Invited Paper

Technology needs for next-generation space-borne lasercom systems

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ABSTRACT

The deployment of laser communications (lasercom) in space depends upon the availability of key technologies that can support these challenging missions. The development of these technologies is important in broadening the addressable applications that lasercom can support. In addition to surviving long-term missions in a hostile environment, a premium is placed upon new techniques and devices that can reduce the on-board size, weight, and DC power consumption by the lasercom payload, while maintaining high reliability. Specific requirements for these next-generation systems are discussed here, with examples of emerging technologies that appear to be insertion candidates.

Keywords: Lasercom, space, technology, satellite, communications, optical

1. INTRODUCTION

The past decade has brought significant advances in the technologies that now make space-borne laser communications (Lasercom) a reality. Such space-based systems possess several key advantages over established RF systems, including significantly increased usable bandwidth, heightened security, and insensitivity to some radiation and electro-magnetic interference (EMI) effects.

Many of today's state-of-the-art technologies have been successfully demonstrated in space applications. These systems include GeoLite, SPOT/Artemis, and NFIRE/TerraSAR-X[1]. These missions have demonstrated the pointing, acquisition, tracking, and communications performance for lasercom payloads, as well as the robustness of certain opto-electronic components that are new to space.

However, the requirements for future space-based lasercom-enabled systems will place greater demands on these technologies to increase performance and reduce size, weight, DC power consumption, and cost. This paper attempts to forecast and highlight those technology areas with the greatest leverage for next-generation space lasercom systems.

2. NEXT-GENERATION SPACE LASERCOM REQUIREMENTS

Next-generation systems are likely to have certain characteristics based upon mission requirements:

- **Proliferation of lasercom terminals due to increased connectivity:** Most, if not all, next-generation satellites will host one or more lasercom terminals. An expanded market will drive the need for increased terminal standardization and low accommodation impact, including minimum size, weight, and DC power consumption (SWaP), to space platforms.
- **Multiple apertures per satellite:** Emerging space-based communications systems will be more network-centric, which is best served by a large number of interconnections within the system. Each satellite will have greater utility in such a system by supporting multiple lasercom terminals. As with the terrestrial Internet, space systems will migrate to more complex meshes of connectivity, with lasercom providing trunking and backbone functions as well as servicing edge users. This requires significant SWaP reductions as compared with today's designs.

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- **Multiple-access terminals:** The ability of a single terminal aperture to support multiple communications links simultaneously is highly desirable. In addition to enabling SWaP reduction, some multi-access solutions, using electronic beamsteering or micro electro-mechanical systems (MEMS) technologies, may also improve system reliability.
- **Multiple-wavelength terminals:** As space systems evolve and bandwidth demands continue to increase, the incorporation of wavelength division multiplexing (WDM) is highly likely. Thus high-efficiency, high-reliability components and techniques to accomplish WDM, including high-power transmission of optical signals, will also be required to implement this function.
- **Complementary concepts for on-board optical interconnectivity:** The utility of the lasercom terminal may be enhanced by upgrades to the satellite's interface buses to migrate significant traffic from traditional copper harnessing to optical fiber.

3. TECHNOLOGIES ENABLING NEXT-GENERATION APPLICATIONS

3.1 The Lasercom System and Technologies

A wide variety of technologies is required to produce a high-performance lasercom system for space. These include optical, electro-optical, high-speed digital, precision analog, and wideband RF. Figure 1 shows the functional block diagram for a space-based lasercom terminal. Even today, the product design and form factor for components varies quite significantly from technology to technology. As a result, it is difficult to integrate them into highly compact subsystems and systems, which is key to meeting several of the requirements listed in the previous section.

