Laser Payloads on Small Satellites

L. S. Lingvay, A. P. Bowman, and A. S. Wallace

Space Applications Corp.
1655 N. Fort Myer Drive
Arlington, VA, 22209

ABSTRACT

LASER PAYLOADS ON SATELLITES have the ability to enhance our communications capabilities and information gathering power from space. Implementation of lasers to Lightsats provides one method to assess the effectiveness of these technologies at reduced risk.

This paper will focus on the main applications of lasers in space and how laser systems may be adapted to the Lightsat environment. This will include a discussion of the different types of lasers, which types are suitable for space based payloads, and which of these is suitable for what types of applications. Included in this discussion will be the selection criteria based on efficiency, weight, lifetime, size, and complexity. A brief description of diode, solid state, and diode pumped solid state lasers will follow. In addition, a detailed examination of the specific factors that are the driving design considerations for laser payloads will be presented.

Lasers in Space

The two primary applications of lasers in space are in the areas of optical communication and remote sensing. Laser optical communication can significantly improve the communication capabilities of satellites. Lasers offer several advantages over conventional technologies, due to the spatial coherence properties and higher frequencies of the emitted radiation. The use of optical frequencies allows a much higher data rate since the maximum input modulation frequency to the optical modulator is the limiting factor and not the carrier frequency itself. The extremely low beam divergence results in a smaller footprint in the plane of the receiver. This increase in energy density produces the same signal at the receiver that an RF link would, with a fraction of the transmitted power. It is also the small footprint and lack of side lobes of a laser communication link, that by definition is Low Probability of Intercept (LPI) compared to RF links.

For example when Voyager encountered Saturn the X-band signal in the plane of the Earth was nearly 2000 times the Earths diameter. If a laser was used, firing a beam with a wavelength of 532 nm ($\sim 6 \times 10^{14}$ Hz) through a 10 cm telescope, it would produce a spot approximately the size of the Earth. This is an increase in the transmitted energy density of nearly 4,000,000 times. [1]

Laser Communication and Radar

The laser communication link for space purposes is basically three fold; space-space crosslinks, space-aircraft and space-ground uplinks/downlinks, and deep space links. Figure 1 shows a few of the links that could contribute to the advancement of

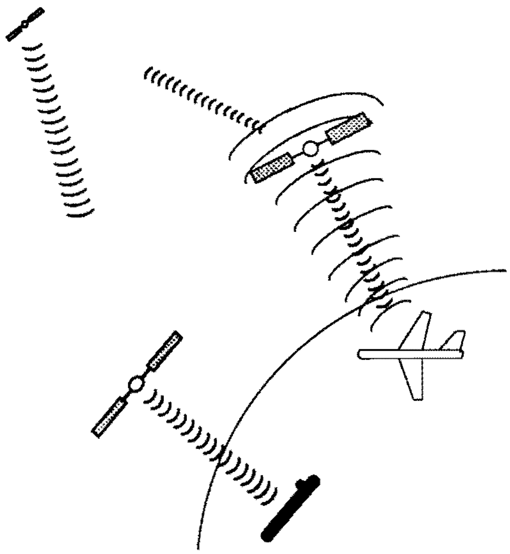

Figure 1 - Laser optical links

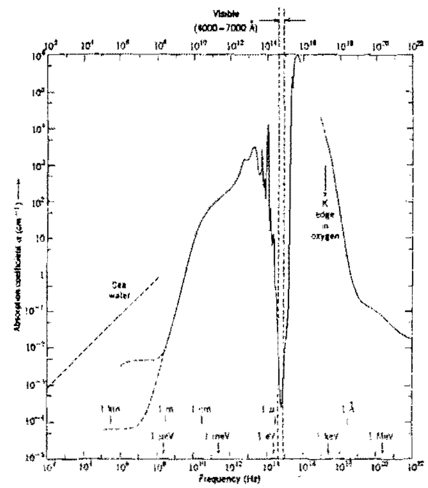

Figure 2 - Water absorption coefficient verses frequency

satellite laser communication through Lightsat technology. Also depicted is a space based laser radar with an optical link to a relay satellite with an optical down link.

