Optical Society of America (OSA), Optical Amplifiers and Their Applications, Topical Meeting and Tabletop Exhibit, Budapest, Hungary; 07.08.2005 - 10.08.2005

Optical Amplifiers in Space Communication Links

Walter R. Leeb

Institute of Communications and Radio-Frequency Engineering, Vienna University of Technology, Gusshausstrasse 25/389, A-1040 Wien, Austria
walter.leeb@tuwien.ac.at

Abstract: In terminals for free-space laser links, optical amplifiers boost transmit powers into the Watt range. As pre-amplifiers, they help obtaining sensitivities of a few ten photons/bit. Concepts and requirements for such applications are discussed.

OCIS codes: (060.4510) Optical communications; (250.4480) Optical amplifiers

1. Introduction

Space communication, as employed in satellite-to-satellite links, is traditionally performed using microwaves. The step from microwaves to light waves, however, means a reduction in beam divergence by orders of magnitude, even if we use transmit antennas of much smaller diameter. As a consequence, one expects that mass, power consumption, and size of an optical terminal will be smaller than that of its microwave version. Since the early seventies efforts towards optical space communications have been undertaken, mainly in the US, in Europe, and in Japan, leading to a number of more or less successful experiments. At last, in November 2001 the first reliably working, non-classified optical intersatellite link has been established between SPOT4 and ARTEMIS, two satellites built by European consortia [1]. A few months before, the US military satellite GEOLite equipped with an optical booster amplifier had demonstrated an optical link to a ground station.

To cope with the ever increasing demand on bandwidth of free-space links, there is the request for high transmit power and for more sensitive optical receivers. This can be satisfied, in principle, by equipping the laser communication system with optical amplifiers (OAs): At the transmitter, a high-power OA can boost the optical transmit power into the several-Watt range, at the receiver terminal, an optical preamplifier may enhance the sensitivity close to values given by the quantum limit. In both cases one can draw from the technology developed for applications in fiber systems.

Note, however, that with *quantum* communications – as, e.g., envisaged for cryptographic key distribution – optical amplifiers can neither be implemented as boosters nor as pre-amplifiers because the photons then involved cannot be cloned, i.e. amplified.

2. Link scenarios

Scenarios for optical free-space links are directly related to the position of space platforms relative to Earth. One may distinguish between satellites in

- low-Earth orbit (LEO),
- geostationary orbit (GEO),
- medium-Earth orbit (MEO)

  and further between

- high altitude platforms (HAP)

  and

- deep space probes.

The respective altitudes above the Earth are typically 600 km (LEO), 36,000 km (GEO), 500 to 20,000 km (MEO), 20 km (HAP), and millions of km for space probes. (One prominent example of a LEO satellite is the International Space Station).

Some of the links that have been considered in the past for specific applications are listed in Tab. 1, together with typical distances and data rates. Also included are links to ground stations and to airplanes, which, however, will suffer from the influence of the Earth's atmosphere.

Table 1. Representative optical communication links (the arrow in the left column indicates the direction of the main data flow)

platforms involved	typical link distance [km]	typical data rate [Mbit/s]
LEO → GEO	45,000	3,000
GEO ← → GEO	5 to 83,000	3,000
LEO ← → LEO	1200	20,000
HAP ← → HAP	5 to 100	1,000
space probe → ground	> 1,000,000	2
LEO → ground, airplane	1,000	500

3. Terminal concepts incorporating optical amplifiers

Terminals for optical communication in space are mostly designed for bi-directional links, at least concerning the optical tracking function. They comprise both a transmitter and a receiver that generally share the optical antenna. Another peculiarity is the necessity of beam steering (or pointing) capability with sub-microradian angular resolution and possibly with an angular coverage exceeding a hemisphere. These requirements lead to a transceiver block diagram as shown in Fig. 1. With the single-antenna concept sketched, it is not easy to achieve the required high isolation between the outgoing beam and the faint optical input signal. Although duplexing can be based on different wavelengths and states of polarization, an imperfect duplexer and the scattering from shared optical devices may result in insufficient transmit-to-receive channel isolation, not at least because of the broad-band booster ASE radiation [2]. Alternatively one might consider a separate transmit and receive telescope – however, at the expense of increased terminal mass.