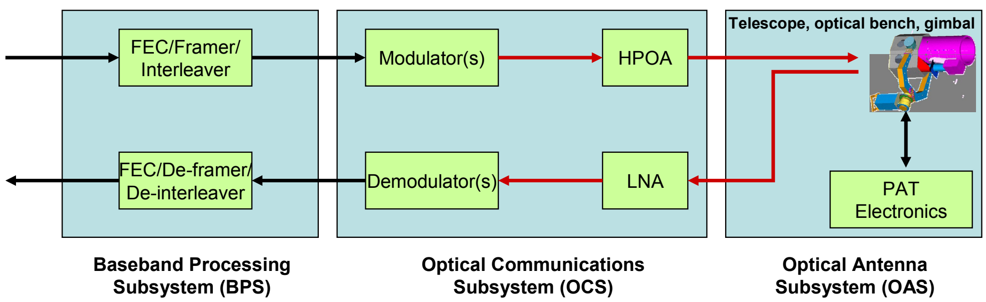

Figure 1: Space Lasercom Terminal Functional Block Diagram

Modern lasercom systems are designed to operate in the commercial C band at wavelengths near 1550 nm. Modulation types vary, but include on-off keying (OOK), binary pulse position modulation (BPPM), and differential phase-shift keying (DPSK). Data rates are usually above 1 Gbps to take advantage of the bandwidth that lasercom systems provide.

3.2 Integrated Opto-Electronics

Semiconductor advances have led to the effective integration of digital and analog circuits on a single substrate, using BiCMOS and silicon germanium (SiGe) processes, for example. Similarly, the next step is to integrate electronic and optical functions onto a single substrate.

Photonic integrated circuit (PIC) research has demonstrated the feasibility of creating optical functional blocks, such as phase modulators and delay lines, within semiconductor substrates. The materials employed include polymers, silicon, indium phosphide (InP), and gallium arsenide (GaAs). The latter three are of most interest for hybrid opto-electronic circuits since they also are used for creating high-speed electronic circuits, and thus may be candidates for hybrid designs.

Early work in demonstrating integrated designs has already been published, for such functions as an electro-optic modulator monolithically fabricated with certain support electronics[2]. Though the performance of such designs must still be improved, this is a significant step in ultimately integrating most of the electronic and optical functions into more compact products. One could easily imagine a complete DPSK modulator fabricated as a single semiconductor chip in the not-so-distant-future (Figure 2).

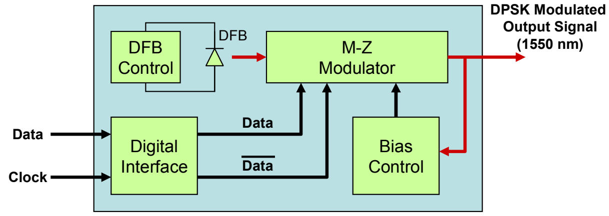

Figure 2: Optical DPSK Modulator Functions

Continued progress in low-loss, high-performance substrate materials suitable for both good electronic and optical performance will be very important, as well as efficient designs to combine the two types of function. In addition, since the performance of optical systems are often sensitive to thermal effects, it will be important to design for low power dissipation as well.

The development of hybrid, integrated opto-electronic devices is only part of the solution. Compact packaging capable of surviving space environments is also a critical need. Many common fiber optic and opto-electronic components today are in large packages, which are then interconnected to produce the desired function. These large separate packages must be significantly reduced in size for future lasercom applications. An example of consolidation of functions into a single package is the integration of driver amplifiers into the same package with an electro-optic modulator. The co-location of these devices improves performance, reduces size, and enhances reliability. These components must survive such environments as three-axis random vibration, pyroshock, total dose gamma radiation, vacuum, and many cycles of wide temperature extremes over a ten- to fifteen-year mission duration. Those requirements are discussed in a later section of this paper.

3.3 Power Efficient Designs

As with size and weight, DC power is at a premium for space missions. Many of today's implementations of critical lasercom functions consume more power than is desirable. There is a great need to reduce the power consumption while maintaining performance and reliability. Once again we can use the electro-optic phase modulator as an example. Standard lithium niobate ($LiNbO_3$) modulators require large V_π to drive the device to full extinction. This in turn requires wideband RF driver amplifiers with large output voltage swings, and the associated high power consumption. Development of modulators with a lower V_π, or a different type of modulator altogether that does not require such drive, is highly desirable.

