A 10.6 MICROMETER LASER COMMUNICATION SYSTEM
FOR TERRESTRIAL USE

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Summary    This paper reports the development of an experimental type 10.6 µm laser communication system consisting of a transmitting terminal and a receiving terminal designed to operate one way over a nominal five mile terrestrial path. The system will provide a 5 Mbit/sec digital data channel utilizing intra-cavity optical frequency modulation, or frequency shift keying modulation format. It uses optical heterodyne detection with a mercury cadmium telluride detector operating at a temperature of 77°K and an i.f. frequency of 30 MHz. Since the system operates from fixed (non-mobile) terminals, acquisition and alignment procedures are simplified. Predicted performance in rain and fog is discussed and compared with a limited amount of actual data.

Introduction    The long recognized wideband potential of lasers in communications is now beginning to be realized. For some applications the technology is now on the threshold of making laser communications competitive with microwave systems. From the wide range of device work now in progress and the significant advances made in the last few years, it is clear that vast new channel capabilities in communications will soon become available.

Since its discovery in 1964, the carbon dioxide laser has been intensively studied. Not only are the physical and chemical processes of the laser well understood, but the laser has undergone significant optical/mechanical engineering development. Currently, these lasers are dependable, stable and have long life. Further, because of its high operating efficiency of the laser and the near ideal detection capabilities of optical heterodyne detection, great operating margin is offered by the system. The large margin is highly advantageous for use over terrestrial paths where extreme variations in attenuation may occur.

The present program provides the opportunity to conduct a unified system engineering approach whereby each component is specially designed for the task for which it is used. The results are an advanced rugged equipment design which makes it possible to examine the true field operation capabilities of the system. The program, in turn, will provide a timely assessment of the communication system performance and reliability and furnish guidance for subsequent related programs.
Engineering Approach  The concept of optical heterodyne detection, and in particular its use at the 10.6 µm wavelength, has been the subject of intensive research at Hughes since 1965. Many techniques which we now accept as state-of-the-art, such as frequency stabilized lasers, wideband detectors, and intracavity laser modulation, were developed in the interim as part of the over-all program of optical heterodyne detection.\textsuperscript{1-4} Extensive effort has been applied to the optimization of the many parameters which go into the design of a laser communication system. These tradeoff studies cannot be included in this description. However, they have been used to aid in the optimization of the system design.

Recently, techniques have been developed which prepare for operation of intracavity modulation of the CO\textsubscript{2} laser to GHz bandwidths.\textsuperscript{5,6} Availability of cadmium telluride and a more complete understanding of the laser oscillator have made this possible, thereby removing the objection that intracavity CO\textsubscript{2} modulation is limited by the Fabry-Perot linewidth.

The design approach makes maximum use of past experience in order to obtain the best possible system within the constraints of time and resource. All available data, computer programs, and optimization criteria are utilized to achieve this “optimized” design. The advantages are that the operational aspects of the system are better determined as well as the design itself being one step closer to a true operational system. Under the most favorable results, it would be possible to go directly to a prototype development, without an interim engineering model development. The successful completion of the integrated system model will reduce the design and development cost of an engineering model.

The 10.6 µm laser communication system consists of a transmitter station and a receiver station, capable of providing a communication channel to handle 5 Mbit/sec of binary digital data over a five-mile path length. The laser transmitter terminal uses a sealed-off CO\textsubscript{2} laser oscillator, frequency stabilized to a suitable P-transition. The laser plasma tube is of the metal-ceramic type, conductively cooled and eventually convectively cooled to the atmosphere. Modulation is provided through the use of an intracavity crystal of cadmium telluride, providing optical frequency modulation. The receiver terminal uses optical heterodyne detection and a HgCdTe detector cooled with liquid nitrogen contained in a dewar. The local oscillator laser is identical with the transmitter laser and is stabilized to track the transmitter laser frequency rather than have self-stabilization. Both -Ehe transmitter and the receiver units are self-contained and require no peripheral equipment other than data interface equipment, as may be required to handle unusual data formats, and liquid nitrogen for cooling the receiver detector.

