Data Transmission At Optical Frequencies

B. A. Boershig

Radio Guidance Operation, General Electric Company

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DATA TRANSMISSION AT OPTICAL FREQUENCIES

B. A. Boerschig
Radio Guidance Operation
General Electric Company
Syracuse, New York

Summary

System analysis of an optical data transmission link and the basic expressions for beam power, received power and signal-to-noise ratio are derived. It is shown that transmission at optical frequencies requires 3-4 orders of magnitude less power than at K band. The effect of background noise, such as sunlit earth, on the signal-to-noise ratio and the improvements obtained by limiting the receiver look-back angle and use of narrow band optical interference filters are considered. In addition, a summary of the design parameters and the problems that were encountered during the development and testing of the Optical Data Transmission System are presented. The system capabilities are given and the successful transmission of a closed circuit television picture over a 2-mile path with a 33 db signal-to-noise ratio is discussed. Atmospheric effects on transmission and the results of a 33 db attenuation of signal over a 2-mile path during a heavy snow storm with 1/4 mile maximum visibility are given. Finally, a comparison of the Gallium Arsenide light emitting diode and the Gallium Arsenide laser diode is presented. It is shown that for otherwise identical systems the beam power is increased by 30 db over the noncoherent system.

Introduction

During the last few years, considerable emphasis has been placed on laser technology and its associated applications. One of the most emphasized applications of the laser has been in the communications field. Unfortunately, in many instances, the laser has been described as a competitor of microwave transmission. This is not the case. More correctly, the laser, when used for communication, should be thought of as a device for specific application where the use of microwave is limited or prohibited. The areas where these specific advantages occur consist of the following:

- The inherent secure transmission of information.
- The elimination of RF interference problems.
- The extremely wide bandwidths obtainable, limited only by circuit design and detectors.
- The tightly collimated beams necessary for space data transmission.

With the above applications in mind, the Radio Guidance Operation of the General Electric Company has developed (and is presently field testing and improving) a light modulated data transmission system (Figure 1).

The following sections pertain to the system analysis associated with this particular system and a brief discussion of the system performance.

System Equations

In general, an optical data transmission system (Figure 2) con-
sists of a modulated light source that is placed at the focal point of a lens system or reflecting mirror. The lens system is so designed that a circular beam of light energy subtends the receiver and covers the receiver aperture with enough spill-over to integrate out any "beam dancing" that might be introduced by an unstable receiver, transmitter platform, or by atmospheric turbulence. The receiver also consist of a mirror or lens system that can focus the collected energy through a combination filter and field stop and onto the photo cathode of the photo pickup device.

Some basic assumptions must be realized before an expression for power density can be written. It must be assumed that the energy radiated from the source is of uniform density throughout the solid angle subtended by the source into the collecting or collimating lens. Furthermore, it is assumed that the diode energy is radiated isotropically in $2\pi$ steradians, much like that of a hot filament.

Therefore, the power collected, $P_c$, by an lens or mirror is given by

$$P_c = P_T (1 - \cos \left[ \tan^{-1} \frac{1}{2f} \right]), \quad (1)$$

where $P_T$ is the total power emitted by the diode in $2\pi$ steradians and $f$ is the lens number. In order to derive an expression for the power density radiated by the emitting source, assume that all of the radiated power of the emitter is collected by the collecting and collimating lens system. The divergence angle of the radiating beam for the diffraction-limited instance can be written as

$$\theta = 1.22 \frac{\lambda}{d_t}, \quad (2)$$

where $\lambda$ is the spectral wavelength, and $d_t$ is the transmitter lens diameter. This equation expresses the angle between the maximum and first zero of the main lobe of the Fraunhofer diffraction pattern of a light beam passing through a circular aperture, with the assumption that the lens system is so designed that the finite source-size is smaller than that determined for a diffraction-limited beam. If this is not true, then the divergence angle can be written as

$$\theta = \frac{d_e}{fd_t} = \frac{d_e}{y} \quad (3)$$

where $f$ is the lens number, $d_e$ is the diameter of the emitting source and $y$ is the lens focal length.

