signal energy and the noise energy are focused onto the optical detector. The optical detector performs essentially as a photon counter supplying photoelectrons to the signal conditioner in proportion to the received photons. The signal conditioner serves three purposes: it synchronizes the data signal, it decides the occurrence or absence of signal pulses in the presence of noise, and it converts the detected signal to a format compatible with user requirements. A prime measure of system performance is the ratio of the error rate to the information rate. Assuming perfect synchronization, this ratio is predictable and will be shown to be a function of the received signal and noise photoelectrons.

This system overview will aid in understanding the system synthesis and performance predictions presented in later discussions.

#### LASER SOURCE CHARACTERISTICS

The characteristics of the gallium arsenide injection laser play an important role in the physical design and performance of the system. The physical size of the emitting area, the radiation pattern and the total emitted power of the diodes significantly influence both the system performance and the design of the transmitter and receiver optics. Depending upon other system requirements, the allowable duty cycle of the laser may limit the information handling capacity of the system. These and other significant operational characteristics will now be discussed.

The spectral output of the GaAs injection laser consists of an envelope of spectral peaks representing the allowable modes of oscillation. This envelope is approximately Gaussian in shape and is approximately  $50 \text{ \AA}$  wide at the 3 dB points.

The geometry of the GaAs laser is shown in Figure 2. The emission from the laser comes from a narrow junction region. The length of the junction varies from approximately  $76$  to  $300 \mu$ , depending on the particular device. The length dimension of the device is easily controlled by manufacturers, and there is no problem of any appreciable variation from specified values. The junction width is not as well specified by the manufacturers. Typical junction widths are between 3 and 9 microns.

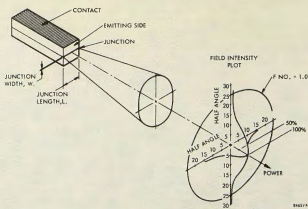


FIGURE 2. GaAs LASER DIODE EMISSION PATTERN

The angular spread of the emitted light from a typical GaAs laser is also shown in Figure 2. The half intensity beam width (total cone angle) is approximately  $10^\circ$  in a plane parallel to the junction and  $30^\circ$  in a plane perpendicular to the junction. These values have been found to be quite consistent with measured beams. However, this pattern is not always well aligned with the axis of the diode package. On some diodes the intensity pattern may be offset by as much as  $20^\circ$ . Such large skew angles for the output beam could cause penalties in optical design. This problem occurs because the diode chips are manually placed on the mount and the assembler has not accurately controlled the placement. More stringent quality control by the manufacturer could probably resolve this difficulty. A typical diode beam pattern is shown in Figure 3.

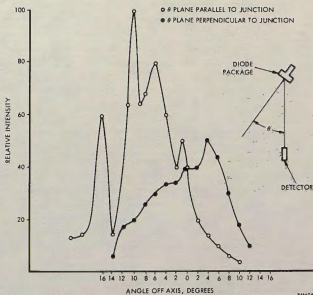


FIGURE 3. IRRADIANCE VS ANGLE OFF AXIS

The multiple peaks in intensity in the pattern taken parallel to the junction plane are due to off axis modes of oscillation in the laser cavity, and

are to some extent dependent on drive current.

An important parameter for transmitter design is the efficiency of a lens in collecting the emitted radiation from the laser diode. This efficiency is defined as the ratio of the radiation collected to that transmitted and is proportional to the integral of the radiant intensity over the solid angle subtended by the collecting lens. A typical plot of the measured collecting efficiency as a function of the F-number of the collecting lens is shown in Figure 4.

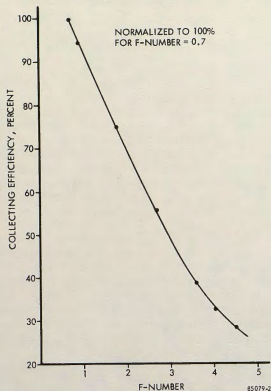


FIGURE 4. OPTICAL COLLECTING EFFICIENCY

Based on these measurements and manufacturers' data, it is concluded that an  $f/3$  collecting lens will collect approximately one-half of the emitted radiation. An optimum optical design would use a smaller aperture in the plane parallel to the junction than in the perpendicular plane in order to take advantage of the smaller beam width.