To obtain maximum reliability, a number of design precautions have been exercised. Critical adjustments are relaxed where possible; signal-to-noise ratio performance margin
is high enough to permit slight misalignment, degradation of laser power, and degradation of path as a result of fog, haze, rain, or snow without loss of information.

Sufficient operating margin is also available to permit operating in a mode whereby the beam is reflected off a diffuse scatterer between two communication terminals. The latter mode of operation may be important in certain tactical applications where the line of sight is obstructed. This technique may be implemented by simply aiming both transmitter and receiver at a common point. Typical scatter losses are on the order of 50 dB, well within the operating margin.

**System Performance** The following sections determine the hardware requirements to meet the desired system performance. The numbers presented in this section are based on first hand experience with heterodyne communications systems and generally represent easily attainable values. In some cases the selected parameters may appear conservative; but experience dictates that conservative values are necessary, whereas first-glance estimates may be overly optimistic. The parameters for performance prediction are shown in Table I.

**Carrier-to-Noise Ratio (C/N)** The rf carrier is produced by the heterodyne process of the optical signal beating with the optical local oscillator on the HgCdTe detector. The carrier is amplified in the i.f. amplifier and drives the FM discriminator. To determine C/N we assume that the receiver is an ideal quantum-limited receiver with a minimum detectable power level of $h\nu B/\eta$.

If all of the signal is captured by the receiver optics, the carrier-to-noise ratio is merely the transmitted power $P_t$ divided by the minimum detectable power

$$(C/N)_{\text{max}} = \eta \frac{P_t}{h\nu B}$$

where

- $P_t =$ transmitted optical power = 1 W
- $\eta =$ quantum efficiency of HgCdTe = 0.1
- $h =$ Planck’s constant = $6.625 \times 10^{-34}$ J/sec
- $\nu =$ optical frequency = $2.83 \times 10^{13}$ Hz
- $B =$ i.f. information bandwidth = 10 MHz.

However, all the transmitter power output does not reach the receiver detector. There are losses at each reflective and transmissive surface, and there is unavoidable phase distortion through the system, preventing true quantum limited operation. For the proposed system,
there are 3 reflections, 2 antireflection (A-R) coated surfaces and one 0.95 reflective surface in the optical path through the transmitter.

Each reflection represents a loss of 0.05, and each coated surface loss is 0.015. Total power transmission through the transmitter optics is about 0.70. Similarly, there are 4 reflections, 4 A-R coatings, one 0.95 mixing beamsplitter and about 0.15 materials loss in the receiver, for a total optical transmission of 0.60. Combined optical losses are approximately 4.4 dB. In addition, measurements in our laboratory indicate that phase distortion and lack of perfect mixing across the diode surface results in a loss of approximately 4 dB. Maximum C/N is thus

\[(C/N)_{\text{max}} = 10 \log \frac{nP}{hv} - 8.4 = 114.3 \text{ dB}\]

However, for path lengths longer than a few thousand feet, propagation and diffraction losses play a part in C/N.

**Propagation** The optical antenna used for this system is a 10 cm diameter parabola. The transmitter is arranged to place the $1/e^2$ points of the gaussian beam intensity at the one half diameter points on the parabola or a 5 cm diameter. For this particular case, the on-axis intensity in the far field is given by the equation

\[I_o = \frac{P_o 2\pi \omega^2}{\lambda^2 R^2} \quad (0.96)\]

where

- $P_o$ = transmitter power
- $\omega$ = radius to $1/e^2$
- $\lambda$ = wavelength
- $R$ = range

The beamwidth for this particular case to the one-half intensity point is

\[\theta_{1/2} = 1.55 \frac{\lambda}{d} \quad ,\]

where $d$ is the antenna diameter. (The factors 0.96 and 1.55 are derived from computer plots of far-field patterns for truncated gaussian beams.)

