INTERSATELLITE (Nd:YAG) LASER COMMUNICATIONS; A SYSTEM FOR THE 1980's

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Summary. It is now a certainty that laser communication systems will be operating in space within this decade. The development of a laser communications satellite package began this fall and is to be launched in 1979. The system is to operate at 1000 megabits per second. Laser communications technology has proceeded from purely exploratory research just over five years ago to the successful completion and operation this year of an engineering feasibility model of the satellite system. Laboratory tests have verified the system capability at a serial data rate of 1000 megabits per second. Thermal and vibrational tests have been successfully completed to the test levels of the Defense Meteorological Satellite program.

Introduction. A 1000 megabit per second Nd:YAG laser communication system is now planned for space launch in 1979. The space flight is to test the capability of intersatellite laser communications by satellite to ground link operating at the levels required for the satellite to satellite link. The laser communications satellite is to be launched into a highly elliptical orbit with apogee at synchronous altitude and 12 hour period. The satellite apogee is to be at 100° west longitude and 60° north latitude once every 24 hours. The satellite will be near apogee for 5-6 hours, and laser transmission will occur from the satellite at apogee to the ground station at Cloudcroft, New Mexico. The space laser communications experiment will establish the feasibility and practicality of laser communications operating in space in the 1980's.

The Nd:YAG laser communications system will essentially be a satellite borne transmitter which will incorporate both a lamp pumped laser and a solar pumped laser. When the satellite can remain in sunlight for extended periods solar pumping will be used. A lamp will be used for low earth orbit applications. A flat reflector is used to direct the solar light down into the satellite and into a solar collector used to focus the light into the laser. By having the solar telescope within the satellite rather than mounted outside, we eliminate serious optical and mechanical difficulties associated with launch conditions and pointing and tracking of the solar energy. In a similar manner, a flat reflector is used to control the pointing of the high data rate laser signal transmitted to the distant receiver.

The development of the present Nd:YAG laser communications system began with technology and component developments 5 years ago. The results were evaluated with regards to their systems applications and demonstrated that a 1000 megabits per second data could in fact be achieved. The system development was furthered by considering each component individually, and optimizing each for maximum performance. We have progressed from purely technological and component development through preliminary subsystem designs, brassboard systems hardware and an engineering feasibility model of the system[1-5]. The engineering feasibility model is a system designed for space use, tested to space system acceptance levels of the Defense Meteorology Satellite Program, and evaluated under laboratory conditions simulating the space use.

A laser communications system is essentially similar in nature to other communications systems based upon other technologies. The main difference is in the source of the carrier wave, here a laser, and the use of optical elements, rather than waveguides, and such. The system has a transmitter, modulator, electronics, data source, and an antenna, here an optical telescope with tremendous gain.

The development of the system is based upon the various technology achievements. These include the development of the optical components, the opto-mechanical structure, a successful acquisition, tracking, and pointing scheme, subnanosecond electronics, and 1000 megabits per second serial data stream performance. I will discuss those areas which have been most difficult to achieve and which reflect the greatest advances in technology. These include the laser, the modulator, the telescope assembly, the optomechanical structure, and acquisition and tracking scheme. I will also include the overall system performance and its relative advances in the past few years.

Opto-Mechanical Structure. A photograph of the engineering feasibility model system is shown in Figure 1. The system package includes the opto-mechanical structure and telescope assembly, the baseplate, and laser and modulator units. A schematic illustration of the system is shown in Figure 2 indicating the location of each component and the various elements.

The opto-mechanical structure is the structural unit which firmly holds the components and optical elements of the transmitter package in critical optical and mechanical alignment. The opto-mechanical structure is fabricated from type 8-A356-T77 heat treated aluminum for an optimum strain-elongation relation. The aluminum structure has the capability to maintain the optical alignment of the many elements to within 1 microradian. This alignment accuracy was held to the required levels even after vibrational testing at the DMSP acceptance levels.