Perhaps the largest power consumer in the lasercom terminal is the high-power optical amplifier (HPOA), a block diagram of which is shown in Figure 3. Modern lasercom systems were enabled by the invention of the erbium-doped fiber amplifier (EDFA). This type of amplifier allows a more compact method of producing continuous multi-Watt power at 1550 nm wavelengths. Unfortunately, the HPOA is very inefficient, with typical wall-plug efficiencies of 10% or less at beginning of life. End of life efficiencies, after suffering degradation due to aging and radiation exposure, can be closer to 5% for a fifteen-year space mission. Consequently, the HPOA is the primary target for reducing power consumption.

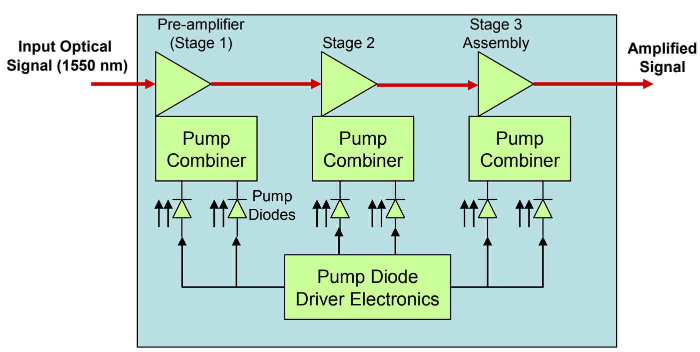

Figure 3: High-Power Optical Amplifier Block Diagram

There are a number of improvements that could lead to improved power efficiency in the HPOA. The input signal is amplified by pumping the erbium-doped fiber using high-power laser diodes. Improvement of the multi-mode pump diode efficiency could significantly improve the overall amplifier efficiency. Likewise, the pump combiner that aggregates the output power from multiple pump diodes has some loss that might be reduced. Finally, improvements to the erbium-doped fiber to raise the energy conversion efficiency are also desirable.

Alternate optical power amplifier technologies, such as semiconductor optical amplifiers (SOAs), are also promising. Existing SOAs exhibit higher wall-plug efficiencies, but do not yet approach the output power and performance of fiber amplifiers. Maximum output powers are currently limited to 1 – 2 Watts, but efficiencies are as high as 20%, compared to 5 – 10% for fiber amplifiers with the same output power.

Yet another target for reducing DC power consumption is in the baseband processing associated with the lasercom link, including data framing, interleaving, and forward error correction (FEC). These digital functions consume a significant amount of DC power at high data rates, and any improved architecture or semiconductor process that can reduce this power will be desirable.

3.4 Precision Beam Steering Advances

One of the key functions of a lasercom system is positioning and steering the optical beams. A block diagram of a typical pointing, acquisition, and tracking (PAT) system is shown in Figure 4. The system must be capable of precise open loop pointing, and scanning an area in space. Subsequently the system is required to acquire and point very accurately in a closed-loop track mode. This accurate beam steering is required over all space environments, including maintenance of low wavefront error.