The power intercepted by the receiver is

\[P_R = I_o A_R = \frac{0.96 P_o \pi^2 d^2 \omega^2}{2\lambda^2 R^2}\]
where \( d_r \) is the diameter and \( A_R \) the area of the receiver antenna. For the case where the range is 8 km,

\[
\frac{p_r}{p_o} = 9.25 \times 10^{-3} \text{ or } -21 \text{ dB}
\]

The one-half power beamwidth is \( \theta_{1/2} = 0.165 \text{ mrad} \). Clear air attenuation is approximately 0.5 dB km. The attenuation over the 8 km path will thus be about 4.3 dB. Combining these numbers, the C/N for clear air operation with full collimation will be 89 dB.

**Demodulated Signal-to-Noise Ratio (S/N)** The S/N is a function of the modulation index. For many system calculations, the S/N is shown to be equal to \( m^2 \) (C/N) where \( m \) is the modulation index. Although this equation applies for large indices with FM systems, the relationship is more complex for low index systems. We have conducted an analysis of hard bandwidth limited systems where only the first sideband is allowed through the i.f. amplifier; the relationship between S/N and C/N is shown in the analysis. For a modulation index of 0.62, \( S/N = 0.84 \) (C/N) or the demodulated S/N will be 0.8 dB down from the C/N.

The necessary S/N to assure a bit error rate of \( \leq 10^{-6} \) for binary frequency shift keying is 14 dB. Combining this with the above modulation index relationship, it is seen that the required C/N is 14.8 dB. Then, for clear air operation at a five-mile range the system margin will be 74.2 dB, comfortably exceeding the required margin of 30 dB and the desired margin of 50 dB.

Measurements with a 10 \( \mu \text{m} \) heterodyne system\(^4\) have shown that atmospheric scintillation noise will cause degradation of C/N that may cause fluctuations of as much as 10 dB from the average level. These fluctuations will be most severe for the highly collimated narrow beam cases. Spoiling the beam by defocusing pan decrease the magnitude of the fluctuations, but this will cause a drop in average signal level. To maintain a required C/N, the transmitter beam may as 100:1, to about 16.5 mrad, or nearly performance will be optimized if the and the receiver field of view are 10 to 1.65 mrad. If attenuation is high or light rain, the turbulence generally will be less and the required defocusing will not be as great.

**Computer Program** A computer program has been developed which determines the best set of communication parameters. This program is implemented to operate with optical communications using direct or heterodyne detection by representing all parameter values in the range equation. The outputs of the program can include optimization of parameter values, printout of S/N or bit error rate as a function of transmitter beamwidth, local oscillator power, receiver aperture, etc.
**Range Performance in Rain and Fog**  Absorption and scattering data of 10.6 µm radiation in rain and fog are available from Refs. 7, 8, and 9 and in clouds from references 10 and 11. These data appear consistent enough to be reliable in computing the C/N performance of the system for typical fog and rain conditions. The resultant transmittance \( T \) is given by

\[
T = e^{-\sigma R}
\]

where

\[
\sigma = \text{the extinction coefficient} = \alpha + \gamma
\]

\[
\alpha = \text{absorption coefficient}
\]

\[
\gamma = \text{scattering coefficient}
\]

\[
R = \text{path length}.
\]

At 10.6 µm, the extinction coefficient, nearly independent of water droplet size, is approximately 0.45 dB/km for each milligram of liquid water per cubic meter of atmosphere. Quite coincidentally, the attenuation in rain is approximately 0.4 dB/km for each millimeter of rainfall per hour.