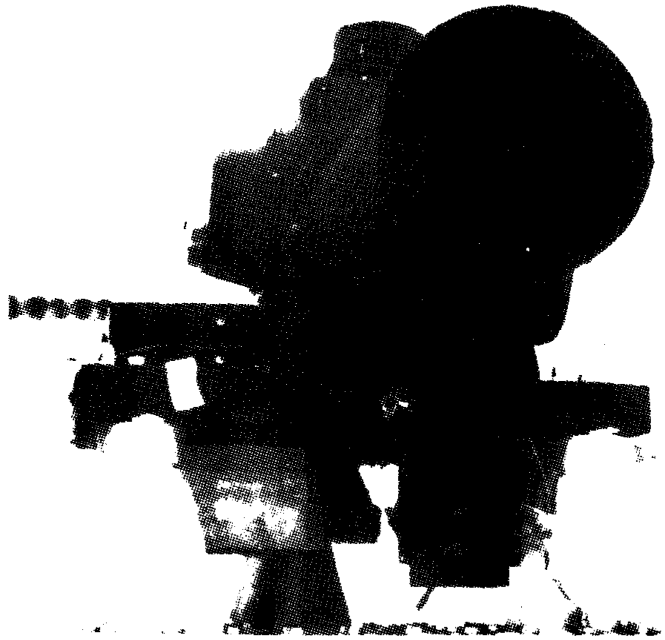

FIGURE 1. Photograph of the opto-mechanical structure and telescope assembly; the engineering feasibility model

The opto-mechanical structure, that is, the aluminum housing without components and elements weighs 5.7 Kg (12.0 lb). The complete unit including telescope, optical bender bimorphs, baseplate, and optical elements weighs approximately 10.9 Kg (24.0 lb). The weight of the three acquisition and tracking detectors is about 7.95 Kg (17.5 lb).

Optical, Acquisition, Tracking, and Pointing. Acquisition between a distant receiver and the transmitter is accomplished by using an active beacon at the receiver. The receiver tracks on the λ0.53 m transmitter laser signal and the transmitter tracks on a λ1.06 m beacon signal transmitter from the distant receiver. The pointing of each is accomplished by actively tracking the laser light from the opposite terminal. The λ1064 nanometer laser light received at the transmitter terminal is collected by the telescope and much of the same optics are used to transmit the high data rate λ532 nanometer laser light.

The arrangement of the optical elements in the opto-mechanical structure is schematically shown in Figure 3. The telescope is a Cassegrain type device and will use a flat folding mirror placed in front to direct the light to the distant receiver. Point ahead and fine tracking functions are accomplished by using sets of small active mirrors, which respond to the control of sequential tracking detectors. We are currently using torquer motor mounted mirrors which have a frequency response in excess of 1 KHZ and a tracking loop of 300 KHZ and the torquer motors have survived vibrational tests of 22g. The tracking detectors are sets of quadrant detectors using a reflective pyramid; these are a coarse acquisition PMT detectors), a fine acquisition PMT detectors) and a quadrant Si APD detector.

