ASSESSMENT OF COMMERCIAL OPTICAL AMPLIFIERS FOR POTENTIAL USE IN SPACE APPLICATIONS

Juan Barbero(1), Michel Sotom(2), Benoit Benazet(2),
Ignacio Esquivias(3), Francisco José López Hernández (3)

(1) Alter Technology Group Spain, Majada 3, 28760 Tres Cantos (Spain),
E-mail: juan.barbero@alter-spain.com
(2) Thales Alenia Space France, 26, av. J-F. Champollion - BP 1187,31037 Toulouse Cedex1(France),
E-mail: michel.sotom@thalesaleniaspace.com
E-mail : benoit.benazet@thalesaleniaspace.com
(3) Universidad Politécnica de Madrid, Escuela Técnica Superior de Ingenieros de Telecomunicación
Avenida Complutense s/n, Ciudad Universitaria, 28040 Madrid (Spain)
E-mail: esquivia@tfo.upm.es
E-mail: dxtn@tfo.upm.es

ABSTRACT

This paper describes the activities and results of an ESA-funded project concerned with the assessment of optical amplifier technologies and products for applications in fiber optic subsystems of future satellite payloads.

On-board applications are briefly introduced, together with associated system-level requirements. Optical amplifier technologies, research achievements and products are reviewed. They are compared in terms of current performance, perspectives and suitability for the target space applications. Optical fibre amplifiers, not limited to Erbium-doped amplifiers, Erbium-doped waveguide amplifiers and Semiconductor Optical Amplifiers are covered. The review includes analysis and trade-off of all performance parameters including saturation output power, noise figure, polarisation maintaining capability, wall-plug efficiency, and mass and size.

A selection of optical amplifier products for further evaluation and testing is presented. Results of extensive testing covering both functional performance and environmental behaviour (mechanical, thermal vacuum, radiations) aspects are reported. Most of the work has been completed, but an extension has been proposed for checking and comparing the behaviour of doped fibers under gamma radiation.

1. PROJECT OVERVIEW

This paper describes the activities performed in the frame of the project High-Efficiency Optical Amplifier for On-board Fiber Optic Subsystem Applications (ESTEC contract n° 19871/06/NL/Sfe). This activity is concerned with the evaluation of optical amplifier technologies and products for applications in fiber optic subsystems of future satellite payloads.

A consortium formed by Alter Technology Group Spain as prime contractor, Thales Alenia Space France (TAS) and Universidad Politécnica de Madrid (UPM), as subcontractors, has carried out the work.

The project has been divided into two phases: a Selection Phase and a Testing Phase.

First, a thorough review of the existing optical amplifier technologies and commercial products has been performed. This review included analysis of all performance parameters including saturation output power, noise figure, polarisation maintaining capability, wall-plug efficiency, mass and size. A trade-off analysis of the performance of the off-the-shelf products with respect to the requirements of the target applications was completed, and a selection of available optical amplifier products was proposed to the European Space Agency for approval for further evaluation and testing.

Second, the evaluation and testing of the selected devices focused mainly on those tests related with space environmental: radiation, vibration-shocks and thermal vacuum.

2. OPTICAL AMPLIFIERS FOR SPACE : APPLICATIONS AND REQUIREMENTS

Optical amplifiers play a key role in terrestrial telecommunications including WDM transmission systems, CATV and Radio Over Fibre applications. They have been considered in space applications such as LIDARs or space-borne laser altimeter for Earth observation and deep space missions, and Optical Inter-Satellite communication links (OISL). Together with other optical technologies, they are expected to bring significant improvements and/or constitute one of the enablers of advanced payload concepts. They may offer major benefits in the development of future telecom payloads with broad bandwidth, wide connectivity, and enhanced flexibility at low mass and small size. These applications include the generation and distribution of local oscillators in the microwave frequency range, the photonic RF frequency conversion, as well as the combinations of these functions into more complex sub-systems such as analogue repeaters with optical switching, or antenna sub-systems and beam-forming networks. Those applications requiring efficient optical amplifiers are briefly reviewed hereafter.

Distribution of Local Oscillators (LO): The distribution of radio-frequency (RF) reference oscillators via an optical fibre network may find application in future satellite payloads. For instance, repeater architectures based on digital processors perform frequency down- and up-conversion, each in two consecutive steps, and thus need the distribution of an Ultra-Stable Reference Oscillator (USRO), typically at 10 MHz, for reconstructing local oscillators within some frequency-converters and the distribution of a Master Local Oscillators (MLO), typically around 1GHz, for direct use by other frequency-converters. As a matter of example, no amplifier may be needed to distribute a MLO to 10's of equipments, whereas the adjunction of an optical amplifier with +18dBm output power would enable for the distribution up to more than 100 equipments.

LO distribution with photonic RF frequency-conversion: Photonic RF frequency mixing for both up- and down-conversion of microwave signals can be achieved optically by means of electro-optical modulators (EOM). One of the most efficient arrangements is shown in Fig. 1 below, and consists in feeding the modulator optical input with a microwave photonic LO.