Satellite to satellite crosslinks are the most straight forward to consider, since the channel is the vacuum of space. Space to ground links are more difficult. Lasers beams propagating through the atmosphere are sensitive to changes in the index of refraction due to moving air masses and changes in air density with altitude. Turbulence in the atmosphere causes temporal flattening of the pulses and de-phasing of the propagating wave front resulting in reduced peak intensity.

Atmospheric propagation increases the difficulty of beam pointing. Uplinks are more complex that downlinks because the air is denser near the Earths surface, resulting in a higher index of refraction. This increase in index of refraction amplifies pointing errors for uplinks from ground based transmitters. Additionally there is a greater demand on tracking equipment for the terrestrial uplink transmitter due to the relatively high velocities of LEO satellites. This is obviously not a problem for geosynchronous spacecraft.

The most complex link to consider is for satellite to submarine communication. In addition to suffering the problems of atmospheric propagation, the laser beam must be able to penetrate the sea. To do this, the laser wavelength must be within the blue-green transmission window of sea water for low loss propagation (see Figure 2). This problem is of considerable interest and a great deal of effort has been made to produce the proper blue-green light from lasers.

Another application of lasers in space is that of laser radar or LIDAR as it is commonly referred to. LIDAR is a very attractive form of radar because it allows for much more accurate distance and velocity measurements than conventional RF radar. Resolution of < 1 cm is achievable with optical radar. One important application for space based LIDAR is target tracking and identification. Other LIDAR applications include Doppler radar of winds, cloud height ranging, ocean surface ranging, and high accuracy land mass topology.

Differential absorption LIDAR or DIAL is a form of radar that is unique to lasers. DIAL is a frequency agile technique, similar to frequency hopping, that provides range resolved concentration measurements of molecular species present in the atmosphere. DIAL measurements require that the laser source wavelength match an optical absorption frequency of the species to be measured, such as CO_2. To make DIAL measurements, the laser frequency is tuned

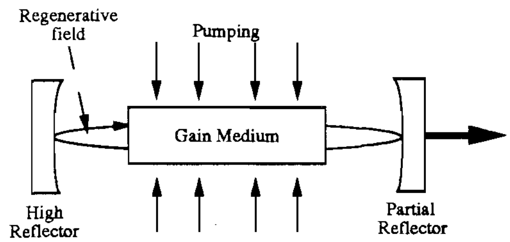

Figure 3 - A generic laser oscillator.

on and off of the absorption frequency and the strengths of the two returned signals are compared, there by giving a relative measure of the concentration of the species. Range resolved information is obtained by using pulse gating techniques during measurement. Some of the species of molecules measured by ground based DIAL systems include Ozone, Hydrocarbons, CO, CO_2, NO_2, and SO_2. Most DIAL experiments involve several optical systems beyond what would normally be found with a laser radar system making them, in general too large and complex for most Lightsats.

Lasers in space can fulfill a wide variety of operational scenarios from secure LPI communication to scientific applications like monitoring aerosol concentrations in the atmosphere.

Selection of the appropriate types of lasers for space deployment as well as their characteristics will be covered in the following section. Lasers for specific missions will be discussed next, followed by a discussion of how one would consider deployment of lasers in the Lightsat environment.

Lasers

There are many different types of lasers one could consider for a space based application. In the following discussion on the types and characteristics of these lasers it will become apparent that there are only a few specific lasers which are suitable for space based applications.

For this discussion to be meaningful, it is necessary to clarify some terms pertinent to all lasers. A laser is a regenerative optical amplifier, that utilizes a "gain medium" as the amplifier. A laser, like any other amplifier needs input energy. This is commonly referred to as "pumping" the laser. This usually takes place as an electrical discharge, an optical discharge from a flash lamp, or pumping by another laser. Another fundamental property of lasers is that they all employ some sort of mirror arrangement that is critically aligned to provide optical feedback. The mirrors and the physical structure that holds the mirrors is referred to as a resonator. These basic laser features are shown in Figure 3 for a generic laser oscillator.

We will consider five main types of lasers; Gas or Plasma, Dye, Diode, Solid State or Crystalline and Chemical. To clarify their suitability for space a figure of merit (FOM) will be developed and the following parameters will be assessed; electrical to optical efficiency, lifetime, weight, size, wavelength, and robustness. In addition to this, certain engineering issues particular to specific lasers will be pointed out, as they pertain to implementation.