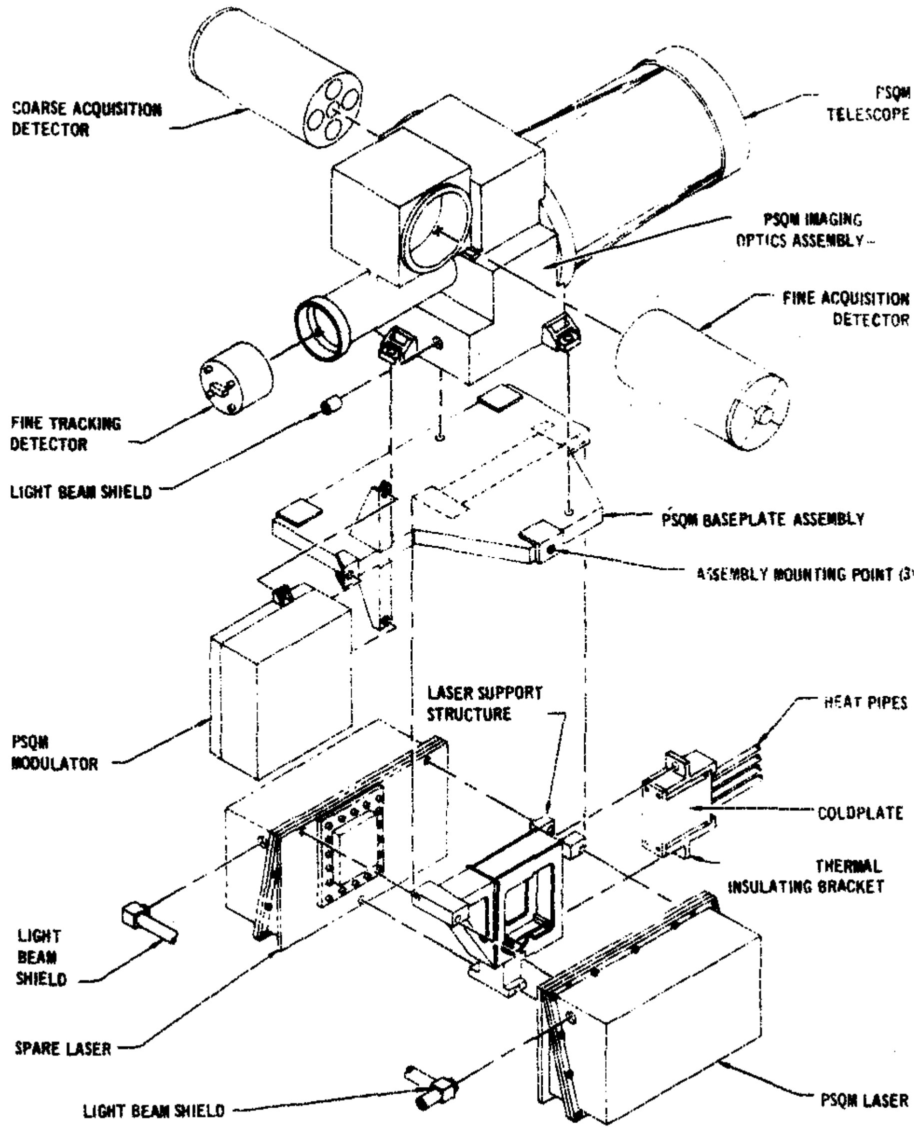

FIGURE 2. Arrangement of the various components of the laser communications system with the opto-mechanical structure to form a single satellite package

Acquisition between transmitter and receiver terminals is accomplished by sequentially detecting the beacon light in a narrower field of view. The incoming λ1064 nanometer light is initially reflected by the bifurcating mirror onto the coarse acquisition detector. This detector drives the flat scanning mirror so that the λ1064 nanometer light falls through the hole in the bifurcating mirror and on through the optical train to the fine acquisition and fine tracking detectors. The tracking detector controls the orientation of the tracking mirrors which center the λ1064 nanometer light on the fine acquisition detector. The beam is then directed to the fine tracking detector by the removal of the solenoid activated fine acquisition mirror. The distant high data rate receiver and the transmitter are thereby aligned, and controlled with provisions for point ahead angles by the active mirrors.