The solid angle $\alpha$ can then be written as

$$\alpha = \frac{\pi \theta^2}{4}, \quad (4)$$

and the power density $P_d$ can be written with the assumption that all wavelength-dependent parameters are constants, since the expected optical bandwidth is less than 200$\AA$. That is

$$P_d = \frac{L_t P_c}{\pi \alpha R^2} = \frac{4L_t P_c}{\theta^2 R^2}, \quad (5)$$
where $L_t$ is the transmitter lens-loss coefficient, and $R$ is the distance between the transmitter and receiver.

The equation for the received power must include expressions for transmission medium, receiving lens, optical filter, and field stop losses.

The receiving lens and field stop are designed to collect a maximum of the radiated energy, limited only by the size of the receiver lens or mirror diameter. The look-back angle for the receiving optical system should be such that the subtended area at the transmitter is only large enough to cover the transmitting aperture (and some spill-over for the same reasons already mentioned in the transmitter design). The loss at the focal plane field-stop is a function of the quality of the receiving lens and the signal-to-noise ratio, i.e., since the focal plane stop is used to limit the field of view of the receiver at the transmitter to some area slightly larger than the transmitter aperture. Thus, the effective background noise is reduced and the signal-to-noise ratio is greatly improved. If the quality of the lens is such that the parallel rays of the received signal were focused to an ideal point-source, then the loss factor can be taken as unity, since no loss in received power would result and the stop would only limit the background noise. This can also be reasoned by simply realizing that for a good quality receiver lens, the image of the transmitter will be at the focal plane, and the background noise is simply a ring surrounding the transmitter aperture. Therefore, ignoring the field stop loss, the received power, $P_r$, incident on the photo cathode of the pick-up device can be written as

$$P_r = BL_tFA_rP_d = \frac{BL_tL_RF_d^2P_c}{\theta^2 R^2}$$

where $L_t$ is the receiver lens-loss coefficient, $F$ is the spectral filter-loss coefficient, $A_r$ is the area of receiver aperture, $d_r$ is the diameter of received aperture, and $B$ is the atmospheric attenuation coefficient. Finally, if a diffraction limited beam is considered, the received power can be written as

$$P_r = \frac{BL_tL_RF_d^2P_c}{(1.22)^2 \lambda^2 R^2}$$

And for beams that are not diffraction limited,

$$P_r = \frac{BL_tL_RF_d^2P_c}{d_t^2 d_r^2 R^2}$$

Equations 6 and 7 are complete expressions for the received power. If the expression for $P_c$ is substituted in equation (8) a rather interesting result is obtained. That is

$$P_r = \frac{BL_tL_tF_d^2P_c(1-\cos \left[ \tan^{-1} \frac{1}{2f} \right])f^2}{R^2 d_e^2}$$

Now realize that for small angles the $\tan^{-1} \frac{1}{2f}$ is approximately equal
to $1/2 f$. Therefore expanding the expression for $P$

\[(1 - \cos \frac{1}{2} f) = 1 - (1 - (\frac{1}{2} f)^2 \frac{1}{2} + \ldots) = \frac{1}{8f^2}\]  

(10)

and noting that the $f^2$ terms cancel in equation (9), it is then seen that for lens $f$ numbers larger than unity the received power is independent of the $f$ number. This indeed is an interesting result and will in general effect system design.

**Signal-to-Noise Equations**

Photo cathodes, in most photo-vacuum diodes and photomultiplier tubes, emit electrons by incident light or thermionic emission by a simple random process which gives rise to random anode currents. The rms value of the random anode current is given by the Schottky law for temperature-limited diodes. That is,

\[\frac{\bar{i}^2}{N} = 2Ie\Delta f,\]  

(11)

where $\Delta f$ is the information signal bandwidth, and $I$ is the total average photo-cathode current given by

\[I = I_d + I_s + I_b,\]  

(12)

where $I_d$ is the average dark current, $I_s$ is the average signal current, and $I_b$ is the average background current. The dark current, which is present even in the absence of incident light, is presumed to be largely thermionic, and arises both from the photo cathode and dynodes in photomultiplier tubes. Bell\(^\text{2}\) has shown that in photomultipliers, not only does the shot noise (inherent in the primary cathode current) exist, but also a noise that is caused by the randomness of the secondary emission of the dynodes is present.

