Control and Communication Technology in Laser Systems

SPIE Proceedings Vol. 295

Proceedings of SPIE—The International Society for Optical Engineering

Volume 295

Control and Communication Technology in Laser Systems

Kay Yong
Chairman/Editor

Cooperating Organizations
The Aerospace Corporation • American Astronomical Society • American Institute of Aeronautics and Astronautics • American Meteorological Society • American Vacuum Society • Defense Nuclear Agency • IEEE Computer Society • Institute of Optics, University of Rochester • Jet Propulsion Laboratory • Los Alamos National Laboratory • Materials Research Society • NASA Ames Research Center • NOAA Environmental Research Laboratories • Office of Naval Research • Optical Sciences Center, University of Arizona • Optical Society of America

August 25-26, 1981
San Diego, California

Published by
SPIE—The International Society for Optical Engineering
P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone 206/676-3290 (Pacific Time) • Telex 67-3205

SPIE (The Society of Photo-Optical Instrumentation Engineers) is a nonprofit society dedicated to advancing engineering and scientific applications of optical, electro-optical, and photo-electronic instrumentation, systems, and technology.

DR98/2

The papers appearing in this book comprise the proceedings of the meeting mentioned on the cover and title page. They reflect the authors' opinions and are published as presented and without change, in the interests of timely dissemination. Their inclusion in this publication does not necessarily constitute endorsement by the editors or by SPIE.

Please use the following format to cite material from this book:
Author(s), "Title of Paper," *Control and Communication Technology in Laser Systems,* Proc. SPIE 295, page numbers (1981).

Library of Congress Catalog Card No. 81-84406
ISBN 0-89252-329-8

Printed in the United States of America.

INTRODUCTION

The recent rapid advancements in laser, electro-optics, image sensors, and data processing technologies yield new grounds for various system applications especially in the communications and control area. The development of the new diode-pumped laser and multiplexer not only makes possible the transmission of data at multi-gigabit rates, but also significantly reduces the weight, size, and power requirements. This makes laser communication extremely attractive for future space applications. Because of high bandwidth electro-optics and image sensor technology developments, control engineers working in the area of tracking and pointing control will be able to point a payload with submicroradian accuracy. However, in order to fully utilize state-of-the-art optical components in systems applications, it is vitally important that both optical and system engineers recognize the importance of each other and that close cooperation and coordination be maintained between the two. This was the intent of having the Control and Communication Technology in Laser Systems meeting within the framework of a larger SPIE symposium. It is hoped that this approach will continue in the future.

The papers in these proceedings were presented at SPIE's 25th Annual International Technical Symposium in San Diego in August 1981. Session 1 was chaired by Prof. R. Gagliardi of the University of Southern California. Papers presented in this session stressed the technology issues of laser communication in deep space and in near-earth applications. Session 2 was chaired by Mr. M. Stuart of Lockheed Missiles and Space Company. This session discussed a very important issue in the space optics system, namely, methods for alignment, stabilization, and calibration. In particular, there were very thorough discussions of the control and alignment methods for the NASA Space Telescope.

Sessions 3 and 4 were chaired by Dr. R. Williamson of The Aerospace Corporation and Mr. J. Abernathy of McDonnell Douglas Astronautics Company. These two sessions included papers describing the control technology in laser systems. A mixture of subjects dealing with acquisition, tracking, and pointing (ATP) issues in space and airborne laser systems, state-of-the-art sensors such as ring laser gyros, vibrating sensors, and precision optical encoders, as well as algorithms for optical processors, were discussed in these two sessions.

Kay Yong
The Aerospace Corporation

CONTROL AND COMMUNICATION TECHNOLOGY IN LASER SYSTEMS

Volume 295

Contents

SESSION 1

COMMUNICATION TECHNOLOGY IN LASER SYSTEMS

Session Chairman
Robert Gagliardi
University of Southern California

Laser space communication technology status

Morris Katzman
Satellite Systems Division, The Aerospace Corporation
2350 E. El Segundo Blvd., El Segundo, California 90245

Abstract

A review is made of the present state of laser communications. The basic characteristics of lasercom are discussed, and the advantages and shortcomings are delineated. Potential application scenarios are given.

A functional block diagram showing the major blocks is discussed, and each is described in terms of present performance parameters. Performance numbers are given in terms of range and bit error rate achieved.

Discussion of the various available laser transmitters is given including the advantage and disadvantage of each. CO_2 being a gas discharge device has potential lifetime problems and requires heterodyne detection - an added complexity. Nd:YAG requires either discharge lamp pumping or diode pumping. Diode pumping involves matching the diode emission line to a fairly narrow Nd:YAG pump band. There is an unresolved question of diode emission line shifting with age.

A summary of the various shortcomings in the technology include, for example, the required heavy optical bench, lack of demonstration of 10-year required life, solid state detector response time, and photomultiplier tube lifetime.

Introduction

The interest in laser communications for satellite applications stems from the much higher operating frequency, some 7 or 8 orders of magnitude higher than RF systems. This provides the three main advantages, i.e., greater bandwidth, smaller beam divergence angles/smaller antennas, and new regions of the available spectrum. Information bandwidth, beam divergence angles, and antenna size are all wavelength dependent. RF or microwave wavelengths cover the range from hundreds of meters to less than a centimeter, whereas those of present laser transmitters appropriate for satellite communications vary from less than a micrometer to 10 micrometers.