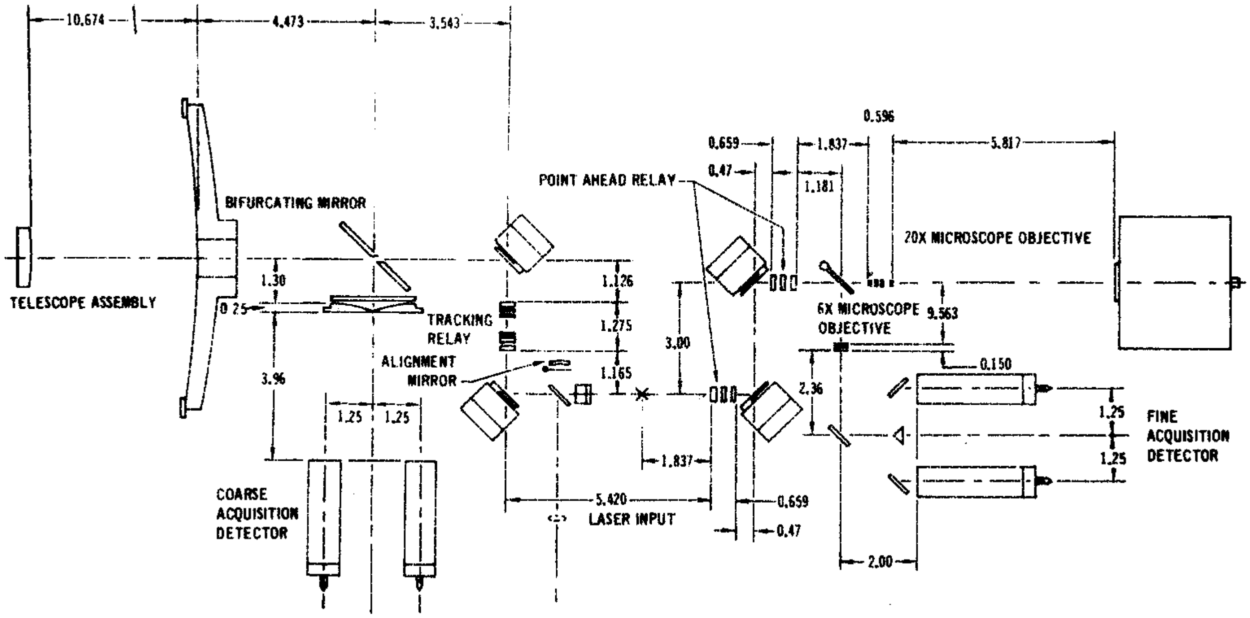

FIGURE 3. Schematic representation of the optical arrangement of the transmitter package, engineering feasibility model

The acquisition of two satellites by laser communications is considered to be difficult. We have evaluated the acquisition and tracking between a laser transmitter and receiver in the laboratory environment. The equipment was operated with the space distance simulated by the appropriate attenuation of the optical signal. Additionally, the relative motions between two space terminals were imposed upon the laser beam by means of a gimballed mirror and a set of motion control mirrors mounted between the transmitter and receiver terminals. The motion inputs included a simulated orbital motion with an angular velocity of 1200 μrad sec^{-1}, limit cycle with an amplitude 2 mrd, a period of 7 sec, thruster duration of 0.4 sec and 10 mrad sec^{-2} , and sinusoidal vibrations with frequencies from 10 to 50 Hz and amplitudes from 2 to 20 μrad peak to peak.

The pointing error measured with 2.4×10^{-10} watt of average power received from the λ1064 nanometer beacon laser was less than 1.2 μradians peak to peak. This corresponds to a beacon laser power of 100 m watt for the low earth orbit to synchornous satellite link with a 6dB power margin. The overall result illustrated that a pointing error of 1 μrad peak to peak is within the capability of the existing technology.

Optical Telescope. The optical telescope developed for the engineering feasibility model is a 19.05 cm (7.5 inch) diameter Cassegrain which will provide a 5.4 μrad full angle beam divergence. A telescope of this type for space use had not been fabricated before. We have used beryllium as the primary material for the telescope and the telescope mirror substrait. The substrait is coated with a Kanogen surface which is polished to the desired optical quality. The Kanogen surface is then coated with a silver reflective surface. The optical quality of the telescope was designed to be better than λ/8. The measured optical quality of the finished telescope was λ/13 before and after vibrational testing.

The clear aperture telescope transmission is better than 95.5%. The total overall transmission at λ1064 nanometer is 76% including a 4% obscuration loss. The λ1064 nanometer transmission is about 64%. The telescope weight is 2.9 Kg (6.3 lb).

Various optical elements of the opto-mechanical structure have been evaluated with regards to their reflective performance. It has been found that the λ1064 nanometer light reaching the fine acquisition detector is about 64% of the incident upon the telescope. A value of 50% was initially expected. The technology of reflective coatings has been improved substantially over the past two years, thereby improving the optical efficiency of the system.