The general characteristics of the five types of lasers are summarized in Table 1. The values of the entries in Table 1 are followed by their respective FOM in parenthesis. The efficiency and lifetime FOM are taken as face value. Weight and size are given an assignment of an arbitrary value from 1-5 with 5 being the best. These values are for typical lasers that are commonly in use and based on existing technology. The FOM is a product of the four parameters with the overall best candidate(s) having the highest FOM. A brief discussion of each of these lasers is given below.

Excimer Lasers

An excimer lasers is an example of a gas laser. It utilize a mixture of the noble gases and the halides as the gain medium.

Table 1 - Laser characteristics

Type	Efficiency	Weight	Wavelength	Lifetime	Size	FOM	Reference
Gas *							
Excimer	1 %	300 lbs (1)	UV	100 hrs	(1)	1	[2]
Ion	0.07 %	300 lbs (1)	VIS	1000 hrs	(1)	0.7	[3]
CO_2	20 %	200 lbs (2)	10 µm	30 hrs	(2)	24	[4]
Dye	0.2 %	150 lbs (2)	VIS	100 hrs	(3)	1.2	[5]
Diode	80 %	1 lbs (5)	0.8 µm	10000 hrs	(5)	2E5	[6]
Solid state **							
Flash pumped	1-3 %	100 lbs (4)	IR	500 hrs	(4)	240	
Diode pumped	40 %	30 lbs (5)	IR	10000 hrs	(5)	1E5	
Chemical	40 %	(4)	1.3 µm	***	(4)	***	[7]

All weight and size parameters include the laser head and power supplies.
* The weight and size parameters are estimated based on a nominal average output power of 20 watts
** The lifetime of crystal lasers is determined by the lifetime of its pump source
*** Chemical laser lifetime is limited by the available fuel charge. They require no mechanical pumps when operated in space

Some of the mixtures used include Argon-Fluoride, Xenon-Chloride, and Krypton-Fluoride. These corrosive gasses are usually contained in a stainless steel and teflon discharge chamber with windows making them very robust, but heavy. Pumping is usually achieved by a pulsed electrical discharge down the axis of the chamber or by axial injection of electron beams. Optical alignment of the resonator is not so critical with excimer lasers because they have extremely high gain, which is why they are sometimes refered to as superfluorescent lasers. The output of excimer lasers is in the ultra-violet (UV) and the beam quality is usually poor and not gaussian in intensity. Their lifetime is limited by degradation of the gas charge, which needs to be replaced approximately every 50-100 hours of operation.

Ion Lasers

Noble gas Ion lasers use Krypton and/or Argon for the gain medium, which is contained in a sealed glass or ceramic discharge tube with windows. Pumping is accomplished by a DC discharge down the tube causing, first ionization of the gas and then excitation of the atoms to a "pumped" or inverted state. The continuous wave output is from the blue to the red at many discrete wavelengths, and the beam quality is very good. Unfortunately ion lasers are very inefficient, and produce a lot of waste heat. Their lifetime is approximately 1000 hours because, they are sensitive to contamination, sputter ion trapping of the laser gas in the discharge tube, and need periodic gas replenishment usually supplied from a reservoir.

Carbon Dioxide Lasers

Carbon Dioxide or CO_2 lasers are the most efficient lasers, next to diode lasers. They have electrical to optical efficiencies approaching 30 % under ideal conditions, but in typical situations it is nominally 20 %. Output is at 8-12 µm and beam quality is adequate. A CO_2 laser for space would probably use a metal waveguide cavity and be RF pumped instead of discharge as with most gas lasers. This configuration would result in a robust device. CO_2 lasers have many different forms and are good candidates for some space applications, however a full discussion on them would be well beyond the scope of this paper.

Dye Lasers

Dye lasers have a liquid dye solution as the gain medium. The dye is a fluorescent converter that takes short wavelength (UV-blue) pump light from a flashlamp or another laser and downshifts it to the visible. When lamp pumped, dye lasers generally have low (~0.2 %) overall efficiencies, but when laser pumped, the optical to optical efficiencies are typically 20 %. The output of a dye laser is continuously tunable over the fluorescent emission profile, this is their attractive feature. The dye is circulated through a transparent cell which is usually glass or quartz. The fact that the dye must be circulated in a closed system with a heat exchanger makes the dye laser complex. The dye is circulated because it "bleaches" very rapidly if it is not continually mixed. Lifetime is limited by the dye, which eventually breaks down and needs to be replaced. Due to the fact that they are not robust and their overall efficiency is low they are not a strong candidate for space operation.