The output power of the GaAs lasers is related to the drive current and threshold current by

$$P_o = \begin{cases} K(I-I_t) & \text{for } I > I_t \\ 0 & \text{for } I < I_t \end{cases} \quad (1)$$

where  $K$  is a constant characteristic of the individual laser diode,  $I$  is the drive current, and  $I_t$  is the threshold current.

The threshold current is strongly temperature dependent. The measured dependence on the temperature is shown in Figure 5. The power law for this dependence lies very close to  $T^3$ . It is

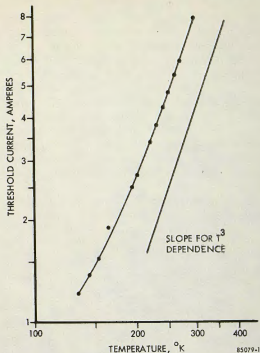


FIGURE 5. TEMPERATURE DEPENDENCE OF THRESHOLD CURRENT

believed that this dependence is typical of "good" quality GaAs lasers and may be expected from selected high efficiency units. This belief is substantiated by published data which shows threshold current versus temperature varying nearly as  $T^3$  in the temperature range from 200 to 300°K.

The maximum allowable duty cycle is theoretically given by

$$\delta_{\max} \approx C/I^2 R_D \quad (2)$$

where  $C$  is a constant characteristic of the individual laser diode and  $R_D$  is the internal resistance of the laser diode. This relationship has been verified with laboratory measurements. Laser diodes with an allowable duty cycle of 0.08 percent when operated at room temperature have been operated at a duty cycle in excess of 3 percent when cooled to 200°K. The corresponding average output powers were approximately 15 mw and 80 mw respectively.

Possibly of more importance than the peak power is the maximum average power of the laser diodes. The maximum average power is given by the product  $P_o \delta_{\max}$  and can be written as

$$P_o \delta_{\max} = CK(I-I_t)/I^2 R_D \quad (3)$$

It can be shown that the maximum average power occurs when the drive current is twice the threshold current. Another important characteristic of the GaAs laser is its power conversion efficiency ( $\eta_D$ ). This is given by



$$\eta_D = P_O/P_{in} = K(I-I_t)/(I(V_J+IR_D)) \quad (4)$$

where  $V_J$  is the junction voltage. It can be shown that the maximum efficiency occurs at

$$I/I_t = 1 + \sqrt{1+V_J/(I_t R_D)} \quad (5)$$

In general  $V_J/I_t R_D$  is of the order of 2 or less; therefore, for maximum efficiency the drive current should be slightly greater than twice the threshold current. It is of interest to note that the condition for maximum average power and maximum efficiency are approximately the same.

The characteristics of a good quality gallium arsenide laser are summarized in Table 1.

TABLE 1

TYPICAL CHARACTERISTICS OF A COMMERCIALY AVAILABLE GALLIUM ARSENIDE LASER DIODE			
Temperature	300°K	300°K	200°K
Threshold Current	10A	10A	3A
Drive Current	40A	20A	6A
Peak Power Out	20W	6.7W	2.7W
Efficiency	0.76%	7.1%	12%
Duty Cycle	<0.08%	<0.32%	<1.3%
Wavelength	0.9 $\mu$	0.9 $\mu$	0.88 $\mu$

### Received Signal Power

The transmitted power is related to the laser power by the relationship

$$P_t(\lambda) = \tau_t(\lambda) P_O(\lambda) \quad (6)$$

where  $P_t(\lambda)$  and  $P_O(\lambda)$  are the transmitted power and laser power respectively, and  $\tau_t(\lambda)$  is the transmissivity of the transmitter optics. Therefore,  $\tau_t(\lambda)$  characterizes the ability of the transmitter optics to collect the available laser power and the power loss in the optical elements. If  $P_t(\lambda)$  is radiated into a solid angle  $\Omega_t$ , the radiant intensity is given by

$$E_t(\lambda) = P_t(\lambda)/\Omega_t \quad (7)$$

The receiver subtends a solid angle with respect to the transmitter given by

$$\Omega_R = A_R/R^2 \quad (8)$$

where  $A_R$  is the area of the receiver optics and  $R$  is the range.