The laser communication system requires a minimum C/N of 14 dB for a bit-error-rate of less than \( 10^{-6} \). For clear air operation at a distance of 8 km (5 miles), the system margin is 74.2 dB. Thus, C/N can be written

\[
C/N = 89 - 20 \log(8/R) - 0.45 \rho R \text{ dB} = 14 \text{ dB}
\]

where \( \rho \) is the density of liquid water in mg/m³ or (approximately) the rain rate in mm/hour. Figure 1 is a log-log plot of these values for the threshold of operation. From this figure, it can be seen that for an 8 km path the maximum liquid water density which can be tolerated is 20 mg/m³, and the maximum rain rate is about 20 mm/hour. These values correspond to the onset of heavy fog or heavy downpour conditions.

**System Description**  The system consists of two stations, a transmitter and a receiver, each station consisting of two units, an optical head mounted on a tripod, and a power supply/electronics unit with associated cabling. The system is constructed to withstand the normal abuses received during handling and shipment. The underlying philosophy has been to overdesign, where possible, to attempt to exceed the component or subsystem requirements. By these means we may be able to meet or exceed performance goals for the system, the most important of which is system reliability. Figure 2 is a photograph of a system receiver.

**Optical/Mechanical Configuration**  The housings for both the transmitter and receiver consist of built-up channel structures which act as optical benches to maintain critical optical alignment. The laser/modulator assembly in the transmitter and the local oscillator laser in the receiver are clamped to positioning rollers located in the channel structure.
Also located in the head are the modulator driver, the detector, preamplifier and associated optics, optical transmitting or receiving telescope, aiming mechanism, beam steering mirrors, and frequency control detectors. Figure 3 is an assembly drawing for the laser transmitter optical head. Figure 4 is an assembly drawing for the receiver optical head. Not shown on this drawing is the rifle scope, used for coarse acquisition, which is mounted and aligned with the output beam.

The over-all dimensions of the package as shown are 11 in. wide by 28 in. long by 6 in. high. The estimated weight is 50 lb. The receiver package is of similar size. The added weight of the receiver dewar is about equal to the weight of the modulator and its driver, so the receiver package estimated weight is also 50 lb. All internal parts are accessible for inspection, repair, and adjustment by removing the top covers. These covers have gaskets to provide an environmental seal.

In Figure 4 it is shown that the telescope optics are mounted in a channel and hermetically separated from the laser and electronics assembly, allowing only an optical path through a coupling lens. This permits maintenance of the transmitting or receiving optics without disturbing the more critical laser optics. The sealed portion of the package includes a desiccator assembly to control moisture. The complete package operates over the required temperature range of 32 to 100°F and the humidity requirement of 95 percent, provided moisture condensation on the telescope components is prevented.

The laser transmitting or receiving telescope consists of a 10.6 µm focusing lens, an output mirror with a small hole in the center, a 4-in. diameter f/4.5 parabolic primary mirror, and an aiming eyepiece. This kind of telescope has the advantages that it has a reflective primary, thereby eliminating dispersion and permitting visible alignment, and because it has no obscuration by a secondary mirror. It is also compact, easy to align, relatively inexpensive, and easily pointed. Fine pointing is incorporated into the telescope by steering the flat output mirror through a limited range. Divergence control is accomplished by adjusting the primary mirror.

All lasers, mirrors, and beam splatters are mounted in adjustable clamp rings, hard mountings of proved design. Experience has shown that this type of spring-free mounting is essential to maintain the critical optical alignment under field conditions.

The laser subassembly is based on a hollowed out 1-1/4 in. thick baseplate that mounts in one of the optical head channels. The laser tube is clamped in a high conductance mount to provide a path for the heat to be transferred to the baseplate. Gasketing is used around the lower edge of the plate to form a sealed chamber between the plate and channel bottom, and cooling air is circulated through this chamber. Fins are attached in the air duct to transfer the heat from the laser tube to the flowing airstream.
The laser subassembly baseplate also supports the tubular invar spacer which in turn supports the laser interferometer mirrors. The modulator oven and modulator driver in the transmitter, and the stabilization beamsplitter and detector, attenuator, and polarizer in the receiver, are also mounted on the laser subassembly. All electrical connections to the optical heads are made to the laser subassembly through an access port in the bottom of the optical head channel. The laser subassembly may be removed and operated outside the optical head, simplifying maintenance and alignment.