Consider specifically the comparison between an x-band (3 cm) communication system and a 1-micrometer laser system. The transmitted beam divergence angle varies indirectly with aperature diameter and directly with wavelength. Comparing a laser wavelength of 1×10^{-6}m with a microwave value of 3×10^{-2}m and assume a 3-meter antenna for the microwave case and a 10-cm antenna for the laser case then the ratio of solid angles is 10^6. If all other elements of system performance were equal, we would need one millionth the power out at optical wavelengths compared to microwave. (Since this is not so, the real ratios are more like 2 orders of magnitude.) This explains the utility of a laser transmitter with only a fraction of a percent efficiency and a fraction of a watt transmitter power.

Additional advantages derived from the small beam divergence angles are the consequent low probability of intercept and resistance to jamming.

Data rates available from laser communications can be as high as multigigabits per second. At 5 gigabits per second for example, about a million telephone channels would be available to provide a kind of "giant trunk line in the sky."

The block diagram shown in Figure 1 shows the main functional blocks. This paper will review the present state of development of the solid blocks, namely the laser modulator optics and receiver and controls. This is a version of a direct detection system. Heterodyne or homodyne is a feasible approach but is not being actively pursued at present at 10.6 μm for a variety of reasons, mostly relating to reliability. An effort is being made to achieve a 10-year system life, therefore, solid state components are preferred over tubes with their cathode, anode, and potential gas leak problems. This is the situation at present but the CO_2 laser with heterodyne detection concept is being considered as a back up in system planning.

Laser communications application to satellites are in various stages of study and design. System feasibility was demonstrated from an aircraft to a ground station in 1980. The

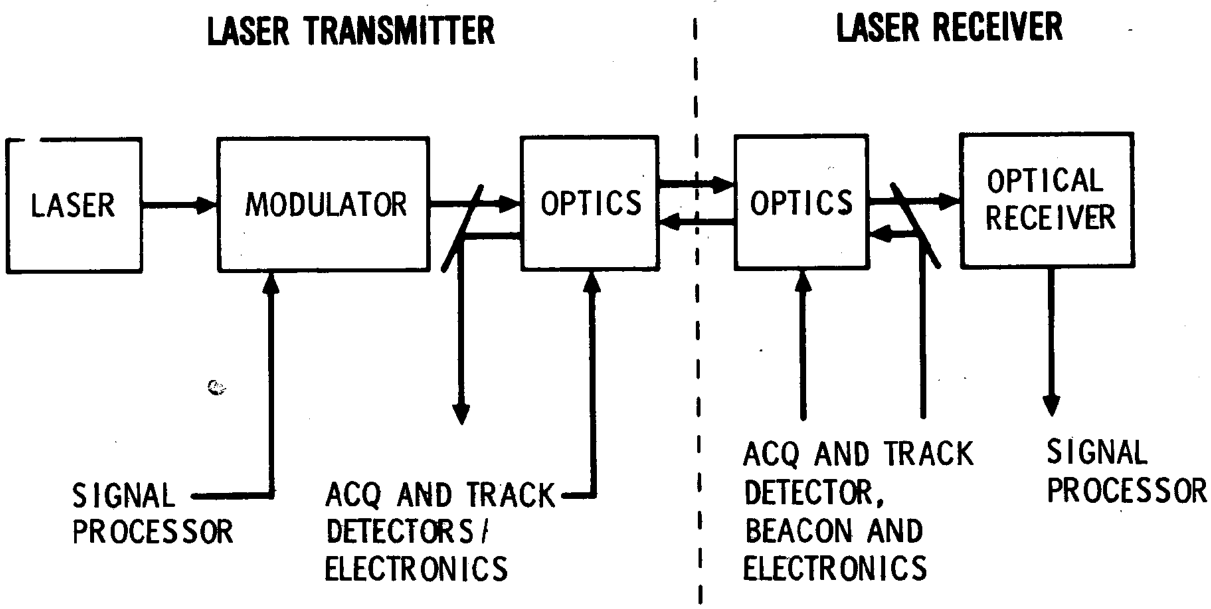

Figure 1. Lasercom link block diagram

critical features that were demonstrated included: (a) automatic acquisition starting with the range tracking radar data (FPS-16 with a beam width of 1.2°) simulating the ephemeris data that defined the position well within the 4° × 4° of the Lasercom acquisition, (b) tracking to within the 5μ radian beam, and (c) transfer of data at a one gigabit/second rate with a 10^{-7} bit error rate. One experimental space system[1] has been designed, fabricated, and is now being tested. This is for a ground station to near earth orbit (400 nmi). The launch availability is mid 1983. Another system in the design phase is for a satellite-to-satellite crosslink. The planned launch date is in the mid 1980s.

Space systems in general involve special design features, mostly because of the special environment of space and the 7- to 10-year reliability requirement. Single point failures are to be avoided and so redundancy is a household word.

Laser transmitters

GaAs diode lasers, GaAs diode pumped Nd:YAG, GaAs diode pumped doubled Nd:YAG, and CO_2 are the four principle candidate laser sources. The main characteristics are shown in Table 1.