Laser and Associated Elements. The evaluation of the capabilities of various laser systems and the status of technology for detectors and modulators led to the choice of the Nd:YAG laser operating mode-locked and frequency doubled at λ532 nanometers[7-9]. Both the solar pumped laser and the lamp pumped laser have similar optical construction. Both use an optically folded three mirror configuration for optimum operation. The laser uses an intracavity lens to collimate the intracavity beam in the laser rod, and to focus the beam properly into the mode-locking, frequency doubling element. The intracavity lens is placed near the confocal position for thermal and mechanical insensitivity. The folded configuration is used to achieve two pass interaction in the frequency doubling crystal, sum the frequency doubled laser light, and direct it out of the laser in one direction. The laser rod is conductively cooled since liquid cooling was unacceptable for satellite operation. In addition, the laser pump cavity has its elliptical surface coated with a dielectric coating which reflects only the pump band radiation between λ700 and λ1000 nanometers, and absorbs most of the other wavelengths.

The operation at λ532 nanometers is achieved by intracavity frequency doubling with a crystal of Barium Sodium Niobate , $Ba_2Na(Nb0_3)_5$. The crystal is thermally maintained at the phase match temperature where the indexes of refraction at λ1064 and λ532 nanometers are equal and optimum generation of λ532 nanometer light may be achieved. $Ba_2Na(Nb0_3)_5$ crystals have been commercially available since about 1969[10]. However, we use crystals with extremely low absorption losses specifically grown for this program and evaluated in our laboratories[11].

Crystal absorption of λ1064 and λ532 nanometer light is deleterious to the laser operation since the crystal is placed within the optical caviity. We now have crystals with absorption coefficients of order, $\alpha \approx 0.001$ cm^{-1}. The visible wavelength absorption coefficients may be 10 to 50 times higher, but they are not as critical as the λ1064 nanometer absorption since the λ1064 nanometer power is about 50 times greater. The optical quality of the crystal has also been improved significantly, which has enabled increased laser performance to be achieved.

We use $Ba_2Na(Nb0_3)_5$ crystal not only as a frequency doubler but also as a mode locking element for the laser[12]. The use of the $Ba_2Na(Nb0_3)_5$ crystal in the dual role of acousto-optical mode-locker and frequency doubling device has resulted in considerable improved operation and eliminated previously used complex electronic circuitry.

The engineering feasibility model laser incorporates only the one $Ba_2Na(Nb0_3)_5$ acousto-optical mode-locker, has been extremely simple to operate, and is much more stable than previous lasers. A depth of modulation of more than 2% at λ1064 nanometers is presently achieved with only 1 watt to the acousto-optical mode-locker. A time independent analysis of the laser indicated that the λ532 nanometer operation is more stable than the λ1064 nanometer operation[13]. The engineering feasibility has an amplitude instability of less than 1%.

We have achieved an optimum laser optical resonator design by using an in-house analytical computer model which include KRb lamp data, the rod fluorescence and birefringence data, the $Ba_2Na(Nb0_3)_5$ data, as well as the induced thermo-optical effects[14]. The absorption of 1.06 micrometer light in the frequency doubling crystal causes a lens effect and diffraction loss which were included in the optical design. The output power of the engineering feasibility model laser has been more than twice that measured with previous similar lasers. The Kr lamp pumped engineering feasibility model laser has generated over 250 mWatt of mode-locked λ532 nanometer power with 10% to 10% pulsewidths of less than 300 per second[15]. Two theoretical treatments of the mode-locked frequency doubled Nd:YAG laser describe the observed laser performance with good agreement relative to power and pulsewidth[16,17].

The solar pumped laser and the lamp pumped laser are different in the manner of optical pumping. The solar pumped laser has the advantage of extended life expectancy and higher efficiency than the lamp pumped laser. The solar light will be filtered before incidence upon the laser rod to eliminate UV and IR wavelengths. The solar pumped laser may use a Nd:Cr:YAG rod rather than Nd:YAG since there is some evidence that the Cr increases the gain due to absorption in the λ400 to λ600 nanometer region. The thermal perturbations are somewhat greater with Nd:Cr:YAG and we are currently evaluating the solar pumped laser for optimum operating conditions. The solar pumped laser has generated over 400mW of λ532 nanometer laser light with pulsewidths of less than 300 psec.

