Use of Commercially Available Fiber Optic Components in Emerging Space Laser Communications Applications: Optimizing Performance, Cost, and Reliability

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Abstract: This paper summarizes recent work in developing space laser communications hardware at MIT Lincoln Laboratory, describing how state-of-the-art fiber optic components provide performance and reliability in emerging lasercom system designs.

1. Introduction

Space laser communications systems are becoming widely used to augment or replace RF based communications because of the many advantages of optical signaling in some situations [1], and the multi-decade quest for robust space laser communications has evolved from early demonstration systems to optimized hardware targeting specific operational utility [2]. As applications proliferate, individual system applications must evaluate the functional performance of a system against the size, weight, power, cost, and reliability of the design. It is widely recognized that the use of telecom-type fiber and electro-optic parts are a key element for optimizing all of these categories. Optical fibers were first used in lasercom hardware to provide mechanical design flexibility by separating free-space telescope front-end optics from lasercom transmitter and receiver elements [3], while the introduction of Erbium-doped fiber amplifiers and related components [4-7] drawn from terrestrial telecom lead to a significant improvement in capability and reliability while reducing cost. This paper will provide examples of the use of these elements in several NASA lasercom programs to show how capable systems can be built using available components. It will also discuss future opportunities and challenges presented by the growing importance of CubeSats and telecom integrated photonic devices.

2. Performance and Cost

The double-pass amplifier [7,8] (see Figure 1) is an example of how available active and passive telecom parts can be used for a high-performance low cost implementation of a lasercom transmitter. The design achieves a polarization maintaining (PM) output that is often important for achieving the high transmit to receive isolation needed for lasercom systems having both a large transmit power and a sensitive receiver. While designs exist using all PM components, the double pass design requires that only the polarization beam splitter be PM. This increases the availability of components such as the doped fiber, Faraday mirror, and narrow bandpass filters needed to reduce out-of-band amplified spontaneous emission. This design was used for the Lunar Lasercom Demonstration (LLCD) and is being employed for the Lasercom Relay Demonstration (LCRD) [9-10].

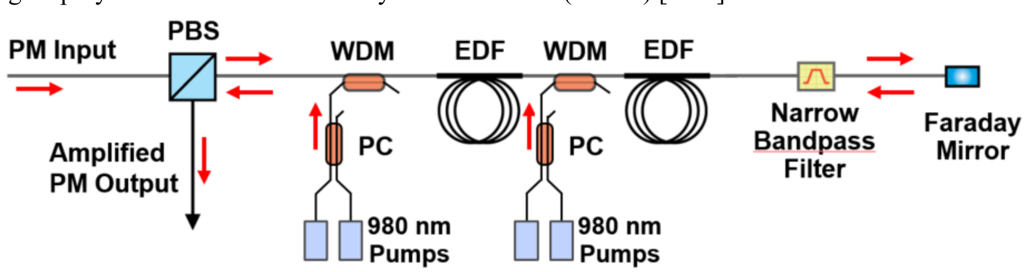

Figure 1 Double pass amplifier schematic. The polarizing beam splitter (PBS) at the input is the only polarization maintaining (PM) component needed in the design. Other elements include Wavelength Division Multiplexer (WDM), Erbium-Doped Fiber (EDF), and fused-fiber polarization beam combiners (PC).

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3. Reliability, Redundancy, and Upscreening

Reliability needs for lasercom systems vary from short ~1 month applications (e.g., for a lunar mission), to multi-year high reliability applications such as LCRD or deep space missions [11]. When available, Telcordia qualified fiber optic parts are excellent candidates for use because of their low cost (compared to the development of custom parts), and because the shock, vibration, and thermal environments tested by the requirements are relevant to many space missions, and the ~20 year lifetime goals needed for some terrestrial applications can exceed many space missions. But Telcordia requirements are qualification rather than screening requirements, and therefore for best reliability all parts used should undergo a reliability and workmanship screening process. Furthermore, parts often need to be upscreened for use in particular mission environments, including vacuum and radiation, that exceed or are not covered by Telcordia. The specifics of an upscreening program can be tailored to the particular mission, but as a general methodology, the following considerations apply.

- Use single lot lifetime buys of Telcordia qualified parts when possible. Unlike serialized space qualified electronics, the concept of a lot is often less clear, but in some cases single lots are available.
- Eliminate known wear out mechanisms that can limit required design lifetime. This requires an understanding of failure mechanisms, and the differences between a random failure mechanism (common in 980 nm pump lasers [12]) vs. wear out mechanisms (e.g., radiation effects, crack growth in fiber splices or fiber bends). Most uses of fiber and electro-optics in lasercom systems have the advantage of no moving parts that often limit the lifetime of mechanical systems.
- Balancing selected redundancy vs. design complexity. The excellent reliability of fused passive fiber optic components permit, for example, pump multiplexing schemes that can greatly enhance transmitter and receiver reliability through derating and the introduction of cold spares.
- Demonstrate suitability for use through functional and environmental testing. Functional testing in prototype hardware and system testbeds is valuable beyond the demonstration of functionality because it often provides a form of a life test, and some sensitive systems (e.g. lasercom receivers with near theoretical performance) can provide sensitive indications of transient behaviors that could provide signatures of failure. Subjecting example parts to environmental testing at the component, subsystem, or system level gives confidence that there are no deterministic design flaws.
- Workmanship screening for the specific parts used through functional and environmental screening tests. As with space qualified electronic parts, these screening tests must be carefully tailored to eliminate workmanship problems without overstressing parts in a way that could reduce lifetime.

For the double pass amplifier, the single-mode 980-nm pump laser diodes are typically the largest factor in determining the long term reliability since the other elements use passive fiber optic components that are generally highly reliable. For a 0.5-W operating point and 40% pump to signal conversion efficiency, the design requires ~1.25 W pump power shared across four pump lasers. This is easily achieved with today's lasers that deliver as much as 1 W. This allows for operation with highly derated pump lasers whose operating point can be increased to compensate for the failure of one or even two pump lasers, resulting in a design that is suitable for multi-year missions with high reliability.

4. Next Generation Systems

The above techniques have proven to be successful in past systems such as LLCD [9] and work is underway to extend these approaches to a broader vendor base being used for the O2O, ILLUMA-T, and DSOC programs [2]. While these systems rely on discrete fiber optic telecom-type parts, terrestrial telecom applications are increasingly benefiting from integrated photonic systems [13] that offer exceptional performance with reduced size, weight, and power. A challenge for future lasercom systems will be how to incorporate these integrated parts given that they are not specifically designed for space lasercom and are harder to tailor to an application because they tend to be systems or sub-systems (e.g. a transceiver) rather than components (e.g., a laser). These challenges apply both to optical, electrical, and mechanical interfaces as well as the command and telemetry interfaces, since these devices often include internal processors with defined interfaces that cannot be altered.

Meanwhile the CubeSat market is generating a focus on reduced cost through a rapid refresh cycle and system-level redundancy. This reduces the importance of the long-term reliability of individual components, and therefore facilitates the introduction of commercial telecom parts into future CubeSat systems.

The TBIRD program [14,15] is demonstrating how to build a highly capable lasercom system using integrated photonic transceivers that provide black box functionality designed for terrestrial fiber optic communications channels. The project is successfully upscreening the transceiver for thermal-vacuum, shock and vibration, and radiation environments, while implementing an Automatic Repeat request (ARQ) protocol at the system level that gives excellent performance on a free space fading channel. This type of simple approach in working within the constraints of available parts is likely to be of growing importance.

5. Acknowledgement

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