Table 1. Characteristics of principle candidate laser sources

Laser Type	Operating Wavelength	Overall Transmitter Efficiency	Laser Oscillator Efficiency	Lifetime
GaAs	0.89 μm	1%	5 to 10%	Laboratory[2] >40,000 hours extrapolate 10^5 to 10^6 hours.
Nd:YAG	1.06 μm	0.5%	0.4 to 1%	Essentially established by laser pump diode array.
Nd:YAG	0.532 μm	0.4%	0.8%	Essentially established by laser pump diode array.
CO_2	10.6 μm	0.7%[3]	10 to 15%	Problem Areas: $CO_2 \rightarrow CO$ reaction, seals, and anode and cathode. RF excitation cures many of these problems.

The GaAs laser is small, relatively efficient, rugged, available over a small frequency range (by the addition of aluminum, approximately 8000 to 9000 Å), can be directly modulated, and has long potential life ($\approx 10^5$ hours). The main disadvantage is the limited power output per diode, so that most applications require the use of arrays, leading to beam combining problems. Another disadvantage is that the projected long life that was listed as an advantage has not been demonstrated. Accelerated life tests are now being conducted. Some shift in output spectrum was observed during accelerated life test. A shift of about 8 Å was observed after about 600 hours at 40°C.

GaAs pumped Nd:YAG avoids beam combining problems and has a well developed modulation technique. Sufficient power is available from the single Nd:YAG rod to close the link. The small disadvantage is that the well-developed electro-optical modulation equipment is fairly elaborate. This is essentially the case for both fundamental Nd:YAG, i.e., 1.06 μm and for the doubled Nd:YAG, i.e., 0.532 μm. Diode pumped Nd:YAG has the diode array lifetime uncertainty problem, as well as wavelength shift with age.

CO_2 laser is considerably different from the GaAs or the Nd:YAG in that it is a gas laser. The two solid-state lasers above are electron injected or optically pumped (for the Nd:YAG). The CO_2 is pumped by a gas discharge, i.e., it is pumped by molecular collision. The significance of this is that CO_2 lasers are essentially discharge tubes with the usual reliability problems introduced by vacuum seals, cathodes, and anodes. To balance the picture, DC pumped CO_2 lasers have been operated in the laboratory environment for over 10,000 hours with no failures. Earlier it was stated that CO_2 suffers from three deficiencies. First is the lifetime limitations because of the nature of gas discharge devices and the fact that CO_2 reacts and goes to CO, second is the added complexity of heterodyne or homodyne detection because of the requirement of critically aligned local oscillator and signal fields on the mixer crystal surface, and third is the requirement for cryogenically cooled detectors. There are factors that serve to mitigate these effects. The development of waveguide CO_2 lasers, replaces the DC gas discharge using the internal anode and cathode with an external RF pumped design for use in the local oscillator. This gives promise of lifetimes in the region of 30,000 hours. Some claim is made of potential of 50,000 hours life.[4] However, this would lead to only a 3- to 5-year life expectancy whereas a 7- to 10-year life is the goal of most programs. At any rate, the design life would have to be demonstrated and since the laser is not solid state accelerated life tests can not be done. The other two factors, i.e., alignment criticality and detector cryogenics are not considered as difficult as the lifetime factor. Radiative cooling might be adequate since the presently used mercury cadmium telluride detectors now operate at 150°K.

In Table 2, the technological issues of transmitter development are summarized.

Table 2. Technological issues of transmitter development

- High Power Laser Diodes
- Increased Laser Diode Lifetime and Reliability
- Stable, Long Lived Single Transverse Mode Laser Diodes
- Power Combining Laser Diode Devices
  - Phase-Locked Laser Diode Arrays
  - Monolithically Integrated High Brightness Laser
- High Data Rate Transmitters
  - High Speed Laser Diodes
  - Hybrid and Monolithically Integrated Opto-Electronic Devices
- Diode Pumped Nd:YAG Laser
  - Stable, Long Lived Transmitters
  - Optimum Pump Coupling Efficiency
- CO_2 Laser
  - Stable, Long Lived Transmitters
  - Transmitter Design Suitable for Satellite Applications
- Laser Transmitter Commonality
  - Evaluate Multipurpose Transmitter Design Feasibility

Power combining technology for GaAs laser diodes will provide a practical way to increase the power and data rates available from laser diodes. Fiber optic passive techniques are promising although fiber optic combiners face fabrication difficulties. Combining of diode arrays in a frequency division multiplex mode is another technological approach that will be developed. Coherent combining technology using integrated optics technology promises dramatic improvements in diode laser brightness by increasing power in the beam while decreasing beam divergence.[5]

Development is also required for high data rate transmitters. Present laser diodes at the required power levels have exhibited one nanosecond pulse reponses. For multigigabit systems, subnanosecond response is needed. This has been demonstrated at low power levels. In addition, advanced techniques for interfacing high speed electronics and optical devices are required to take advantage of the speed potential in optical systems. Hybrid microwave opto-electronic systems promise data rates of a few gigabits per second. Advanced system applications will make use of monolithically integrated microwave devices and GaAs laser diodes for the multigigabit applications.