If the transmissivities of the medium and the receiver optics are  $\tau_a(\lambda)$  and  $\tau_r(\lambda)$  respectively and if  $\tau_p$  is a relative loss due to pointing, the signal power collected by the receiver is

$$P_{rs}(\lambda) = E_t(\lambda) \Omega_R \tau_a(\lambda) \tau_r(\lambda) \tau_p \quad (9)$$

The total signal power incident on the optical detector is

$$P_{rs} = \int_{\lambda} (A_R/R^2) E_t(\lambda) \tau_a(\lambda) \tau_r(\lambda) \tau_p d\lambda \quad (10)$$

Since the transmissivity of the receiver, which is dependent primarily on the optical filter used to suppress the background radiation, and the laser output are the only two parameters which are significantly wavelength dependent,  $P_{rs}$  can be written as

$$P_{rs} = (A_R/R^2) \tau_a \tau_p \int_{\lambda} E_t(\lambda) \tau_r(\lambda) d\lambda \quad (11)$$

The preceding equation is known as the range equation, and relates the received signal power to the parameters of the system. Since the laser diodes are limited in output power, it may be necessary to simultaneously pulse a group of diodes in order to obtain the required radiated power. In addition, for a given data rate requirement, more than one radiating group may be required to overcome the duty cycle limitations of the diodes.

### Data Rate Calculations

Two modulation formats which may be used in the system are the binary pulse code modulation (PCM) and pulse position modulation (PPM). With a PCM format with an equal likelihood of a pulse or no pulse, the data rate is related to the average duty cycle ( $\delta$ ) of the individual laser diodes, the number of radiation groups ( $R_g$ ), and the pulse width ( $\tau$ ) by

$$\text{Data Rate} = 2 \delta R_g / \tau \quad \text{bits/sec.} \quad (12)$$

In this case the data rate is limited to  $1/\tau$  by the restriction that the product  $2 \delta R_g$  cannot exceed 1.

That is to say that one radiating group operating at an average duty cycle of 50 percent would completely fill the time scale. Thus for a pulse duration of 10 nanoseconds, it is theoretically possible to achieve a data rate of 100 megabits/sec. Physical restraints of the transmitter and the transmitter optics limit the number of radiating groups and permissible duty cycle of the lasers. These limitations restrict the maximum achievable data rate. For example, with four radiating groups operating at an average duty cycle of 2.5 percent and a 10 nanosecond pulse, the data rate would be 20 megabits/sec.

With PPM the data rate is the product of the pulse repetition frequency ( $\delta R_g/\tau$ ) and the number of bits per pulse. This may be expressed in terms of the system parameters as

$$\text{Data Rate} = (\delta R_g/\tau) \log_2 (1/\delta R_g) \quad \text{bits/sec.} \quad (13)$$

The quantity  $(1/\delta R_g)$  corresponds to the number of possible positions in which the signal pulse may occur in a period equal to  $\tau/\delta R_g$ . In practice, the available number of pulse positions ( $M$ ) is an integer.

Plots of the product of data rate and pulse width as a function of duty cycle and number of radiating groups are shown in Figure 6.

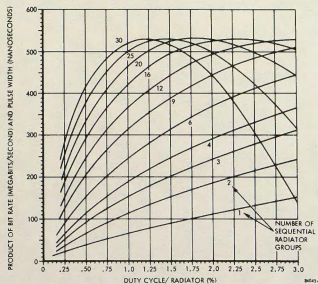


FIGURE 6. INFORMATION RATE WITH PPM FORMAT

In actuality these plots should not be continuous, but discrete points corresponding to integer values of  $M$ . The interesting feature of these plots is the fact that for a given pulse width the maximum theoretical data rate is a constant and occurs when  $1/\delta R_g$  equals the constant  $e$ . However, since  $1/\delta R_g$  must be an integer, the realizable maximum occurs when  $1/\delta R_g$  equals 3. Recall that with PCM the maximum data rate with a 10 nanosecond pulse is 100 megabits/sec. This is well in excess of the 52 megabits/sec. maximum that can be obtained with PPM. However, with a limited duty cycle of 2.5 percent and four radiating groups, the data rate with the PCM format is only 20 megabits/sec. The corresponding system operating with a PPM format can achieve 33 megabits/sec. Therefore, the choice of a modulation format will depend upon the operating parameters of the system.