Chemical Lasers

Chemical lasers are a unique form of laser due to the fact that pumping is achieved from the gain medium itself. The medium is a mixture of gases that under goes combustion when mixed. This burning of the fuel is the mechanism of excitation or pumping. In the laboratory, the gases flow down the combustion chamber at supersonic speed and are then expelled. This requires large, high speed vacuum pumps and a large supply of fuel, which make up the bulk of the laboratory laser. The available output energy per unit volume of gain medium is dependent on the chemical potential of the gases or fuel. Typically the operating efficiency is 40 %. Hydrogen-Fluoride chemical lasers are the most powerful continuous wave operating lasers in existence, and have demonstrated output powers in excess of 2 Million watts CW. For this reason most of their applications are of a weapons nature. Chemical lasers are ideal for space operation since the vacuum of space can be used to generate the supersonic flows. This eliminates the bulk mass of the gas handling hardware and pumps, reducing the laser to a very simple flow tube with no moving parts, resulting in an extremely robust device. The operating lifetime of a chemical laser is determined by the available fuel charge. This is the limiting factor that precludes the use of chemical lasers on Lightsats for anything other that demonstration purposes, and short duration experiments.

Diode Lasers

Diode lasers are solid state devices based semiconductor materials. High power diode lasers utilize Gallium Aluminum Arsenide (GaAlAs) active regions. Many junction geometries exist, but the most common is the Quantum Well (QW) structure. Single emitting areas are typically 100 Å x 10-60 μm wide and produce a maximum output of 100 mW. The emerging beam is elliptical and has typical divergences of 15 ° x 30 °. Multiple emitters or stripes (~ 10) are fabricated on a single substrate to form an *array*. In turn these arrays are packed onto large linear substrates, usually 1 cm long, to form a laser diode *bar* with linear power densities approaching 50 W/cm. Finally the bars are stacked together to form 2D arrays with power densities of ~ 2 kW/cm^2. The laser diode arrays can be used directly for communication or as pump sources for solid state lasers.

GaAlAs diode lasers have electrical to optical conversion efficiencies ranging from 50-80 % depending on their packing configuration and operating wavelength, which is nominally 0.82 ± 0.5 μm. They are capable of direct current modulation to frequencies in excess of 1 GHz, pulse widths as short as 10 ps, and are intrinsically radiation hard.

Output beam quality is the single largest issue of concern for diode lasers. Large beam

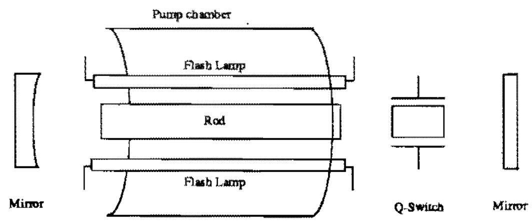

Figure 4 - Schematic of a flash-lamp pumped Nd:YAG laser.

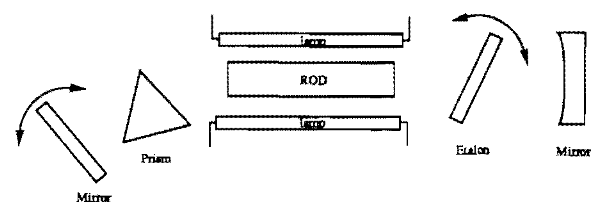

Figure 5 - Tunable laser cavity

divergences are inherent with semiconductor devices because of the extremely small emitting volumes. Substantial progress has been made to control the output quality of diode lasers using active and passive phase manipulation.

The individual emitters have some phase differences which contribute to the overall beam characteristics. These phases can be taylored to produce single lobe output patterns. In the case of 2D arrays, work has been done to electronically control the phases to produce a single lobed output. Diode lasers are well suited for modest range space-space cross links, but because they have marginal beam quality they are not the best choice for long distance communication, such as with deep space probes. For pumping solid state lasers with 2D arrays, beam quality is not as critical.