10.6 μm remains a possible laser operating wavelength as a backup. The required 10-year life would have to be addressed and designs suitably small, light, and impervious to space environment would have to be demonstrated.

Current technology programs are developing diode pumped Nd:YAG lasers to meet the power and efficiency requirements for the future. Following are near term (1984) goals:

a. Output power - 500 mW at 0.53 μm and 1.06 μm
b. Pulse Width - 300 picoseconds (for mode locked laser)
c. Pulse repetition rate - 500 Mpps
d. Lifetime/Reliability - 10 years with 0.95 probability
e. Demonstrate compatibility with shuttle launched spacecraft and airborne platform environments

Longer term goals for the 1990 time frame would include increased output power (2W), shorter pulse widths (100 ps) (subpicosecond pulses have been demonstrated with dye lasers in the laboratory[6]), and increased pulse rates (Gpps) to support multigigabit communications.

The GaAs semiconductor laser is undergoing continued development for spaceborne optical communication systems. Life limiting wavelength shifting mechanisms and mode degradation need to be understood so that lifetime can be improved and the devices can be used with confidence. Development of space qualifiable, high power laser diodes (>20 mW average, >1 W peak) needs to be pursued, as should stable, long lived single transverse mode lasers.

Modulation formats and techniques

GaAs diodes require the simplest circuitry to implement modulation. The input current, is modulated to generate the required laser pulses. This direct modulation is practical over a very wide frequency range from near DC to 1 GHz at very low output powers. Figure 2 shows laser diode output as a function of modulation frequency for two conditions. The upper curve represents the diode being pumped at 10 percent above threshold and the lower one just at threshold.

For the Nd:YAG lasers there are basically three control methods that are important for communications, i.e., "Q" switching, mode locking, and cavity dumping. Q switching made possible the development of ranging systems despite the extremely low efficiencies of the ruby laser. It was found that by modulating the "Q" of the cavity, the peak power levels of the pulses were increased by orders of magnitude. This is done by either electro-optically modulating the "Q" or mechanically rotating one mirror of the Fabry Perrot resonator. Modulating the "Q" at the right frequency produces mode locking. The critical frequency is c/2L, where c is the speed of light and L is the optical cavity length. For one particular laser oscillator, the required pulse repetition frequency is 5×10^8 Hz, so that L is 30 cm, which is a reasonable cavity length. Cavity dumping is the opening and closing of a cavity port. One way of doing this is to polarize the radiation in the cavity with a prism. The preferred polarization sense is transmitted through the cavity and the other polarization is suppressed. Opening the port is done by electro-opticlly rotating the plane of polarization so that the preferred polarization is now reflected out of the cavity. The important aspect of cavity dumping for communications is that the pulses can be generated at controllable time locations. Pulse repetition frequencies up to the multimegahertz rate are available using cavity dumping.

The modulation formats described below are variations of pulse position modulation. Laser communications people speak of pulse position modulation (PPM) and pulse interval modulation (PIM) the distinction being mostly in the use or non-use of a synch pulse. PPM employs a synch pulse to define a major time division, often called a "window." The window is then divided into time slots and is defined by the particular data value, depending upon which slot the pulse falls on. In PIM, there are no synch pulses and the window is defined by the first data pulse and basically the data point is the time interval between data pulses. Again, the window is divided into time slots to define the interval. Figure 3 is an illustration of the PPM and PIM formats.

Obviously, the pulse width must not be large compared to the time slot in order to avoid ambiguity. For communications at the gigabit per second data rate, the pulse widths would have to be in the neighborhood of 300 picoseconds and the pulse rep rate in the neighborhood of 10^8 pps. This requires mode locked operation.[8]

For the 1-Mbps region, the pulse width can be in the region of 10 nsec. Table 3 gives an example of the modulation parameters for the 1-Mbps data rate region. It is seen that the pulse width is about one-third of the slot width.

In general, it is found that the particular characteristics of laser oscillators can be utilized to provide very effective transmitters for PPM communication systems.

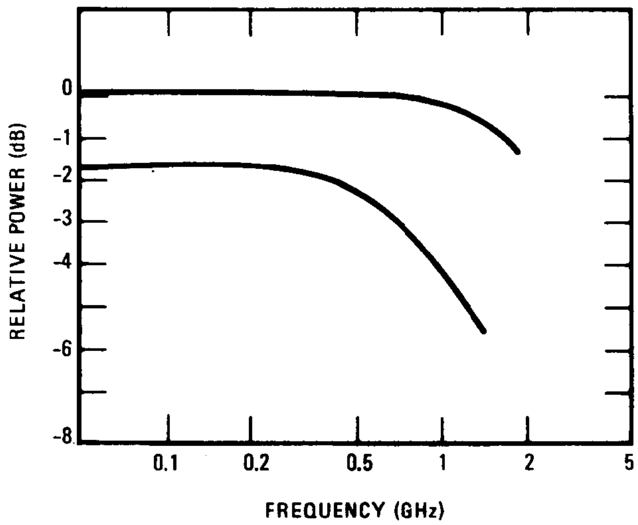

Figure 2. Frequency characteristics of ML-2000 series laser diodes.[7] (the vertical scale shows detected electrical power).