#### Error Rate Performance

A most important performance criteria of a communication system is the ratio of bits or symbols that are erroneously detected to correctly detected bits or symbols per unit time. This ratio is commonly called the bit or symbol error rate. Expressions for the symbol error rate in a shot noise limited optical communication system have been developed for pulse code modulation (PCM) and pulse position modulation (PPM) formats

and certain detection techniques.

In a shot noise limited operating mode the detector is functionally an electron counter. Consequently, the actual number of signal electrons ( $S_e$ ) and noise electrons ( $N$ ) observed during individual pulse intervals determine the error rate. Because these electron counts are Poisson distributed, Poisson statistics are used to determine error rates. For given mean numbers of signal electrons ( $\bar{S}_e$ ) and noise electrons ( $\bar{N}$ ) received, the probability density distributions for both the actual number of noise electrons and the cumulative number of signal and noise electrons will typically have the form shown in Figure 7.

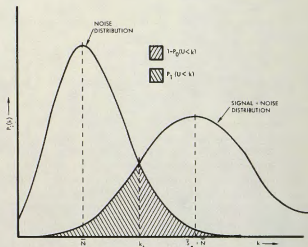


FIGURE 7. POISSON DISTRIBUTIONS OF NOISE AND SIGNAL

Although these distributions are discrete functions, they are depicted as continuous for easier viewing. The shaded portions of the graph are explained later as part of the optimum threshold detection performance discussion.

In this discussion, Poisson probability density functions are defined as

$$P[U = k | m_j] = p_j(k) \quad (14)$$

That is, the probability that the received signal ( $U$ ) equals a level  $k$ , given that the signal  $m_j$  was transmitted, is  $p_j(k)$ . The signal  $m_j$  is defined as

$$m_j = \begin{cases} m_1 & \text{when a pulse was transmitted} \\ m_0 & \text{when no pulse was transmitted.} \end{cases}$$

Therefore,

$$p_1(k) = P[U = k | m_1] = \left[ \frac{\bar{S}_e + \bar{N}}{k} \right]^k e^{-(\bar{S}_e + \bar{N})} \quad (15)$$

and

$$P_0(k) = [U=k | m_0] = \bar{N}^k e^{-\bar{N}} / k! . \quad (16)$$

The cumulative probability distribution will be defined as

$$P[U < k | m_1] = P_1(U < k) = \sum_{n=0}^{k-1} p_1(n) . \quad (17)$$

That is, the cumulative probability or the probability that  $U$  is less than some level  $k$  is equal to  $P_1(U < k)$ , which equals the summation of the discrete probabilities that the signal equals any level less than  $k$ . Therefore,

$$P_1(U < k) = \sum_{n=0}^{k-1} [(\bar{S}_e + \bar{N})^n / n!] e^{-(\bar{S}_e + \bar{N})} \quad (18)$$

and

$$P_0(U < k) = \sum_{n=0}^{k-1} \bar{N}^n e^{-\bar{N}} / n! . \quad (19)$$

These expressions can be used to determine the error rates for various modulation techniques of interest.

The error rate performance for a binary PCM channel utilizing a threshold decision device will now be discussed. During each pulse interval, the number of output electrons is counted and the decision whether  $m_1$  or  $m_0$  was transmitted is based on comparing this count level to a threshold level  $k_t$ . The probability of error ( $P_E$ ) in a binary channel is written

$$P_E = P_1(U < k_t) P(m_1) + P_0(U \geq k_t) P(m_0) \quad (20)$$

where  $P(m_1)$  is the a priori probability that message  $m_1$  was transmitted and  $P(m_0)$  is the a priori probability that message  $m_0$  was transmitted. Utilizing the fact that  $P_0(U \geq k_t)$  equals  $[1 - P_0(U < k_t)]$  (shown as shaded area on Figure 7) and Equations 18 and 19,  $P_E$  can now be written as

$$P_E = P(m_1) \left[ \sum_{n=0}^{k_t-1} (\bar{S}_e + \bar{N})^n e^{-(\bar{S}_e + \bar{N})} / n! \right] + P(m_0) \left[ 1 - \sum_{n=0}^{k_t-1} \bar{N}^n e^{-\bar{N}} / n! \right] . \quad (21)$$