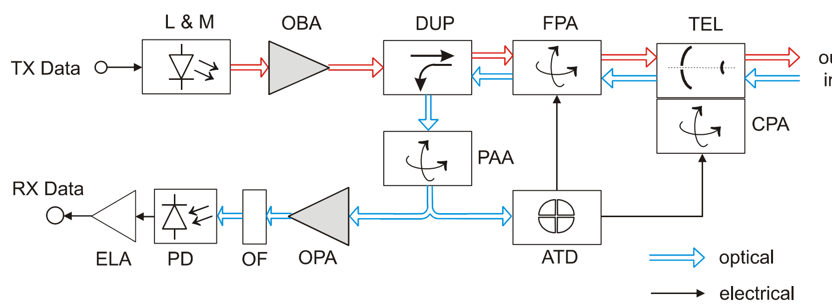

Fig. 1. Basic block diagram of an optical transceiver for space-to-space links (L & M..laser and modulator, OBA..optical booster amplifier, DUP..optical duplexer, FPA..fine pointing assembly, TEL..telescope (optical antenna), CPA..coarse pointing assembly, PAA..point ahead assembly, ATD..acquisition and tracking detector, OPA..optical pre-amplifier, OF..optical bandpass filter, PD..photo detector, ELA..electronic amplification and data recovery).

Many applications ask for a transmitter with an optical output power on the order of 1 Watt. Lasers providing such output powers and being at the same time capable of direct modulation at data rates above several Mbit/s are not available. Here an optical booster amplifier can jump in. It will be preceded by an external modulator based on the electro-optic or the electro-absorption effect, which allows also for a broader range of modulation formats. For bridging long distances, the outgoing beam has to be diffraction limited. Therefore the beam entering the telescope should be of single-transverse mode, a requirement met with single-mode fiber amplifiers. With many system designs the output beam is required to have a stable, well-defined state of polarization. On the one hand, this allows polarization duplexing (see above). On the other, it is a must for systems based on coherent reception (see below). In case of a fiber booster amplifier this requires the use of a polarization-maintaining fiber.

For space applications, high receiver sensitivity is an extremely valuable asset, because it can be traded against telescope size (and hence terminal mass). Maximum achievable sensitivity is determined by modulation format and detection method. The best values are obtained for phase shift keying (PSK) in connection with homodyne detection, where a local laser oscillator is coherently superimposed with the received light. With this scheme, an optical pre-amplifier with its noise figure ≥ 3 dB would only reduce sensitivity. On the other hand, direct detection of on/off keyed signals (OOK) or of differentially phase shift keyed signals (DPSK) will benefit from optical pre-amplification. For the latter two schemes sensitivities as low as 35 photons/bit and 19 photons/bit, respectively, have been reported for return-to-zero coding at 10 Gbit/s for a bit error ratio of 10^{-6} [3-5]. This sensitivity will be worsened if background radiation is present. If the transmitter is equipped with an optical booster amplifier, its amplified spontaneous emission (ASE) constitutes a background source [2] in addition to that which may come from celestial bodies.

On the other hand, the otherwise unwanted booster ASE radiation can possibly be used as a beacon for pointing, acquisition, and tracking (PAT) purposes. As it occupies the same single spatial mode as the data signal, both fields are perfectly co-aligned. At the receiver, a frequency selective beam splitter then directs all but the data spectrum to the acquisition and tracking detector.

4. Concepts planned and tested

Investigations of free-space laser systems that employ optical amplifiers have been focused on two carrier wavelengths, namely 1.06 µm and 1.55 µm.