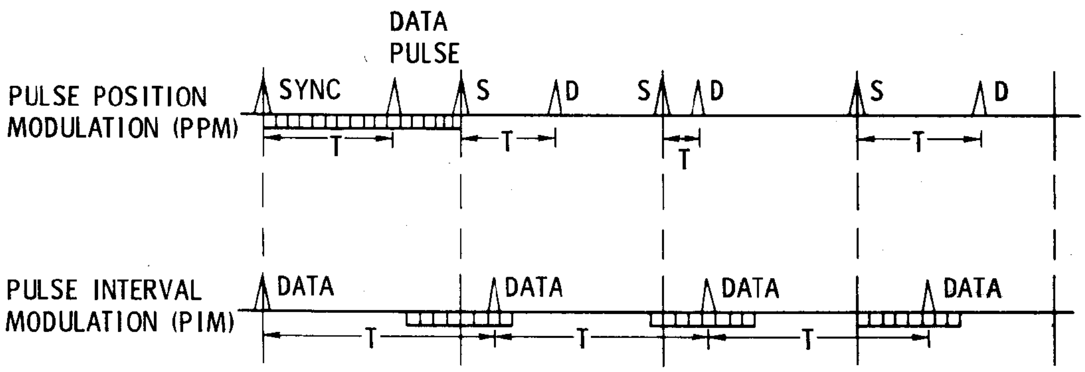

Figure 3. Short pulse time interval modulation methods

Table 3. Typical modulation parameters for a 1-Mbps data rate

Window Time Width	640 nsec
Slots Per Window	32
Bits per Pulse	5
Average Interpulse Period	3 μsec
Slot Width	20 nsec
Pulse Width (FWHM)	7 nsec

Optics design aspects for space applications

McDonnell Douglas Corp. has developed a frequency doubled, mode locked Nd:YAG laser transmitter.[9] The crystal for doubling is $Ba_2Na(NbO_3)_5$ and is kept at the temperature for phase matching the 1.06 μm fundamental with the 0.532 μm doubled wavelength. The same crystal is acoustically driven to modulate the cavity at the mode locked frequency. The resulting output with CW pumping is a pulse train of 500 MHz PRF with about one-third nsec pulse width (FWTM). This pulse train, which is plane polarized, is then sent through an electro-optic switch ($LiTaO_2$), which can rotate the plane of polarization by 90 deg according to the modulation requirements. Rotating the plane of polarization causes the beam to be deflected through a longer path to cause a 1-nsec time delay. An unrotated pulse would be undelayed. The two pulse trains are then recombined and the result is modulated pulse train carrying the binary data of ones and zeros at a 500-MHz data rate and of the two polarization planes at 90 deg to each other. The additional 500 Mbps is obtained by imposing the additional data with a second modulator similar to the first but on the unrotated pulses, thus obtaining the 1 Gbps data rate total.

In general, space applications require the special effort of reliability proven designs. As was mentioned above, redundancy is used to avoid single point failures. Mechanically active components in particular are subject to very careful design. Weights are important for several reasons, i.e., effective total weight budget, effect on bearing life and noise, rotation momentum requiring a counter momentum (expending fuel). A detailed description of present designs is outside the scope of this paper, but some general remarks will be made.

The basic choices in optics design are (1) reflective or refractive optics and (2) gimballed mirror flat or gimballed telescope for beam steering.

Refractive optics offer a simpler, well developed technology, but a weight penalty is extracted so that presently the preferred direction is toward reflective optics.

Cassegrain optics is often used and a single telescope can be used for both transmitter and receiver. One way to perform the duplexing function is through the use of circularly polarized beams. Each lasercom can transmit one sense of polarization and receive the other polarization. A circularly polarized beam when passed through a quarter wave plate changes to a linealy polarized beam. A half wave plate rotates the plane of polarization by 90 deg. The plane of polarization in the transmit optics path is at a 90 deg angle from the plane of polarization of the receiver optics path. By insertion or withdrawal of the half wave plate, the receive and transmit polarization planes can be reversed. Using these techniques, one station of a crosslink can transmit right hand polarization while receiving left hand, and the other end can transmit left hand polarization while receiving right hand.

Figure 4 shows a basic functional optical block diagram of such a station showing the common optics, duplexer, transmitter optics, and receiver optics. Note the two-stage detector array for acquisition and track. This is a generic representation of a multistage acquisition and track subsystem.