Assuming a Poisson distribution for this secondary emission, he has shown that the deterioration of the signal-to-noise resulting from this secondary emission is given approximately by

\[\frac{A}{A - 1} = \kappa,\]  

(13)

where $A$ is the gain per stage. Then for a 10-stage photomultiplier tube with an over-all gain of $10^6$, the signal-to-noise ratio deteriorates by a factor of $3/4$. The signal-to-noise power ratio after detection for a photomultiplier tube can, therefore, be written as

\[\frac{S}{N} = \frac{I_s^2}{\frac{\bar{i}^2}{N} \kappa} = \frac{I_s^2}{2eIe\Delta f}.\]  

(14)

The signal-to-noise ratio can be calculated in another manner. As in the derivation of the Schottky formula for temperature-limited diodes, the emission of electrons from the photo cathode is presumed to follow a Poisson-type distribution. The premises for the Poisson distribution is that in all cases the events are independent of each other and there is a constant probability, $vdt$, that one of them will occur during a short interval, $dt$. 

119
One of the important properties of the Poisson distribution is that the variance is equal to the mean. That is,

$$\sigma^2 = \frac{1}{n} \sum_{K-1}^{n} (N_K - \bar{N})^2 = \bar{N}. \quad (15)$$

Therefore, in the interval $\Delta t$ the mean square fluctuation about the average value is given by

$$\frac{(\Delta N)^2}{\bar{N}} = \bar{N} = \bar{N}_d + \bar{N}_s + \bar{N}_b, \quad (16)$$

where $\bar{N}$ is the average number of signal and noise electrons emitted in the interval $\Delta t$.

This signal-to-noise power ratio after detection can then be written in terms of $N_s$, the average number of signal electrons emitted by the photo cathode in an interval $\Delta t$, and given by

$$\frac{S}{\bar{N}} = \frac{1}{\bar{N}} \frac{N_s^2}{(N_d + N_s + N_b)}. \quad (17)$$

Since a representative system should operate during the daylight as well as night hours, the limiting noise-source is the sunlit earth. This background noise should be calculated for the worse case, but in general it can be assumed that the receiver will not subtend an angle into the direct sunlight. However, the subtended angle does include such surfaces as hillsides where the spectral reflectance could be as high as 75 percent.

If the spectral radiance of the hillside is known, and the area of the hillside subtended by the receiver is also known, the noise power can be calculated on the assumption that the hillside is an isotropic radiator.

For a representative number, if the receiver beam angle is (for example) 2 milliradians, the expected spectral power collected is approximately .25 microwatts. For the same example the dark current for a normal photomultiplier might be 3 orders of magnitude less. Generally, the dark current can be neglected. Dark current information is supplied by the tube manufacturer for a given operating point and bandwidth and is independent of the presence or absence of external light. Dark current is a function of tube operating temperature and can be controlled by regulating the photo-cathode temperature.

The signal-to-noise ratio in terms of the received power can now be written. The average number of photons transmitted to the photo cathode in an interval, $\Delta t$, is given by

$$\frac{P_{\text{r}} \Delta t}{\hbar \nu_o}, \quad (18)$$

where $\hbar \nu_o$ is the energy per photon of which $h$ is Planck's constant, and $\nu_o$ is the optical frequency. Then the average number of signal photo electrons leaving the photo cathode in the interval $\Delta t$ is
where \( q \) is the quantum efficiency of the photo cathode (number of electrons per incident photon). Therefore, the average signal current is found by multiplying the average rate of the signal photo electrons by \( e \), the charge per electron

\[
I_s = \frac{eqP_r}{h\nu_o}.
\]  

(20)