The lamp pumped frequency doubled Nd:YAG laser for space must operate with a potassium-rubidium (KRb) lamp due to the low input power requirements. The KRb lamp for the lamp pump laser is an air operated, KRb filled, arc lamp[18]. Early problem areas included inadequate end seals, rapid frosting of the highly polished sapphire envelope, and voltage control problems. Significant advancements have been made in these problem areas during the last year. Frosting was greatly inhibited by adopting a larger bore size, the use of a getter external to the bore, and improving the lamp processing. Controlability was greatly improved by providing direct thermal contact between the reservoir heater assembly and the cold spot control point. Maximum lifetime was once limited to 40 hours and few on-off cycles. We are now achieving more than 70 cycles, and more than 500 hour lifetimes during lamp tests. Lamps have been thermally and vibrationally tested and survived.

The KRb lamp operates in the laser pump cavity in the conductivity and radiatively cooled modes. The central envelope temperature is about 1100°C and as such is a thermal perturbing influence upon the laser rod. The lamp to rod interaction was carefully evaluated. In addition to the distortion of the laser rod due to the thermal load from the lamp[19], we found by fluorescence tests that the KRb lamp arc image can pump the laser rod in a non-uniform manner, and the λ1064 nanometer power can thermally distort the intracavity frequency doubling crystal.

Experiments were performed to evaluate the influence of thermal lensing, thermally induced birefringence, and the arc image distribution in the rod. It was found that the rod was thermally distorted with the KRb lamp and thermally induced lens in the rod was a focal length of 140cm, as compared to 250-300 cm with the water cooled Krypton (Kr) lamp operation of the same laser[20]. The evaluation of thermal birefringence and fluorescence distribution of three identical laser rods operated in the laser pump cavity and pumped KRb lamp led to a change in the rod dimension from 3 x 54.5 mm with earlier lasers to 4 x 66 mm. A 1.5 mm beam in the rod can be supported which improves the laser performance.

We have also found that increased gain may be achieved by optically finishing the cylinder surface of the rod. Fluorescence tests using KRb and Kr lamps, and equally doped rods but with varying cylinder surface finishes indicated that a highly polished rod has higher gain than does a ground surface rod. Additionally, we have some preliminary data that suggest that a rod cylindrically AR coated at 8000Å has increased gain.

The engineering feasibility model laser is constructed from a single piece of invar for maximum thermal and structural stability. The optical elements are firmly mounted and the end mirrors have slight adjustments by means of locking flexure mounts. The laser rod and pump cavity are differentially conductively cooled by separate heat pipes so that the rod may be kept at 0°C or less and the cavity at 20°C. The laser operated within 90% of its initial power after the vibration tests. This is the first time that a solid state laser has been designed and fabricated to withstand a launch environment and operate hands-off. A photograph of the laser mounted for vibration testing is shown in Figure 4. The laser weighs 6.6 Kg (14.5 lb).