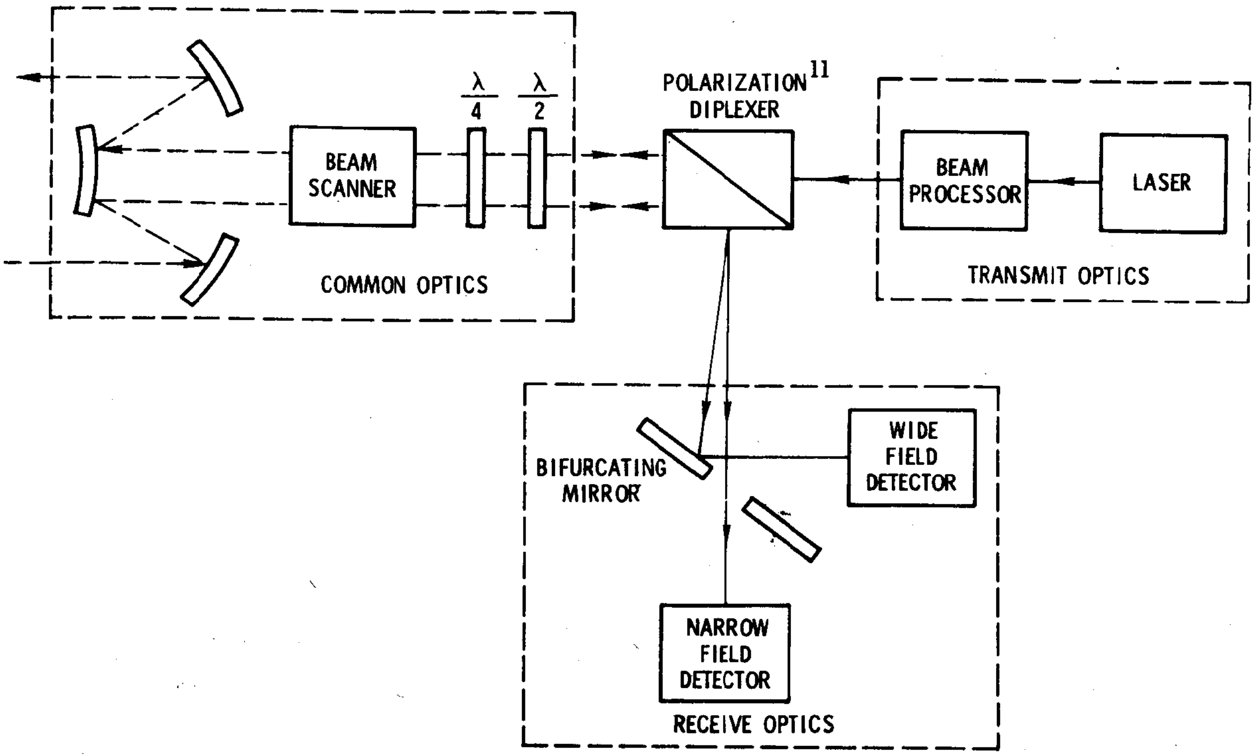

Figure 4. Basic functional optical block diagram[10]

Optical receivers

Optical receivers can be designed for direct detection, heterodyne detection, or homodyne detection. Direct detection is efficient for cases where large intrinsic gain is available from the detector. Photomultiplier tubes or avalanche photo diodes are examples of high available gain, i.e., each signal photon causes the generation of large numbers of photoelectrons. A properly designed receiver can provide shot noise or background limited detection. This condition is true for signal photons below 1 μm in wavelength. For longer wavelengths, because of the work functions of the photo emissive surface, the intrinsic gain rapidly falls off. The signal photons simply are too low in energy for the work function energy barrier. From about 1.1 μm to the far infrared, detection is usually thermal-limited and heterodyne (or homodyne) detection is required.

Heterodyne detection (the mixing of local oscillator beam with the signal beam) provides conversion gain and thus can make the detection process shot noise limited. The heterodyne detection process can be thought of as the mixing of two fields to produce a current proportional to the product. Since one of the fields is the local oscillator field, it can be made large enough so the shot noise produced is larger than the thermal noise in the circuit. For optical heterodyne receivers, CO_2 is the important candidate. The local oscillator is about 92 to 95 percent and the signal is 5 to 8 percent of the total field strength. The difference frequency is detected by a cooled HgCdTe detector, amplified in a 30-MHz IF amplifier and detected in a limiter discriminator. This 30-MHz difference frequency must be maintained within the passband of the IF and so a frequency lock circuit is necessary. This is accomplished by having the resonator frequency of the local oscillator laser controlled by a Piezo-electric transducer (PZT) unit. One of the laser resonator mirrors is mounted on the PZT unit.

The local oscillator can be tuned over a frequency range of 600 MHz through the use of this PZT controlled mirror. The frequency stabilization is achieved through the use of a stark cell to control the PZT unit. Basically, the frequency is locked on the stark absorption line. A dc electric field applied to the cell shifts the frequency of the absorption line and in this way the local oscillator (LO) frequency is tuned.

This ability to tune the LO makes laser heterodyne detection possible for space communication where there is relative motion between stations. The resulting doppler frequency shift is sensed and the LO frequency is adjusted to compensate for the doppler shift so as to keep the difference frequency within the passband of the IF amplifier.

As discussed above for heterodyne detection only the frequency relationship must be maintained, the phase relationship need not be maintained. It is interesting to note that in practice both frequency and phase of the LO can be controlled by the PZT controlled mirror. An element of confusion exists in that "optical people" often refer to heterodyne detection as a coherent process whereas RF people usually reserve the word coherent for phase coherent detection.

In general, the FM-frequency locked receiver is effective up to about 30 Mbps whereas the phase locked (homodyne) receiver is effective from 100 Mbps to about 5 Gbps.

CO_2 heterodyne receivers involve certain development risks as was discussed. The detectors must be cooled to about 150°K, the LO and the signal fields must be kept in alignment and lifetime of the CO_2 discharge tube is considered high risk for the desired 7- to 10-year life. Recent advances in waveguide lasers with RF excitation give promise for 3- to 5-year life. An effort is underway at Lincoln Lab to explore injection laser heterodyne detection.