Finally, for the signal-limited case (that is, when background and dark current noise is much less than \( I_s \)), the signal-to-noise ratio is given by

\[
\frac{S}{N} = \frac{qP_r}{2kh\nu_o\Delta f}.
\]  

(21)

Generally, the average current that is caused by background noise power exceeds the average signal current. The amount that it can exceed the signal current for a given signal-to-noise ratio is a function of the magnitude of the signal current or signal power received. Therefore, a more general expression for the signal-to-noise ratio can be written where the background noise current (or noise power) is expressed as a ratio of the signal noise current

\[
\frac{S}{N} = \frac{I_s^2}{2kI_s(I + \chi) e\Delta f},
\]  

(22)

where

\[
\chi = \frac{I_b}{I_s}.
\]  

(23)

Then, the signal-to-noise ratio can be expressed more generally in terms of received power by the following:

\[
\frac{S}{N} = \frac{qP_r}{2kh\nu_o\Delta f(I + \chi)}.
\]  

(24)

This equation expresses the signal-to-noise ratio for the photomultiplier tube at the output where the limiting noise is in the detection process and not in any amplifiers that might follow.

Equation (24) can be solved for \( \chi \), thus giving an expression for the amount of background signal noise as a function of the signal-to-noise and received signal power.

**Transmission At Optical Versus Radio Frequency**

An expression for the ratio of the transmitted power for an optical system versus that for a radio system would be of interest. It is assumed that losses in the transmission medium are neglected, and, in order to simplify the end results, the losses in the lens and filter for the optical system are also neglected. The transmitted optical beam is considered diffraction limited, and, therefore, the received power for the optical system can be written as
Prior to writing the signal-to-noise ratio for the optical system it is necessary to attach a representative number for the amount that the background noise current exceeds the signal current. For an optical system working in bright daylight a four-to-one ratio is not too uncommon. Therefore, the signal-to-noise ratio can be written as

$$S\frac{P_r}{N} = \frac{q\rho_r^2d_r^2p_t^2}{10\hbar v_o\Delta f} = \frac{q\rho_r^2d_r^2p_t^2}{10(1.22)^2\hbar v_o\Delta f\lambda_o^2R^2}$$ (26)

Now for the radio system, when parabalas or metal lens are used, the received power can be written as

$$P_r = \frac{A_rA_tP_o^2}{R^2\lambda_R^2} = \frac{\pi^2d_r^2d_t^2p_t^2}{64R^2\lambda_R^2},$$ (27)

where the symbols are defined as in the optical system. The signal-to-noise ratio in the radio system is given by

$$S\frac{P_r}{N} = \frac{P_r}{(NF)\kappa T\Delta f} = \frac{\pi^2d_r^2d_t^2p_t^2}{64R^2\lambda_R^2\kappa T\Delta f}$$, (28)

where NF is the noise figure (which will be taken as unity), K is Boltzmann's constant, T is the absolute temperature, and Δf is the signal bandwidth.

If Equations (26) and (28) that concern the radio and optical expressions for signal-to-noise ratio are now equated and with the receiver aperture, transmitter aperture, bandwidth and range the same in both systems, the following expression is obtained:

$$\frac{\text{Received Radio Power (Equation 26)}}{\text{Received Optical Power (Equation 28)}} = \frac{qK\lambda_o^2}{3\hbar v_o\lambda_o^2}$$ (29)

Equation (29) can be evaluated with the following representative inputs:

- Optical wavelength of 9000Å
- Radio wavelength of 1 cm
- Temperature of 300°K
- Quantum efficiency of 0.004.

The ratio of the optical system over a radio system with the given inputs is then found to be $3 \times 10^3$. As previously stated, this number assumes a diffraction-limited beam for the optical system. The ability to obtain this narrow beamwidth is discussed in a subsequent paragraph.