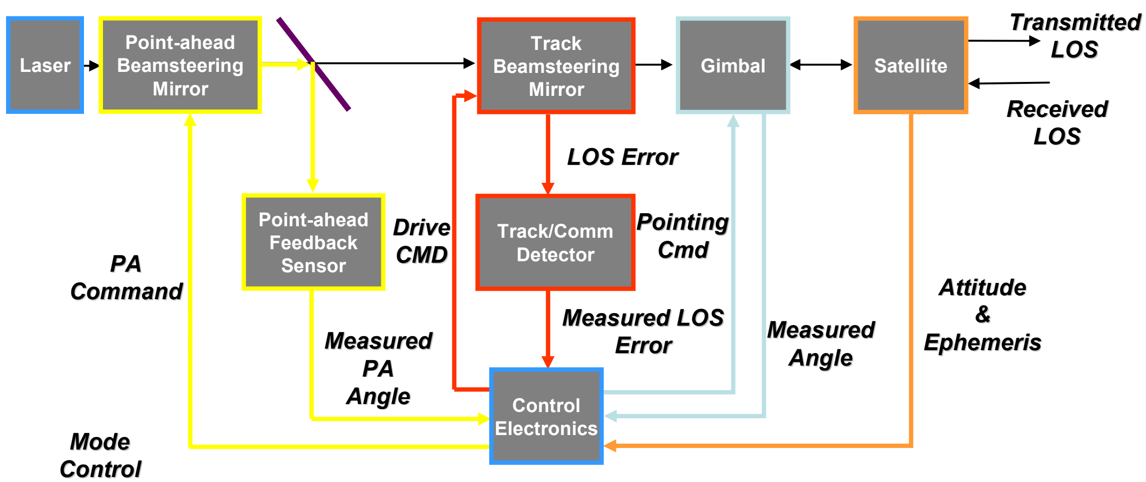

Figure 4: Pointing, Acquisition, and Tracking System Block Diagram

Manipulating the optical beams requires free space optics and high-speed mechanisms for many lasercom applications. Conventional glass-based optics is large and heavy. The high-speed mechanisms are relatively large and expensive. Lasercom PAT systems usually require separate beam paths for transmit and receive communications, acquisition, and tracking. This complicates the optical bench and adds significant SWaP. Additionally, these designs support only a single communications beam, restricting operation to a single access per aperture unless additional complexity is added (wavelength or polarization diversity within the field of view).

New technologies have shown promise but still require considerable development to meet current mission needs. These are generally categorized as electronic beam steering methods. In these designs the aperture is fitted with some type of optical phased array, which is analogous to the electronic equivalent. In this case, multiple optical elements, often implemented using liquid crystal display[3] (LCD) or MEMS[4] devices, are driven electronically to form transmit and receive beams. This approach can allow multiple beams to be formed simultaneously, enabling multiple accesses through a single aperture. Among the many challenges is designing such arrays to achieve a wide field of view with acceptable optical performance. This encourages a hybrid coarse and fine pointing approach, with the optical phased array providing mainly the high-speed, fine pointing function. A recent example of research and development is DARPA's Steered Agile Beam[5] (STAB) program, from 2000 - 2004.

Another area that continues to evolve is the development of high bandwidth control loops for fast steering mechanisms. In general, the higher the bandwidth, the lower the residual tracking jitter for the PAT system. This requires advances in both the mechanisms and the tracking electronics and algorithms.

3.5 Improved Fiber Optic Interconnects and Bus Technologies

Accommodation of lasercom terminals on space platforms is a significant challenge. In addition to low SWaP, interface compatibility is important. Required spacecraft interfaces include attitude control subsystem (ACS), telemetry and command subsystem (T & C), power subsystem, as well data interfaces to other payloads, such as on-board processors or data storage units.

The communications subsystem hardware built using today's technologies and processes is much larger than desired. As mentioned previously, the form factor for many optical components results in single-function partitioning and does not allow for optimization of size or weight. In addition to improving component packaging, enhancements to optical interconnects are required. Often connectors are the limiting factor in how compact assemblies can be made. Given the small size of optical fibers, there seems to be a great opportunity to develop compact multi-fiber optical connectors to enable full SWaP reduction.

The use of low-loss, precision self-aligning connectors also overcomes another key drawback to the deployment of optical systems: difficulty in repair and maintenance. To date, very few fiber optic interfaces have been implemented on satellites. Partly this is due to the difficulty of splicing and reworking fiber. Though once launched, these systems cannot be repaired on orbit, rework and troubleshooting activities on the ground prior to launch are commonplace. The need to splice in areas with poor access is a significant drawback to insertion in place of conventional copper or coaxial cables, which can be more easily reworked. The use of connectors is a key enhancement in making fiber interconnects competitive with existing harnessing implementations.

In addition, optical bus components and systems are also not optimized for spaceflight use. Optical transceivers were designed for terrestrial applications, which use long (multi-kilometer) lengths of fiber between signal repeaters. As such, the transmit powers are much higher than that required for much shorter runs on a satellite (several meters).

As satellite data bus designs migrate to towards more optical content, we would expect new bus topologies to provide maximum utility for high data rate transmission, including interfaces to and from the lasercom terminals. Many conventional topologies are based upon the use of wavelength division multiplexing (WDM), and add/drop components to access this architecture. While sufficient, this approach may not be acceptably flexible for spacecraft applications.