Direct detection is conceptually much simpler and since at this time most effort in satellite communication is at 1.06 μm and below in wavelength, direct detection is more actively being pursued. Basically, it is a pulse threshold detection process. Direct detection receivers have been built for a 1983 launch of a ground-to-satellite experiment.

Summarized below is a description of the problem areas still facing high data rate (Gbps) receiver designs.

The dynamic crossfield photomultiplier (DCFP) is the communications detector for present high data rate laser communication systems. These detectors are bulky and face lifetime problems. Avalanche photodiodes (APD) offer significant space and weight advantages plus reduced power requirements in comparison to DCFPs. However, present silicon APDs are inferior to DCFPs for high speed applications. On the other hand, III to V alloy heterostructure avalanche photodiodes are attractive detector candidates. The devices offer high speed response (<35 ps rise time, FWTM 150 ps), high quantum efficiency (>95% at 0.53 μm) and small dark currents ($<3.4 \times 10^{-8}$ A/cm^2 at one-half breakdown voltage). They are useable in the 0.4 to 1.8 μm wavelength band. At present, these APDs are still in development but space qualifiable hardware should be available by the middle of the decade.

A common bane of all avalanche photodiodes is radiation-induced false alarms. Present information on the radiation susceptibility of APDs and on ways to mitigate this susceptibility is inadequate. Experimentation in this area needs to be carried out.

Advanced detection technology is being pursued. For example, GaAs photo transistors could play a role in future systems as an alternate high speed, low noise photodetector. Also, monolithically integrated opto-electronic receivers are attractive as high data rate optical front ends.

Conclusions

System aspects will be discussed in this session by several authors and so will not be covered in this paper. At this state of the technology, the weight and power performance envelope for the megahertz data rate region seems to be about 150 to 200 lb and 150 to 200 watts input. A great deal of progress is expected in these parameters in the next decade.

References

1. Lt. G. L. Lanham, "Air Force Lasercom Space Measurements," Paper presented National Telecommunications Conference, Nov and Dec 1980.
2. M. Ettenberg and H. Kressel, "The Reliability of Al(Ga)As CW Laser Diodes," IEEE Journal of Quantum Electronics, Vol. QE-16, p. 186 (Feb. 1980).
3. J. H. McElroy, et al, "CO_2 Laser Communication Systems for Near Earth Space Applications," Proc. IEEE, Vol. 65, p. 246 (Feb. 1977).
4. J. Peuso, J. J. Degnan, and E. Hochuli, Life Test Results for an Ensemble of CO_2 Lasers, TM 79536, p. 1, NASA, Goddard Space Flight Center, Greenbelt, MD (April 1970).
5. G. A. Evans, et al. Progress Toward a Monolithically Integrated Coherent Diode Laser Array, SD-TR-81-7 The Aerospace Corp., El Segundo, CA.
6. J. C. Diels, E. Van Stryland and G. Benedict, "Generation and Measurement of 0.2 psecond Optical Pulses," Optics Communications, Vol. 25, No. 1, p. 93 (April 1978).
7. Laser Diode ML-2000, Mitsubishi Technical Note, p. 10 (Dec. 1978).
8. M. Ross, et al, "Space Optical Communications with the Nd:YAG Laser," Proc. IEEE, Vol. 66, pp. 327, 328 (March 1978).
9. J. D. Barry, et al, "1000 Mbits/s Intersatellite Laser Communication System Technology," Trans. IEEE Comm., p. 473 (April 1973).
10. J. D. Barry, et al. "1000 Mbits/sec Intersatellite Laser Communication System Technology" Trans. IEEE Comm., Vol. 24, No. 4, p. 477 (1976).
11. J. Geusic and H.E.D. Scovil, BSTJ, Vol. 41, pp. 1371-1397 (July 1962).

Coherent optical space communications system architecture and technology issues

Vincent W. S. Chan
Massachusetts Institute of Technology, Lincoln Laboratory
Lexington, Massachusetts 02173

Abstract

Optical communications can be an attractive alternative to microwave technology in commercial and military space communications, particularly when the data rate required is high. System analysis at the optical frequencies often differs significantly from that at lower frequencies due to the vastly different technology of sources, modulators and receivers and also due to the important role that nonclassical (quantum) noise plays in determining system performance. In this paper important optical communication system architectures and critical system and technology issues that affect system designs will be examined. Coherent (heterodyne or homodyne) systems will be compared to incoherent (direct detection) systems in the context of space communications. Examples will be drawn from current state-of-the-art technologies and projected future technologies.

Introduction

Optical communications can be an attractive alternative to microwave technology in commercial and military space communications, particularly when the data rate required is high. Figure 1 depicts some examples of applications of optical communications in space. One main advantage of optical systems over microwave systems is the antenna sizes used in an optical system are typically much smaller. Figure 2 compares the antenna sizes required for 60 GHz and optical crosslinks. These data are not the results of a mere antenna scaling exercise but correspond to system designs based on state-of-the-art transmitter and receiver technologies. It is evident that as the data rate required becomes high (> 10 Mbps), optical systems will be the logical choice. Figure 3 compares the terminal weight required for 60 GHz and optical systems. The differences are somewhat smaller and less significant. System analysis at the optical frequencies often differs significantly from that at lower frequencies due to the vastly different technologies of sources, modulators and receivers and also due to the important role that nonclassical (quantum) noise plays in determining system performance. In this paper we will examine important optical communication system architectures and critical system and technology issues that affect system designs. Examples will be drawn from current state-of-the-art technologies and projected future technologies.