Solid State Lasers

Solid state lasers utilize crystals as their gain medium. These crystals have been "doped" with metal ions as their active lasing agent. Some typical dopants are the trivalent (+3 ionic charge) rare earth ions (Nd, Tm, Er, Ho) and the divalent (+2) transition metal ions (Cr, Ni, Co, Ti, V).[2] Crystal lasers are intrinsically small in size and very robust. They operate at very high pulse repetition frequencies (PRF) and peak power, making them ideally suited for communication and ranging applications.

The most common crystal laser is the well established Neodymium Yttrium Aluminum Garnet (Nd:YAG) laser. A typical flash-lamp pumped Nd:YAG laser is depicted in Figure 4. Optical input power is supplied to the laser rod by the high energy flash-lamps which are housed in a reflective pump chamber. The pump chamber is a sealed housing which allows a coolant to flow over the laser rod and lamps. The mirrors form the resonator cavity and provide optical feedback. The Q-switch is an electro-optical device which is responsible for producing the ~10 ns laser pulses. As it turns out, the optical pump bands of Neodymium doped crystals have the advantageous feature that they can be pumped by GaAlAs semiconductor lasers, and solar radiation in addition to flash lamps.

Usually lasers emit on one specific wavelength or several discrete wavelengths. However there are a number of crystal lasers that have a broad enough emission profile that they can be operated as tunable lasers. A wide variety of crystal lasers are continuously tunable over the near IR range, but the most common tunable laser crystals have Cr, Ni, Co, Ti, and Tm as their dopants. Tuning of the laser frequency is accomplished by placing a frequency selection device in the resonator cavity. These optics include reflection gratings, prisms, Fabry-Perot (F-P) etalons, and birefringent plates. Figure 5 shows a tunable laser cavity with a dispersion

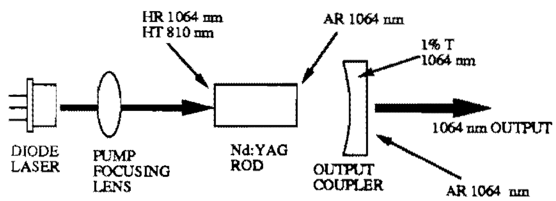

Figure 6 - Schematic representation of a diode laser pumped Nd:YAG laser

prism for coarse wavelength tuning and a F-P etalon for fine frequency selection. In this manner, continuous tuning of the laser output within the emission profile can be achieved. Tunable lasers are especially important for remote sensing applications.

For applications where visible wavelengths are needed, there are nonlinear frequency up-conversion methods that can shift wavelengths from the IR to the visible. In one commonly used nonlinear process, incident photons of frequency w_1 are summed to a frequency w_2 in a nonlinear optical material such that $w_1+w_1= 2w_1=w_2$. This process is called second harmonic generation (SHG).

Diode Pumped Solid-State Lasers

Diode-laser pumping of solid-state laser media offers significant practical advantages over conventional flashlamp-pumping schemes for the production of high-efficiency, compact, coherent sources operating in the visible and near infrared. Diode-pumped devices have been shown to be substantially more efficient, longer-lived and smaller than lamp-pumped devices with comparable output powers. Additionally, the beam quality of diode-pumped lasers is substantially better due to an improved spatial match of the pump beam to the solid-state laser mode.

Diode-laser pumping has also been found to reduce the spectral and amplitude noise of the laser emission. Pump discharge fluctuations in a lamp-pumped laser are translated into strong ringing or relaxation oscillations of the output amplitude. Diode lasers have significantly less amplitude noise than discharge lamps and, when used as pump sources for solid-state lasers, tend to produce far less relaxation oscillation noise in their output. Substantial amplitude noise can also be introduced by the flow of coolant in the pump chamber and mechanical resonances of the resonator structure. Because there is much less waste heat for diode pumping, passive cooling can be employed for the laser rod, there by reducing the amplitude noise encountered in the previous case.

A typical diode-laser-end-pumped Nd:YAG laser is shown schematically in Figure 6. In this device, the output from a semiconductor laser (index-guided single-stripe, large optical cavity or coherent array) is focused with a short focal length lens onto the pump face of the Nd:YAG rod. The lens is chosen to maximize the geometric overlap of the pump beam and fundamental mode of the solid state laser over the distance in which there is an appreciable absorption of pump radiation. The fact that the laser can be designed in such a way that almost all of the pump light is absorbed within the fundamental mode volume is one reason that the quantum conversion efficiency of pump photons to usable laser output in a diode-pumped laser can approach unity. High pump conversion efficiency is also due to the fact that the spectral overlap of the pump radiation with the neodymium absorption bands is excellent.