For a given  $\bar{S}_e$ ,  $\bar{N}$ ,  $P(m_1)$ , and  $P(m_0)$ , there is an optimum  $k_t$  that minimizes  $P_E$ . The value of the optimum  $k_t$  is, from Curran and Ross<sup>(1)</sup>,

$$k_t = \{ \bar{S}_e + 1 n_e [P(m_0)/P(m_1)] \} / \ln e [1 + (\bar{S}_e/\bar{N})] . \quad (22)$$

In a binary channel with maximum signal entropy,  $P(m_0) = P(m_1) = 0.5$ . Under this condition, the expressions for  $k_t$  and  $P_E$  reduce to

$$k_t = \bar{S}_e / \ln e [1 + (\bar{S}_e/\bar{N})] \quad (23)$$

and

$$P_E = \frac{1}{2} \sum_{n=0}^{k_t-1} [(\bar{S}_e + \bar{N})^n e^{-(\bar{S}_e + \bar{N})} - \bar{N}^n e^{-\bar{N}}] / n! + \frac{1}{2} . \quad (24)$$

A computer program was written to evaluate  $P_E$  using the optimum threshold  $k_t$  (rounded to the nearest integer). Some results are shown in Figure 8 for optimum threshold detection of a binary PCM signal.

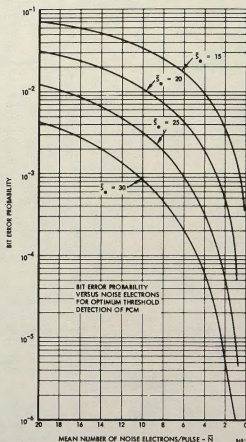


FIGURE 8. OPTIMUM THRESHOLD DETECTION OF PCM

Although the optimum threshold decision device could be used for detecting PPM signals, it was determined that the maximum likelihood detection method could locate pulses in an  $M$  position, PPM signal with greater probability of being correct. To support this conclusion, a comparison will be made at the end of this discussion.

Having established signal synchronization, the maximum likelihood method of processing corresponds to counting the number of electrons in each of the  $M$  intervals and selecting the interval with the largest count as the proper

pulse position. Because a Poisson process allows equal counts in more than one time slot, consideration must be given to likelihood draws. When one or more of the slots (namely  $r$  time slots) containing only noise have a count equal to the signal slot count ( $k$ ) and when  $k$  is greater than the count during the remaining  $M-(r+1)$  time slots, a random selection of slots with counts  $k$  will be made to choose the pulse position. This random selection will be correct in  $1/(r+1)$  of the cases. The number of ways in which a given signal level can equal  $r$  other levels and exceed the remaining  $M-(r+1)$  levels is the combination of  $M-1$  levels taken  $r$  at a time, or  $\binom{M-1}{r}$ . From these hypotheses, the following expression for the probability of correction detection ( $P_C$ ) can be derived:

$$P_C = \sum_{k=1}^{\infty} \sum_{r=0}^{M-1} \left\{ \left[ \frac{1}{(r+1)} \right] \binom{M-1}{r} \left[ (\bar{S}_e + \bar{N})^k / k! \right] e^{-\bar{S}_e - \bar{N}} \left[ \bar{N}^k e^{-\bar{N}} / k! \right]^r \left[ \sum_{n=0}^{k-1} \bar{N}^n e^{-\bar{N}} / n! \right]^{M-(r+1)} \right\} + (1/M) e^{-\bar{S}_e + M\bar{N}} \quad (25)$$

A computer program was written to evaluate this equation. Some resulting symbol error rate curves are shown in Figure 9.