General Mission Requirements and Constraints

The class of optical channels encountered in space communications includes the satellite-to-satellite channel, the ground/aircraft-to-satellite and satellite-to-ground/aircraft channel and the satellite to underwater receiver channel (see Figure 1). The data rate requirements of an optical channel span a wide range (1 bps - 1 Gbps). Commercial requirements are typically on the higher data rate regions (1 Mbps - 1 Gbps). The data rate requirement of an application can sometimes determine the system architecture to a considerable extent. In addition, atmospheric turbulence, aircraft boundary layer effects, weather and ocean effects are channel characteristics that can affect system architectures in important ways. Other factors that need to be considered in the design of a sound system are link distance, relative velocity, point ahead angle, angular tracking rate, doppler shift, background radiation and satellite platform stability. We will not discuss all the ramifications of the channel characteristics and applications parameters in this paper, except mention in passing that all these factors should be considered carefully during the process of choosing a system architecture.

Desirable System Characteristics

The following is a list of desirable characteristics for an optical point-to-point space communication system. They are by no means absolute requirements.

1. Small antenna sizes (≤ 10 cm) -- this characterisitc is particularly desirable when there are multiple transmitters or receivers in a single platform such as the case of a satellite relay node where real estate for antenna is precious.

*This work was sponsored by the Department of the Air Force.

2. Modest weight (100-200 lbs) and power (100-200W) -- this is desirable because some of these communication packages may appear as secondary payloads in satellites with other primary functions.

3. Technology and system commonalities for a wide range of data rates - this is desirable both from the point of view of economics (supporting only a common technology and a common system architecture for a wide range of applications can be more cost efficient) and the prospect of having some system interoperability in the fiture.

4. Easy multiplexing/demultiplexing and switching, which is desirable for applications in space communication networks.

5. Continuous operations with Sun in receiver field-of-view.

6. Seven year life time.

7. Reliable source of supply for components.

8. Cost effective.

Optical Communication System Architectures

There are two basic classes of optical system architectures, coherent (heterodyne or homodyne) and incoherent (direct detection) systems. One usually finds for a particular application that one of these two basic system concepts emerges as being more appropriate. System requirements and channel effects will usually influence system architectures and choices of system parameters.

In an incoherent (direct detection) system, the received optical field is energy detected by means of a photodetector that usually also provides gain. (Fig. 4) (e.g., PMT or APD). Some front-end gain right at the detector and preferrably integrated with the detector is required because of the low signal power received (typically around 100 photons per bit). Modulation schemes for such systems are limited to intensity modulations since the frequency and phase of the optical field is irretrievably lost in the energy detection process.

Multi-mode direct detection can usually be assumed. This means the detector either observes many spatial modes (i.e., a large field of view) and/or many temporal modes exist. Observation over a large number of temporal modes occurs when the optical detector bandwidth B_c times the expected photon arrival time t_a is much bigger than one ($B_c t_a >> 1$). Since $t_c = 1/B_c$ is the coherent time of the arriving photons, the above condition becomes $t_a >> t_c$, which is called the "Weak Photon Coherence Assumption." Under this assumption the stochastic photon arrival rate parameter can be replaced by its expected value, and the resulting detection process for coherent light in background noise becomes Poisson. Given that one chooses binary signaling, on-off-keying is the optimum signal set. However, the optimality of this signal set depends largely on exactly known signal levels at the receiver which is typically not the case. Thus binary PPM is usually the preferred signaling scheme. Binary PPM is only 3 dB away in performance from on-off-keying and PPM is actually asymptotically the optimum signal set for large symbol sizes.

For equiprobable inputs, the maximum-likelihood decision receiver minimizes output symbol error probability. The sufficient statistic is $\{n_j\}$ $j = 1, \ldots, N$, where n_j is the photon count in the j^{th} time slot. If the message m_i was sent, the expected number of photons in the j^{th} slot is λ_n for $j \neq i$ and $\lambda_s + \lambda_n$ for $j = i$, where λ_n is the average background noise count per time slot and λ_s is the average signal count per channel symbol. The optimum receiver picks the message m_k corresponding to the slot which yielded the maximum photon count.

The Chernoff Bound that gives the tightest exponential bound to the channel symbol error probability is,

$$\begin{aligned} Pr[\varepsilon] &\leq (M-1) \exp\{-(\sqrt{\lambda_s + \lambda_n} - \sqrt{\lambda_n})^2\} \\ &= (M-1) \exp\{-\lambda_s E(\mu)\} \end{aligned} \quad (1)$$

$$\lambda_n = \eta\lambda^2 \Delta\lambda N_\lambda T/hv \quad (2)$$

is the average number of background counts, with T being the duration of a slot, $\Delta\lambda$ the bandwidth of the optical filter in wavelength units and N_λ the background light spectral irradiance.