System Description

The system (Figures 1 and 2) consists of two self-contained packages each incorporating the necessary electronics and optics to perform as a transmit, receive pair. A minimum signal-to-noise ratio of 30 db
is achieved with a 12 mc bandwidth for path lengths up to two miles, when operating with a maximum of the expected solar background noise. The modulated light source is obtained by employing a noncoherent Gallium Arsenide light emitting diode. The transmitter output power is 380 microwatts in a 1 milliradian beam. The receiver beam angle is variable from 50 milliradians to less than 0.5 milliradians. Reflecting telescope optics are used in both the transmitter and receiver. The receiver employs an f/4, 12.5 inch mirror and the transmitter an f/4.5, 8 inch mirror. Modular construction is utilized in both packages resulting in a versatile system capable of being modified readily for various applications. The system has not been specifically designed for minimum size but rather with the intentions of future expansion and modifications. For instance the present diode is cooled to -40°C with a thermoelectric cooler. However, this cooler can be replaced very readily with a cryogenic cooler capable of cooling the diode to 30°K at a maximum diode power of 2 watts. All necessary controls are mounted on the back panels including the AC power plugs and the input, output signal jacks. The system has the capability of operating in the CW or pulsed mode simply by adjusting a diode bias control located on the rear panel.

Transmitter Design

The transmitter design is basically concerned with collection and collimation of the diode emitted energy. The collection efficiency can be defined by equation (1). That is

\[ \frac{P_C}{P_T} = (1 - \cos \left[ \tan^{-1} \left( \frac{1}{2f} \right) \right]), \]  

and obviously a function of the lens f number. Referring to equation (10) the power density for an isotropic emitting diode is not a function of f number and therefore a high collection efficiency does not necessarily result in the best transmitter lens design. However, the power density is a function of the square of the transmitter lens diameter and therefore restricted only by size and cost. The lens focal length is a function of beam divergence or spot size (equation 3) and therefore fixed for a given beam divergence and diode emitting area.

The f/4.5, 8 inch transmitter lens results in a collection efficiency of 0.5 percent and a beam power of 380 microwatts in the 1 milliradian beam.

Receiver

The receiver design is concerned with limiting the look-back angle that is subtended at the transmitter in order to reject excessive background noise. However, the area subtended at the transmitter, as already mentioned, should be large enough to effectively cover the transmitter aperture during the maximum-expected displacement of the beam. The collecting lens or mirror must be high quality such that the collected energy is focused to an ideal point source, thus allowing the look-back angle to be decreased with little or no loss of collected energy.

At the field stop, an optical filter is used to limit the spectrum of the received energy to that of the transmitted energy. The filter, a Fabry-Perot interference filter has been designed to have a 300Å
bandwidth centered at 8960Å. The system can also be operated with a Wratten Gelatin Filter #37C and still maintain the required 30 db signal-to-noise ratio at 2-miles. The spectral response of these filters are shown in Figure 3. It can be seen from this plot that the interference filter blocks approximately 10 times more background noise power than that of the #87C. The peak pass of the interference filter is 70% where the peak pass of the #87C is 80%. Also plotted on this graph is the relative output of the diode at -40°C, and the spectral response of the S-1 surface. In addition, the results of Yates and Taylor for the expected atmospheric attenuation over a 10 mile path on a day with a relative humidity of 66 percent is plotted.

The quantum efficiency has been shown to be proportional to the signal-to-noise ratio. Most photo cathodes found in presently available photo-vacuum devices have efficiencies of about 0.4 percent. The solid-state silicon photo diodes now available have efficiencies as high as 80 percent, which would represent a 23-db improvement in signal-to-noise ratio. However, their output levels are extremely low and require preamplification. The ability to design low noise preamplifiers that can compare with the gain-bandwidth products that can be obtained with the electron multiplication inherent in photomultiplier tubes appears to be the limiting problem. Basically it can be said the limiting noise in a photomultiplier tube is background noise and secondly quantum noise. In the silicon diodes the background and KTB noise are very close in magnitude and secondly dark current noise. Of course, background noise would be small in both cases if the data transmission was performed during the dark-sky hours. Under this condition the quantum noise is the limiting noise source for the photomultiplier and KTB noise for the silicon photo diode.