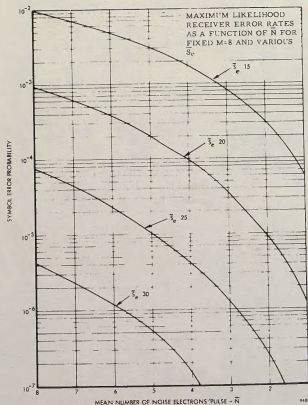


FIGURE 9. MAXIMUM LIKELIHOOD DETECTION OF PPM

By altering the threshold via Equation 22, the optimum threshold method of detection can also be used for an  $M$  position PPM channel. Now  $P(m_0) = (M-1)/M$  and  $P(m_1) = (1/M)$ . Figure 10 is a plot of symbol error rate as a function of  $\bar{N}$  for various values of  $\bar{S}_e$  and  $M=4, 8$  for the two detection methods.

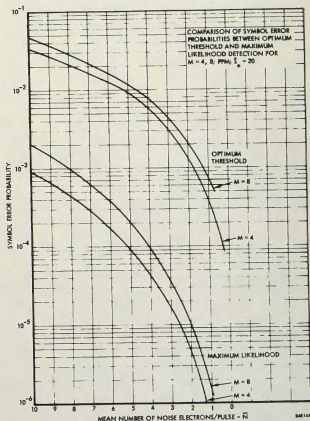


FIGURE 10. COMPARISON OF DETECTION METHODS

It is concluded from the comparison of the two methods of detection shown in this figure that the maximum likelihood method of detection is superior for a PPM channel.

The information provided in Figures 8 and 9 is subsequently used in determining communication system design parameters.

#### Diode Array Concept

By employing a number of emitters in the system it is possible to pulse groups of them simultaneously in order to increase the output power. Also, the various groups can be pulsed sequentially to improve the system duty factor.

Using the diode array concept an optical antenna assembly was designed which efficiently collects the emitted radiation and projects it into a



uniformly divergent beam. The divergence of the beam is dependent upon the parameters of the optical components. The collecting efficiency data presented in Figure 4 was used in calculating the projected radiant intensity per unit power per diode. The results of these calculations are shown in Figure 11, which illustrates the trade-offs of antenna size and beam divergence for radiant intensity.

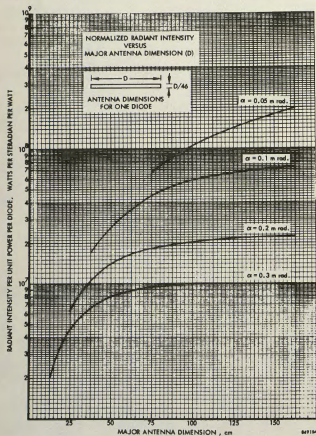


FIGURE 11. OPTICAL ASSEMBLY PERFORMANCE

## SYSTEM SYNTHESIS

A gallium arsenide laser communication system with assumed performance criteria will now be synthesized using the previously presented material. The assumed system provides a data link between two earth synchronous relay satellites separated by 45,500 miles. This system was selected mainly for two reasons. (1) Both the military and the scientific communities have requirements for large information handling capacity data relay satellite links. (2) If the GaAs system with the limited output power of the diodes can be shown to be competitive at the range of synchronous relay satellites, it will very possibly be competitive at shorter ranges where the power requirements are less. The performance criteria selected for this system were an information capacity of 25 megabits per second and an error probability per bit of less than  $10^{-8}$ . The lifetime, prime power requirements, weight, and size were to be kept competitive with existing systems and other

proposed systems.

The first step in synthesizing the system is to establish values for some of the parameters. Only values that could be achieved if the system were to be built with currently available commercial components will be used.

The assumed characteristics of the GaAs laser diodes for the base system are given in Table 1. These assumptions are a direct result of the material formerly discussed about the laser source characteristics.

In the discussion about data rate calculations, it was shown that the data rate for both PCM and PPM was inversely proportional to the pulse width. Consequently, to obtain high data rates, it is necessary to operate with narrow pulses. Laboratory measurements at Radiation Incorporated have confirmed that the laser diodes can be operated at pulse widths of 20 nanoseconds, and successful operation at 10 nanoseconds is anticipated. Therefore, it appears reasonable to assume an operational pulse width of 10 to 20 nanoseconds. At this point in the synthesis the choice of an exact pulse width within the given range is somewhat arbitrary. However, to be definitive, a pulse width of 15 nanoseconds will be used. The effects of shorter pulses will be discussed later in this report.