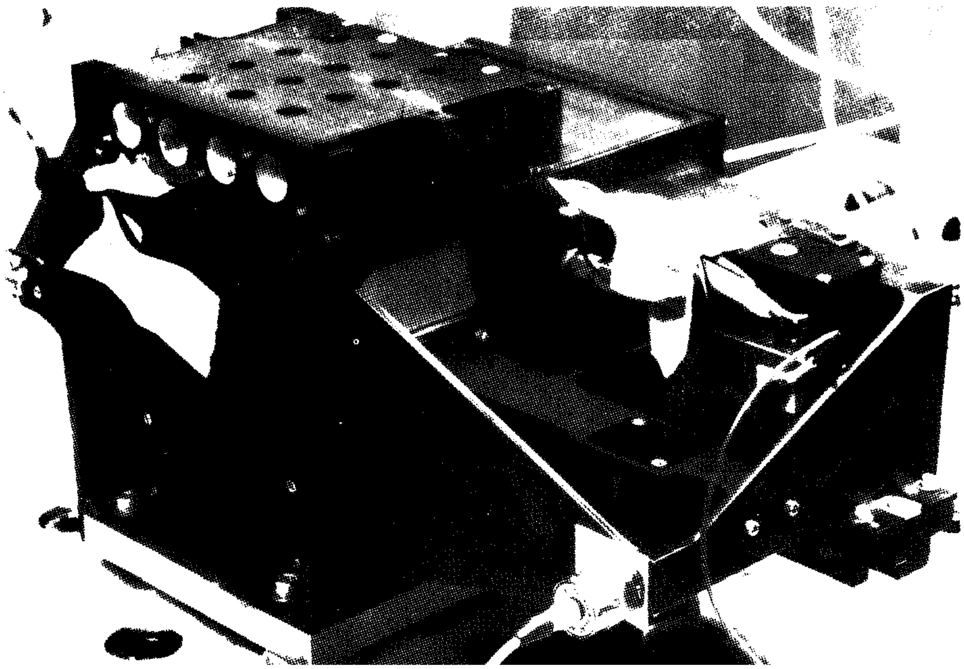

FIGURE 4. Photograph of the 6.4 Kg (14.0 lb) engineering feasibility model laser as mounted for vibrational testing

Optical Modulator. The engineering feasibility model system uses a modulation data format different from that used in the brassboard system. A pulse quaternary modulation (PQM) is used rather than pulse gated binary modulation (PGBM) because of increased efficiency with PQM. We illustrate this increased efficiency in Figure 5 where the system operation asynchronously with zero background; asynchronous means that the laser rate and data rate are not synchronized to one another. The modulator depth of modulation was 20 to 1 and the data codes are indicated.

The PQM format modulator uses one 500 Mbps and one 1000 Mbps modulator placed in a series with a 1 nanosecond optical time delay unit between the two modulators. The PQM operation may be classified as a sequential series action. The polarization of an incident light pulse is rotated by 90° by the first modulator for a binary one or not rotated for a binary zero. The pulses enter the delay, the unrotated pulse are undisturbed while the rotated pulse is time delayed by 1 nanosecond and then is optically recombined into the main optical path.

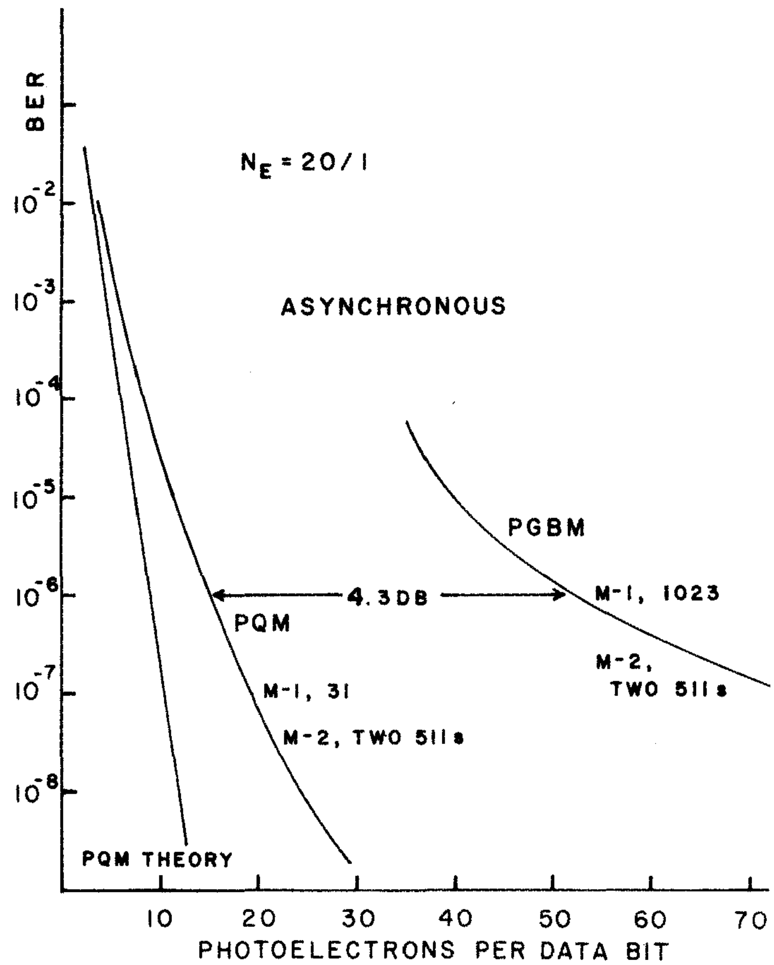

FIGURE 5. Comparison of the operation of the 1000 megabit per second laser communication system operating with PQM and PGBM formats

The combined pulse stream is then caused to enter the second modulator. The second modulator causes polarization rotation or non-rotation similar to the first modulator. The second modulator is coded electronically relative to the first modulator to account for the unequal time interval between pulses. The incident 500 megapulses per second light is thus coded in time and polarization to a 1000 Mbps data rate.