**Power Supply and Control Units** The electronic power supplies and laser frequency control circuitry are packaged in a single unit. Also included is the high voltage power supply for operating the laser and a blower to provide cooling air to the optical head through ducts. The cabinet is cabled to the optical head via a four cable bundle. Two coaxial cables are necessary for the laser high voltage; a third cable is a 50 Ω transmission line for carrying video information either to or from the optical head, and fourth cable is a multiple conductor bundle for control functions and low voltage power leads.

**Conclusion** Of all the laser wavelengths available for use in terrestrial communication systems, the 10.6 µm radiation from the CO$_2$ laser offers the greatest capability for penetrating rain and fog. The great power and efficiency of the laser, and the greater sensitivity of the receiver through the use of optical heterodyne detection, give the large system margin necessary to provide this capability. The model system described in this paper gives the opportunity to obtain quantitative data on the operational aspects of such a system through a real atmosphere.

**References**


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**TABLE I**

Physical, Electrical, and Performance Characteristics of System

**MECHANICAL**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter Head Weight</td>
<td>50 lb goal</td>
</tr>
<tr>
<td>Receiver Head Weight</td>
<td>40 lb goal</td>
</tr>
<tr>
<td>Optics Diameter</td>
<td>10 cm</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>32° to 100°F</td>
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<tr>
<td>Operating Humidity</td>
<td>95% maximum</td>
</tr>
<tr>
<td>Transmitter Size</td>
<td>30 x 14 x 6 in</td>
</tr>
<tr>
<td>Receiver Size</td>
<td>30 x 11 x 6 in</td>
</tr>
<tr>
<td>Dewar Extension</td>
<td>8 in diam x 14 in below receive</td>
</tr>
<tr>
<td>Power Supply and Control Unit</td>
<td>22 x 18 x 13 5/8 in high</td>
</tr>
</tbody>
</table>

**ELECTRICAL**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>Laser Power Output</td>
<td>1.0 to 2W</td>
</tr>
<tr>
<td>Collimated Beamwidth</td>
<td>0.165 mrad</td>
</tr>
<tr>
<td>Maximum Power Density</td>
<td>66 mW/cm²</td>
</tr>
<tr>
<td>Modulation Format</td>
<td>PCM/FM (FSK)</td>
</tr>
<tr>
<td>Maximum Frequency Deviation</td>
<td>±3.1 mHz</td>
</tr>
<tr>
<td>Frequency Response</td>
<td>50 Hz to 5 mHz ±3 dB</td>
</tr>
</tbody>
</table>
Modulation Index (5 MHz BW) 0.62
Maximum PCM Rate (NRZ) 10 Mb/sec
Digital Error Rate <10^-6
Warmup Time <30 min
Acquisition Time 1 to 5 min
Dewar Hold Time >50 hours
Transmitter Prime Power ~250 W
Receiver Prime Power ~250 W

PERFORMANCE (5 mile range, clear air)

Transmitter Power (10.6 µm) 1 to 2 W
Receiver NEP 2.5 x 10^-19 W/Hz
Bandwidth 5.0 MHz
Carrier to Noise 89 dB
System Margin (excess of 14 dB required for 10^-6 bit error rate) 74 dB
Extinction in Fog or Rain 20 mg/m^3 liquid water content or 20 mm/hr rainfall

Figure 1. Estimated Range Performance in Rain and Fog
Figure 2. Photograph of System Receiver (Dewar and Electronics not shown)

Figure 3. Assembly Drawing of Laser Transmitter Head
Figure 4. Assembly Drawing of Laser Heterodyne Receiver