Assuming that the laser diodes are cooled to  $200^{\circ}\text{K}$  with a temperature stability of  $\pm 10^{\circ}\text{K}$ , the energy spectrum of diode emissions indicates that a practical optical filter should have a bandwidth of  $100 \text{ \AA}$  and a center frequency corresponding to  $\lambda_c = 0.88 \mu$ . A typical transmissivity ( $\tau_T$ ) of optical filters meeting these requirements is 0.6. This cooling could be accomplished using a passive space radiator.

It has been determined that a likely candidate for the optical detector is a photomultiplier. Of the numerous commercially available photomultipliers considered, one with a quantum efficiency of approximately 1.5 percent at a wavelength of  $0.88 \mu$  was included in this system synthesis.

In order to reduce background noise, minimization of the receiver field of view is required. This would suggest using as long a focal length as possible and a small aperture stop. However, with a very small field stop, high quality optics would be required. In addition, decreasing the field of view of the receiver complicates the problem of acquisition and tracking. Practical considerations limit the focal length of the space optics to the order of 3 meters or less. With a typical effective diameter of the detector of 2.5 mm and a focal length of 3 meters, the field of view of the receiver would be approximately  $5.7 \times 10^{-7}$  steradians, which is a reasonable value in view of the considerations above. A receiver area of  $0.5 \text{ m}^2$  was selected for the system. This area and a focal length of 3 meters

corresponds to an F-number of approximately 3.5. In consideration of background noise reception and receiver weight and size, it is desirable to have small receiver optics. However, to minimize both the prime power required by the transmitter and the complexity of the transmitter optics, large receiver optics should be used. The optical area for this analysis was not obtained from an in-depth study of this trade-off, but instead is an estimate of a practical receiver size.

Having selected the preceding parameters, the mean number of noise electrons per pulse ( $\bar{N}$ ) due to background radiation can now be calculated. The three principal background noise sources for a system of this type will be planets, stars, and possibly the moon. Background noise values were calculated for three sources, the moon, brightest planet (Venus), and brightest star (Sirius). At  $0.88\mu$  these values were  $\bar{N}$  (Moon)  $\approx 20$ ,  $\bar{N}$  (Venus)  $\approx 3$ , and  $\bar{N}$  (Sirius)  $\approx 0.1$  electrons per pulse.

The probability that the moon or Venus would remain in the field of view for any extended period of time is small. Therefore, choosing either 20 or 3 as the mean number of background noise electrons per pulse is not justified when calculating system performance. A more reasonable choice of  $\bar{N}$  would be 1 or even less than 1. To allow for some margin of error and to insure that the system would perform satisfactorily even if several stars were in the field of view, an  $\bar{N}$  of 1 was chosen for use in the calculations.

Recall from previous discussions that because of the limited duty cycle of individual laser diodes, it is possible, under some conditions, to achieve higher data rates with a PPM format than with a PCM format. The conditions are dependent upon the number of radiating groups. For this system synthesis a PPM format is chosen, however the possible use of the PCM format will also be considered at the end of this discussion.

It was shown that in general the error rate is less with a maximum likelihood detector than with an optimum threshold detector. This was illustrated in Figure 10 for the case of four and eight pulse positions. For this reason the receiver of the synthesized system will employ a maximum likelihood detector.

From Figure 6 it is seen that with a limited duty cycle of 3 percent or less at least five radiating groups would be required to obtain 25 megabits per second. With five radiating groups and a 2.5 percent duty cycle, the data rate would be 25 megabits per second. Furthermore, using five radiating groups and a 2.5 percent duty cycle there would be 8 pulse positions (M) in the PPM format. This corresponds to 3 bits per pulse.

With a PPM format having an M of 8, a maximum likelihood detector, and an  $\bar{N}$  of 1, the mean number of signal electrons per pulse ( $\bar{S}_e$ ) required to satisfy the maximum allowable error rate requirement can now be determined. Referring to Figure 9, it is determined that approximately 20 signal electrons are required to ensure a symbol error rate of less than  $10^{-5}$ . Given that the signal wavelength is  $0.88\mu$ , the photodetector quantum efficiency is 1.5 percent, and the signal pulse width is 15 nanoseconds, the incident power required at the photodetector for  $\bar{S}_e$  equal to 20 is calculated to be  $2.0 \times 10^{-8}$  watts.