3.7 Improved Optical Sensor Bandwidth and Sensitivity

A barrier to high data rate communications in optical systems is the bandwidth of optical sensors and detectors, such as photodetectors. Bandwidths of PIN photodiodes are currently in excess of 60 GHz, supporting single wavelength communications at 40 Gbps. Bandwidth enhancements will allow even greater data rates, and will provide the opportunity to use m-ary pulse position modulation (PPM) formats at much higher symbol rates than is currently proposed, at large values of m. As an example, implementing 128-ary PPM for a 10-Gbps rate would require detector bandwidths of greater than 100 GHz.

4. ENVIRONMENTAL REQUIREMENTS FOR SPACE

In addition to the key electrical, optical and mechanical performance requirements next-generation technologies must also meet performance in space environments and be capable of exhibiting high reliability over missions extending up to 15 years. The following is a brief summary of these key requirements, the specific values of which vary from mission to mission.

4.1 Vacuum

Component and systems must be capable of maintaining performance and functionality in the vacuum of space, which is less than 10^{-6} torr. The need to operate in vacuum can also cause the rejection of components that require convection cooling to maintain acceptably low junction temperatures. Many common compounds also exhibit outgassing when placed in a hard vaccum. This can liberate contaminants that may damage or degrade free-space components, such as lenses, mirrors, and optical filters.

4.2 Thermal Extremes

The temperature extremes developed on three-axis satellites can be very high. Generally units are categorized as either in-board or out-board. In-board units are mounted within the payload module and see restricted temperature extremes, whereas out-board units, such as antenna assemblies, low-noise amplifiers, and star trackers are subjected to much wider temperature ranges. Typical acceptance baseplate temperature extremes for in-board components are -10 to +50°C, and survival temperatures from -30 to +70°C. Outboard units can be required to perform over -30 to +80°C, and survive over -40 to +90°C. Acceptable on- orbit junction temperatures for semiconductor devices is a maximum of 105°C.

4.3 Random Vibration

Satellite hardware must survive launch vibration environments. This is generally expressed through a three-axis random vibration requirement. Typically a vibration profile is provided as a requirement (see Figure 5), and hardware is qualified by vibration testing in each axis for up to three minutes.

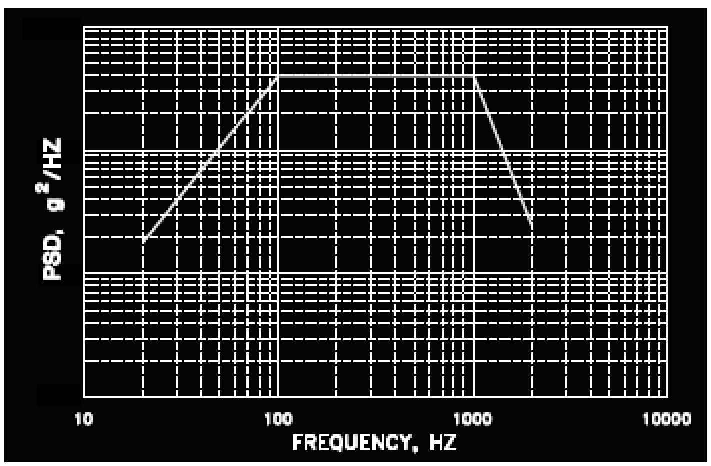

Figure 5: Representative Random Vibration Requirement[6]

4.4 Pyroshock

Deployment of various satellite antenna assemblies and mechanisms is often accomplished through the ignition of pyrotechnic devices (small explosives). These events result in high-acceleration, short-duration shock pulses that will impact neighboring components. As with random vibration, pyroshock requirements are sometimes described by a shock profile detailing acceleration versus frequency. Clearly, fragile devices, including many fiber optic components, are susceptible to failure when exposed to these kinds of shocks, depending upon the levels. NASA, among others, has documented pyroshock design guidelines[7]. It is important to note that specific shock levels vary with the location of the hardware relative to the source of the shock, and is different for all spacecraft.