System Performance and Atmospheric Effects

System testing and evaluation over a 2-mile path has resulted in good correlation of the actual and expected results. The transmitter beam width of 1 milliradian corresponds to a spot-size diameter of 10 feet at a range of 10^4 feet. During testing, the beam was measured to be approximately 6 feet in diameter. The calculated power loss at 10^4 feet is approximately 17 db and the actual was 15 db. Since both the spot size and power loss at 10^4 feet was less than expected, the only reasonable explanation is that the diode was not emitting uniformly across the entire 37 mil diameter. This has since been verified in the laboratory.

A 33 db signal-to-noise ratio was measured during a time of maximum expected solar noise. The transmitter was located on a fresh, snow-covered hillside on a very bright sunlit day. Humidity was 88% and there was no snow in the atmosphere.

During testing, the normal expected atmospheric problems of scintillation (or the fluctuation in the average arrival time of photons from a constant emitting source) and attenuation of the received signal by snow and rain was apparent. The diurnal cycle of scintillation was measured to be about 17 cps, with a maximum depth of modulation of 10 percent during daylight hours and becoming less than 5 percent within a few hours after sunset. Attenuation losses of 33 db were noted during a snow storm when normal visibility was approximately 1/8 to 1/4 mile. During a heavy rain storm (drop size large, visibility 4 miles), a 3-db loss was apparent. During a peak modulation time
of scintillation effects, an 800-line closed-circuit television picture was transmitted with a 33-db signal-to-noise ratio in the 12-megacycle bandwidth. The 17 cps rate of modulation was apparent on the monitor, but with the use of a stabilizing amplifier the flicker was noticeably reduced. The stabilizing amplifier established a constant dc level by removing the amplitude variation of the sync pulses.

**Comparison of the PN Junction Laser Diode and The Noncoherent GaAs Diode**

In contrast to the noncoherent diodes are the JL-10 (CW, coherent, p-n junction) laser diodes. At cold-finger temperatures below 30 degrees Kelvin, the radiated energy is emitted from a point source of about a 0.002-inch diameter along the plane of the junction and subtends a total cone-angle of 20 degrees. The efficiency of the total power that is contained in the cone over the input power is 10 percent. Therefore, if the laser diode were used in place of the noncoherent diode with the same optics as in the described system and for the same input power, the output beam power would be increased by 20 db for the same input of 2 watts.

In addition, the laser provides still another advantage over the noncoherent diode by virtue of its finite emitting point source of energy. Even more important is that the energy emitting from the laser junction is coherent and therefore diffraction limited. This can be verified by using equation (2) and the actual diode junction dimension of $10^{-4}$ inches. That is

$$
\theta = \frac{(1.22) \times (8400 \times 3.9 \times 10^{-9})}{1 \times 10^{-4}} \approx 0.4 \text{ radians} = 23 \text{ degrees. (31)}
$$

So indeed this checks rather close to the published 20 degree beam expected from the laser diode. However, the actual shape of the wave front leaving the diode is not known. Therefore, it is not justified to simply use a spherical mirror for improved collimation and still assume a diffraction limited beam. Neither would it be justified to simply assume the diode junction a finite point source (as is the case of the noncoherent diode) unless the junction is less than the diffraction limit of the given lens or mirror. But in any case, a much tighter beam width can be achieved resulting in a minimum beam power density improvement of 10 db.

**Conclusion**

With the feasibility established from the design, development, and testing of the described system, it is felt that data transmission of information at optical frequencies will become common practice in the near future. The limitations that result from atmospheric attenuation is an obvious obstacle, but the advantages of such systems for specific applications are unique. The potential for improvement in system design is challenging. For instance, in the described system the received power can be increased by 3 orders of magnitude by using the laser diode at 30°K with the same input power and modulation. Indications are that, in a very short time, the lower temperature limit will be increased to 77°K with CW power outputs of 2-6 watts. Much room is left for detector improvement both in sensitivity and bandwidth. Many other limiting factors can be improved such that transmission of data and tracking at optical frequencies will be difficult to beat.
References


Figure 1. Optical Transmitter and Receiver
Figure 2. System Block Diagram
Figure 3. Optical Filter