The problem of tracking and its associated power loss due to pointing error has not been analyzed in depth for this discussion; however, based on the results of other investigators a conservative maximum loss of 3 dB due to pointing error is assumed.

The required radiant intensity of the transmitter can now be calculated from the range equation. Assuming an ideal optical filter such that  $\tau_r$  equals 0.6, a flat irradiance spectrum of the source, and a range of  $7.35 \times 10^7$  meters,

$$E_t = 7.2 \times 10^9 \text{ watts/sr.}$$

For this radiant intensity, the required number of laser diodes per group can be determined using the transmitter optics design. A beam divergence of 0.1 m rad. will be assumed. This is not necessarily the optimum divergence, but it is an achievable divergence with which no insurmountable tracking problems should be encountered. It is concluded from Figure 11 that with a 0.1 m rad. beam divergence the major antenna dimension should be between 50 and 100 cm. This conclusion is based on the facts that the normalized radiant intensity falls off rapidly for dimensions less than 50 cm and increases slowly for dimensions greater than 100 cm. A nominal dimension of 75 cm will be chosen. With these parameters the normalized radiant intensity of the transmitter would be  $4.4 \times 10^7$  watts per steradian per watt per diode. With 2.7 watts per diode, the required radiant intensity of  $7.2 \times 10^9$  watts per steradian can be obtained by simultaneously pulsing 7 diodes. Thus each of the 5 groups must consist of 7 diodes making a total array of 35 diodes.

In Table 1 it was shown that the efficiencies of the laser diodes were approximately 12 percent when cooled to 200°K. With a peak output power of 2.7 watts, a duty cycle of 2.5 percent and an assumed electronics efficiency of 50 percent, the prime power required per diode is 1.12 watts. Therefore, the total prime power required by the transmitter will be less than 40 watts.

The parameters of this system are summarized in Table 2.

TABLE 2

SYNCHRONOUS SATELLITE TO SYNCHRONOUS SATELLITE SYSTEM PARAMETERS	
Data Rate	25 megabits/sec
Range	$7.35 \times 10^7$ m
Bit Error Rate	$<10^{-8}$
Transmitter Prime Power*	$\approx 40$ watts
Receiver Antenna Diameter	76 cm
Transmitter Antenna Dimensions	75 cm $\times$ 57 cm
Number of Laser Diodes	35
Radiant Power Per Diode (During Pulse)	2.7 watts
Center Wavelength	0.88 $\mu$
Transmitted Radiant Intensity Required	$7.2 \times 10^8$ watts/sr
Transmitted Radiant Intensity	$8.3 \times 10^8$ watts/sr
Angular Divergence	0.1 m rad.
Detector Quantum Efficiency	1.5%
Modulation Format	PPM
Symbol Detection	Maximum Likelihood

\*An electronics efficiency of 50 percent is assumed.

It was pointed out that only commercially available components were used in the preceding synthesis. Consider now the impact that an advance in the state-of-the-art would have on the system performance. For example, detector quantum efficiencies of 7 percent at 0.88 $\mu$  have been reported. (2) With a PCM format and 1 noise electron per pulse, 25 signal electrons per pulse are required for an error probability of less than  $10^{-8}$ . Incorporating a detector having a 7 percent quantum efficiency, two laser diodes per group would provide sufficient radiated power. Therefore, with 20 radiating groups (40 diodes), 10 nanosecond pulses and a 2.5 percent duty cycle, the data rate would be 100 megabits per second. With the exception of an increase of prime power to 45 watts the other parameters would remain essentially the same. Enhancements in duty cycle and/or radiated power of the laser diodes would yield similar results.

## CONCLUSIONS

This synthesis has shown that gallium arsenide injection laser diodes can be used in exoatmospheric, high data rate, optical communication systems. Further, continuing advances in the state of the gallium arsenide technology promises significant improvement in the performance of similar systems.

Most optical communication systems naturally provide both privacy and anti-jam characteristics necessary to many missions. However, when

mission requirements also dictate the use of long lifetime, low prime power, reliable, and lightweight hardware, gallium arsenide lasers might well provide the modern solution.

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