The laser source at λ = 1.06 µm is typically a Nd:YAG laser, offering sub-kilohertz linewidth. At the receiver usually homodyne detection – and thus no optical pre-amplification – is implemented. The booster amplifier is realized as a double-clad Ytterbium-doped (or Neodymium-doped) fiber amplifier, pumped at 977 nm (or at 805 nm) [6-8]. With pump powers in the 5 Watt range the data signal is boosted from a 10 mW level to an output power of $\geq$ 1 Watt. Optical efficiencies of 55% and polarization extinction ratios $>$ 20 dB are claimed.

Systems operating at λ = 1.55 µm have a distributed feedback laser diode as carrier source. Booster amplifiers based on polarization-maintaining Erbium-doped fibers are available today. They are pumped at 980 nm and/or at 1480 nm, provide output powers well above 1 Watt, and exhibit noise figures of approximately 5 dB [4,8,9]. At this wavelength, usually OOK or DPSK modulation is employed where the receiver sensitivity can be enhanced by optical pre-amplification. Here one can resort to the excellent devices developed for fiber communications.

5. Requirements on optical amplifiers

Table 2 summarizes the main requirements for optical amplifiers to be implemented as power amplifiers in the transmitter or as pre-amplifiers in the receiver. For the pre-amplifier, the possibility of efficient and stable input coupling from a freely propagating beam is mandatory, while single-mode operation is not. These requirements could be met by a multi-mode fiber amplifier.

Table 2. Amplifier requirements (✓ .. required, ✗ .. of advantage)

	large small signal gain	high saturated output power	good power efficiency	low noise figure	polarization maintaining	transverse single-mode output
booster		✓	✓	✗	✓	✓
pre-amplifier	✓			✓		

6. References

[1] T. Tolker-Nielsen and G. Oppenhaeuser, “In-orbit test result of an operational optical intersatellite link between ARTEMIS and SPOT4, SILEX,“ in Free-Space Laser Communication Technologies XIV, Proc. SPIE, 4635, 1-15 (2002).

[2] P.J. Winzer, A. Kalmar and W.R. Leeb, “Role of amplified spontaneous emission in optical free-space communication links with optical amplification – impact on isolation and data transmission; utilization for pointing, acquisition, and tracking,” in Free-Space Laser Communication Technologies XI, Proc. SPIE 3615, 134-141 (2005).

[3] S. Tanikoshi, K. Ide, T. Onodera, Y. Arimoto and K. Araki, “High sensitivity 10 Gbit/s optical receiver for space communications,” 17th AIAA International Communications Satellite Conference, 178-183 (1998).

[4] M. Pfennigbauer and W.R. Leeb, “Optical satellite communications with Erbium doped fiber amplifiers,” Space Communications **19**, 59-67 (2003).

[5] W.A. Atia and R.S. Bondurant, “Demonstration of return-to-zero signaling in both OOK and DPSK formats to improve receiver sensitivity in an optically preamplified receiver, ” Proc. LEOS’99, 226-227 (1999).

[6] G. Baister, T. Dreischer, E. Rugi Grond, L. Gallmann, B. Thieme and K. Kudielka, “The OPTEL terminal development programme – enabling technologies for future optical crosslink applications“, AIAA Space Conference, Paper No. AIAA-2003-6229 (2003).

[7] L. Bartelt-Berger, F. Heine, U. Hildebrand, D. Lange, T. Schwander, S. Seel and B. Smutny, “1 Watt laser transmitter for intersatellite links”, Proc. ECOC’00 1, 29-30 (2000).

[8] T. Araki, S. Yamakawa, M. Furuya and Y. Hisada, “Latest results and trade-off of high power optical fiber amplifiers for optical inter-obit communications,” in Free-Space Laser Communication Technologies X, Proc. SPIE 3266, 42-48 (1998).

[9] Y. Koyama, E. Morikawa, H. Kunimori, K. Shiratama and Y. Yasuda, “Components development for NeLS optical terminal,” in Free-Space Laser Communication Technologies XVII, Proc. SPIE 5712 (2005).