The electro-optical modulators are fabricated using two small tapered crystals of lithium tantalate, $LiTa0_3$. The use of $LiTa0_3$ rather than some other crystal material is also a technological advancement. $LiTa0_3$ has been historically difficult to obtain in the contaminant (particularly iron) free state. $LiTa0_3$ which has an iron content of only 2-10 ppm was developed for use in these fast modulators[21]. This is over 100 times lower than is normally available. Optical damage was once a problem. The new material has been tested with optical densities of order 1×10^7 watts cm^{-2} for extended periods without deleterious effects.

Each modulator uses two $LiTa0_3$ crystals placed end to end. The crystals are 10 mm in length and are tapered along the length. The end dimensions are 0.25 x 0.25 mm and 0.15 x 0.25 mm. The crystals have their A-faces perpendicular to the incident laser light. The E and 0 axes of the two crystals are rotated 90° relative to the polarization of the incident laser light. The crossed axes configuration tends to self-compensate the natural birefringence of $LiTa0_3$ and reduces temperature sensitivity. The incident laser light is optically focused between two crystals with a beam waist of order 75 x 10^{-4} cm.

The modulator uses a solid state driver which provides a nominal 20 volt pulse with a rise and fall time of order 200 picoseconds. Each modulator requires about 30 watts, including driver and heater. The crystal temperature must be kept at 150°C to allow self annealing and eliminate possibly optical damage. The voltage pulse must be applied to the crystals simultaneously with the passage of the optical pulse which has a 10% to 10% point pulsewidth of about 300 picoseconds. A precision retimer is provided in the premodulator electronics to synchronize the modulator drive to the master clock derived from the optically detected laser pulse rate at the laser. The modulator optical transmission is currently about 0.50 with an expected improvement to about 0.75 due to improvements in optical coatings.

A problem which exists as of this writing is optical coatings. We have observed some humidity caused degradation. We are now involved in long term degradation, optical index variation, and polarization study of the system coatings, The coatings in the laser, for example, must be evaluated differently from those on the solar tracking assembly due to the different environmental conditions. We do not yet have sufficient data to establish the definite degradation causes.

CONCLUSIONS

The technology developments for visible laser communications has been significantly advanced in the past few years. Recent system models have proven the capability of fabricating visible laser space hardware. A serial data rate of 1000 megabits per second is now the state of the art. Table 1 illustrates the parameters of a possible low earth orbiting satellite laser communication system. The major advantages for space use are associated with the weight and power requirements. We are now at the threshold of laser communications for space use. The planned space test will set the stage for laser communications system operating in the 1980’s and beyond.

Wavelength	532 nm	**Power**	
Beam Divergence	5.4 μrad	Margin	6 dB
Dia. Tr. Ant.	20 cm	Optical	100 mW
Tr. Ant. Eff.	0.75	Laser, Control	27[illegible].1 W
Tr. Optics Trans.	0.70	Modulator/Driver	64.5 W
Dia. Scan Flat	28 cm	Electronics, Optical	85.9 W
Dia. Rec. Ant.	47.7 cm	Tracking	97.5 W
Rec. Ant. Eff.	0.8	Power Conditioning	178.2 W
Rec. FOV	100 μrad	Pkg consumption	525.0 W
Filter Width	10 Å		
Photocathode QE	0.2	**Weight**	
Excess Noise	2 dB	Laser/Modulator	8.3 Kg
Bit Error Rate	1×10^{-6}	Electronics	62.4 Kg
Pointing Loss	0.94	Telescope	2.3 Kg
Pointing Error	1 μrad	Tracking Assembly	17.1 Kg
Modulation Depth	1.0	Opto Mechanical	39.8 Kg
Telescope	λ/13	Pkg. Total	129.8 Kg

TABLE 1. System characteristics of the space Nd:YAG laser communications transmitter package in development for a low earth orbit to synchronous satellite laser link

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