GaAlAs laser diode arrays are available in the spectral range from 780 nm to 850 nm and, through appropriate device selection and temperature tuning, the output can be made to overlap one of the strong neodymium absorption lines near 800 nm. In practice, the pump diode is usually placed in thermal contact with a thermoelectric cooler and kept at a constant temperature which maximizes the pump absorption. The 20 Å emission

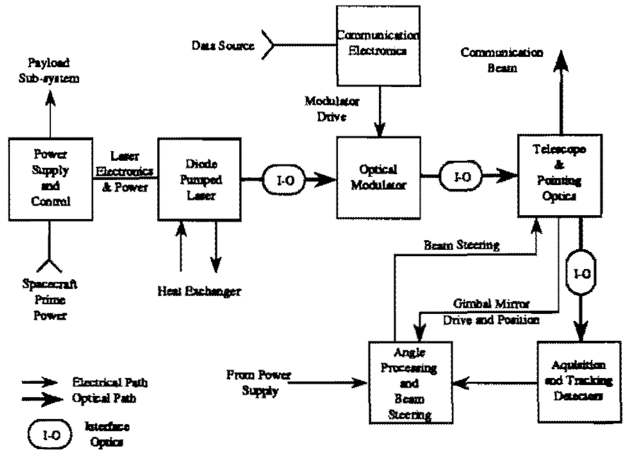

Figure 7 - Schematic of a generic laser transmitter

Some values of the above parameters are listed in Table 2. These numbers represent typical reported values of experimental observations.

Supplementary Payload Systems

Implementation of lasers to space requires more than just the laser oscillator itself. There are additional systems required to operate a laser and there are systems particular to the application of the laser. To illustrate some of the ancillary components of a laser payload, consider the generic laser transmitter depicted in Figure 7.

Starting at the left the first sub-system encountered is the power supply and control unit. This unit is responsible for supplying power to the diode pumped solid state laser and for controlling diode laser and rod temperature. The laser driver has to provide voltage regulated, high current pulses of ~10-100 μs in width to the laser diodes. Temperature and current stability are very important issues with diode lasers. Diode lasers chirp in frequency when pulsed with injection current and typically tune at a rate of 3 Å/°C with temperature. To maintain optimum spectral overlap of the Neodymium pump bands (~ 20 Å wide), temperature and current need to be regulated very closely.

Power regulation and supply systems that control power to the laser and all of its sub-systems have been developed that operate with 73 % efficiency.

The space based diode pumped solid state laser is basically equivalent to the one previously described. The major differences are the number of pump sources used. Instead of being end pumped, the space qualified diode pumped solid state laser is likely to be side pumped by bars that are radially positioned around the rod. Also a nonlinear crystal is placed inside the laser cavity so that visible light is generated. The space laser will be modelocked or Q-switched so that high peak powers can be realized.

Cooling to the laser head assembly is provided by a separate sub-system. For our given example of the diode pumped solid state laser, two different cooling systems are needed. The first cooling system is used to remove heat from the diode lasers. To control the diode laser arrays, silicon thermo-electric devices are employed. Thermo-electric (TE) devices are solid state heat pumps based on silicon. A direct current applied to the TE device will produce a temperature gradient across the device. In order to maintain the temperature difference, the TE cooler must be attached to a heatsink to remove the waste heat. A thermo-electric cooling system usually involves the use of a thermistor or a current proportional device and a closed loop feedback servo amplifier to control current to the TE coolers. Temperature control to the pump laser diode must be maintained to with in 1.0 °C in order to maintain optimum pump efficiency.