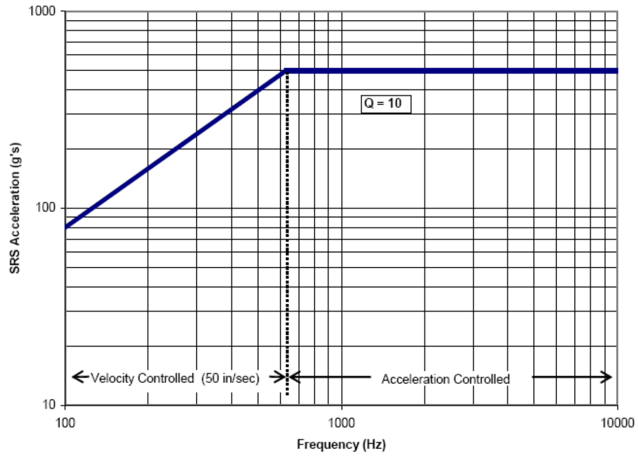

Figure 6: Representative Pyroshock Requirement[8]

4.5 Radiation Exposure

Satellite components are exposed to a number of different types of radiation during a mission. Satellite radiation environments are categorized as natural and man-made. Natural radiation is that found naturally in space, including gamma radiation, heavy ion, and others. The exact content depends largely upon the satellite's orbit. Low-Earth orbiting (LEO) satellites are exposed to higher levels due to their proximity to the Van Allen Belts.

Man-made radiation is that imparted upon satellite components in the event that a nuclear device is exploded near the vehicle, and includes prompt dose (flash X-ray), neutron fluence, and effects such as system-generated electro-magnetic pulse (SGEMP), and internally generated electro-magnetic pulse (IEMP). These requirements are restricted to military applications.

Most important is usually the total dose of gamma radiation, which is proportional to mission life. After shielding is considered, components may see a total dose of between 20 krad (Si) to greater than 1 Mrad (Si). It is essential that components maintain their performance despite the incident radiation.

Exposure to gamma radiation can cause the degradation of a number of materials, including epoxies and bonding compounds, glass, and integrated circuits.

4.6 Electro-magnetic Interference / Compatibility (EMI/EMC)

It is also important that satellite components do not result in signals interference between one another on the spacecraft. This is most pronounced when considering electrical circuits and systems, including digital, analog, and RF circuits. One of the great benefits of optical systems is the relative lack of EMI and crosstalk. However, as mentioned before, lasercom systems contain all key technology types and thus key components must be designed with EMC in mind. In general this means ensuring that components do not excessively radiate RF signals, nor are particularly susceptible to nearby radiated emissions. As with pyroshock, many design guidelines and handbooks are available to provide guidance in designing to eliminate EMI. These references provide techniques for controlling EMI including shielding, and proper grounding. It should be noted that specific EMC requirements are developed for each particular mission, when emitters are known so that specific risk areas can be analyzed.

4.7 Prohibited materials

Several materials are prohibited from use for space flight applications. An example is pure tin, known to result in so-called 'tin whiskers,' which are metal filaments that can cause short circuits in a vacuum. NASA has also prohibited cadmium and zinc plating for most applications.

4.8 Reliability

Space applications are synonymous with very high reliability. The combination of harsh environments, long missions, and the inability to maintain and repair the hardware leads to stringent reliability requirements for all components. It is essential that reliability is designed into the components and demonstrated through qualification programs. The failure modes and mechanisms must be well understood. For optical and electro-optical components, Telcordia qualification is a good starting point, but may not be sufficient to meet space (S-level) requirements.

Reliability is usually specified at the mission or system level and then allocations are flowed down through the component level. Specifications are often in terms of failures in 10^9 hours, or FITs. FIT rates for common electrical components such as capacitors or transistors are typically less than 100 FITs, often less than 10 FITs. Likewise, for new optical and electro-optical components, we expect similar allocations. Historically reliability prediction methodologies have been described in such U.S. Government documents as MIL-HDBK-217, but derating guidelines and other information for many optical and electro-optical components is not included.

Achieving high reliability in any product also implies an inherent need for manufacturing processes that are stable repeatable, and well controlled.

5. CONCLUSIONS

Given the wide variety of technologies that make up space-borne lasercom systems, it is clear that there are many areas for improvement, leading to deployment of next-generation systems. Higher levels of integration, improved power efficiency, development of advanced electro-optic technologies, and robust products capable of meeting space environments are all needed to successfully take the next step in development of such systems.

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