The second cooling subsystem is a heat exchanger to remove heat from the TE cooler heat sinks and the laser rod. This can be a passive heat exchanger utilizing conduction through heat pipes to a free space radiator or a closed loop circulating system. A closed loop system incorporates sensors to monitor temperature and pressure and flow rate of the coolant. Choice of the coolant is also important. On earth water is usually used, which will not work in space since its freezing temperature is too high. Some commonly used coolants are methyl alcohol,

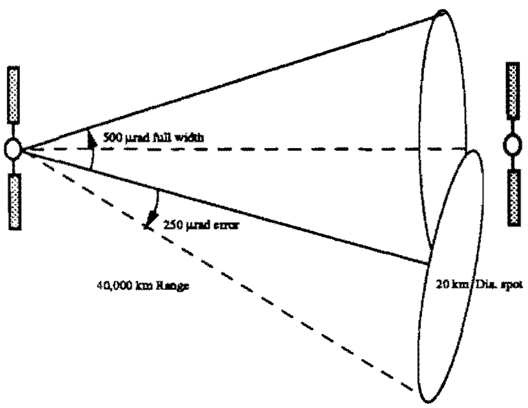

Figure 8 - Satellite crosslink illustrating pointing error

ethylene glycol, and Freon. As in any closed cycle heat exchanger, a pump and a waste heat radiator is required along with the associated plumbing.

Next we will consider the supplementary optical systems needed to deliver the signal to its target. As in all RF systems, the transmitter consists of a source and an antenna. For lasers the antenna is replace by an optical telescope which is characterized by its radiation pattern or gain as in RF. This antenna may be fixed or free to move. For a fixed telescope system, a flat mirror in front of the telescope is used to steer the beam. Delivery of the optical signal is accomplished by a system of interfacing optics. Interfacing optics can be any combination of optical elements depending on what what is being done to the beam. Fiber optics can also be used, however they are not appropriate for all situations.

To accomplish bi-directional optical communication, an active acquisition, tracking, and pointing (ATP) system is required. Autonomous optical acquisition between two remote terminals requires complex optical systems and algorithms. To establish a link one satellite must be able to locate the other. To do this the searching laser can scan the orbital position where the other is supposed to be located. When the second terminal receives a signal from the first it points itself toward the source and iteratively reduces its optical field of view and readjusts its direction until it is pointed toward the source with an angular resolution equal to the coarse field of view of the tracking optics. At this point the second terminal can direct a return beam to the first to close the loop, at which point the iterative process is repeated by both satellites to establish fine tracking between the two.

Angular pointing and tracking requirements are determined by the half angle of the full beam divergence of the transmitting source. Figure 8 shows this graphically for a crosslink between two satellites at a distance of 40,000 km with a full width transmitted beam divergence of 500 µrad. At this distance the spot size at the receiver is approximately 20 km in diameter. If the pointing error becomes larger than the half angle, which is 250 µm in this case, the transmitted spot will move > 10 km and miss the target. This example illustrates that the maximum permissible pointing error is $\simeq$ to the half angle beam divergence of the transmitting source.

Optical light modulators are extensively used in laser systems. These are electro-optical (EO) and acousto-optical (AO) devices and require, high speed switching supplies. These modulators are responsible for the high data rates capable with lasers. Acousto-optical modulators are inside the laser itself and used for modelocking, which produces the high rate (~500 MHz), narrow (~300 ps) pulses. An electro-optic modulator external to the laser is responsible for encoding the data on the optical beam.

There are many modulation formats used to encode information on optical carriers. The modulation formats usually employed for free space laser communication are Pulse Position Modulation (PPM) and Pulse Interval Modulation (PIM). Both formats rely on temporal positioning of the pulse relative to a sync pulse. Pulse Quantary Modulation (PQM) is a combination of pulse position and polarization modulation.[9] To accomplish the encoding, the EO modulator assembly rotates the polarization of the light to switch it between two orthogonal states and, to switch it in and out of an optical delay line to vary the interpulse period. In this manner two bits per pulse may be encoded onto each pulse, to produce a data rate that is twice the laser PRF.

Conclusion

An evaluation of different types of lasers to examine suitability for space operation based on efficiency, weight, lifetime, size, and complexity was presented. A brief description of the strengths, weaknesses and engineering issues of each of the lasers was also presented. Our conclusion is that diode, solid state, and diode pumped solid state lasers are the best candidates for implementation to Lightsats, as well as larger and heavier satellites in general. Based on this conclusion a brief description of a diode end-pumped solid state lasers was presented to illustrate some of the pertinent engineering issues. Finally some of the ancillary sub-systems necessary for application of laser systems to satellites was discussed.

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