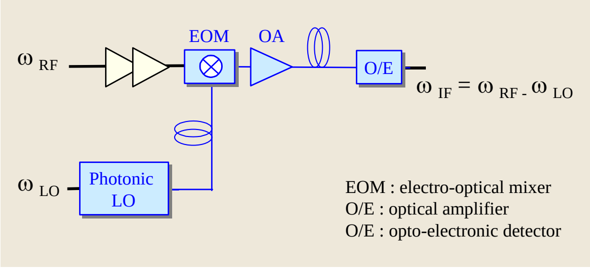


Figure 1: LO distribution with photonic RF frequency-conversion

Electro-optical mixers feature specific attributes, but one critical item is the limited efficiency of the conversion process (i.e. conversion gain/loss). This can be improved by increasing the optical power level available at the detector by using an optical amplifier. The optical amplifier to be included in the photonic LO should then be able to maintain the state of polarisation from the LO to the modulator, and feature relatively high power especially if the photonic LO is shared by a large number of modulator-based photonic mixers.

Analogue repeater with microwave photonic cross-connect: Future broadband telecom satellites with multiple antenna beams will require flexible beam-to-beam connectivity for supporting broadband, transparent, and cross-connection of hundreds of radio-frequency (RF) channels. Analogue repeaters with microwave photonic cross-connect sub-systems can meet such requirements, providing re-configurable connectivity at moderate complexity, mass and volume. They are expected to exceed the capabilities of microwave implementations and to grow up to larger connectivity (10's of beams) and cross-connect a large number of channels. The optical cross-connect made of passive splitters and optical switching matrices requires optical amplifiers in order to compensate for optical losses. Most critical requirements put to these optical amplifiers are compactness, linearity and low power consumption.

Microwave photonic antenna sub-systems: The antenna sub-systems of broadband telecom payloads constitute other potential applications. Fig. 2 below shows an advanced receive antenna concept based on digital beam-forming to provide re-configurable multiple-beam coverage.

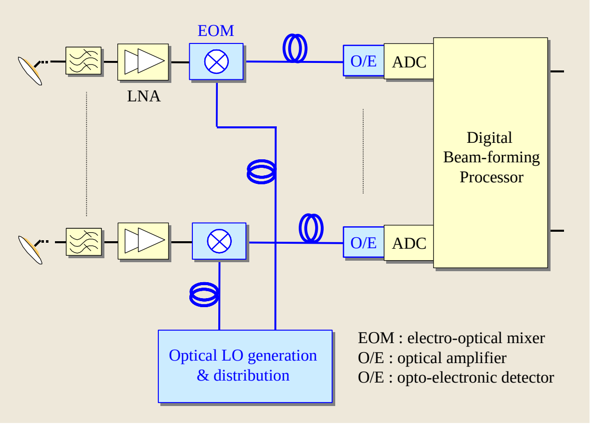


Figure 2: Advanced receive antenna with optically-assisted digital beam-forming

The up-link microwave signals are received by multiple antenna array elements, frequency-converted and transmitted to centralised analogue-to-digital converters (ADC). Once digitised, the signals are processed so that any set of antenna beams can be formed on demand. This concept may apply to various arrayed antenna architectures, but its implementation in Ka-band imposes to reduce the pitch of the receiver array down to the centimetre range. Optical solutions are thus well-suited for distributing LO’s directly in the microwave range and performing frequency-mixing. Such antenna sub-systems involve optical amplifiers in order to distribute a photonic LO to more than one hundred of optical mixers, and further push the requirements of high output power and polarisation maintaining capability at acceptable size and mass (see Ref [1]).

System requirements: Summarizing, whereas LIDAR and OISL typically call for booster fibre amplifiers with output powers in excess of a few Watts, on-board applications require high-efficiency, medium output power optical amplifiers to compensate for insertion losses of optical devices and optical splitting losses, at minimum power consumption. Most of existing amplifiers have been neither being designed for these specific applications, nor been qualified for operation in space systems. Such a high-efficiency optical amplifier shall, in particular:

- operate in the telecom wavelength range (to take best benefit from photonic technologies),
- provide medium-to-high saturation output power,
- operate under low power consumption (to lower the consumption of the overall system),
- come in small size and low mass packages (to accommodate easily in payloads),
- and withstand the space environment constrains.

Table 1 hereafter summarises the most general and critical requirements put onto optical amplifiers for use in the advocated satellite photonic applications.

APPLICATIONS	REQUIREMENTS					
	High Output Power	*Low Noise Figure*	*Linearity*	*Polarization Maintaining*	*Low Power Consumption*	*Small size & low mass*
Reference Oscillator distribution	X	X			X	X
Master and high - freq. LO distribution					X	X
LO distribution with freq. conversion	X	X	X	X	X	X
Microwave photonic repeaters		X	X		X	X
Microwave photonic antenna sub-system	X	X	X	X	X	X

Table 1: General requirements versus on-board applications

Taking into account the previous table, it was decided to give a set of major specifications for low-medium and high power optical amplifiers required for the implementation of the various on board fiber optic sub-system architectures. These performance requirements are presented in Table 2 below dividing the optical amplifiers in particular in the 2 groups below arbitrarily named as A and B.

ITEM	TARGET FIGURE	
	Type A	Type B
Operating wavelength	1530 nm - 1560nm	
Optical output power	+18 dBm	+24 dBm
Small signal gain	> 25 dB	> 30 dB
Small signal noise figure	< 5 dB	
Optical input/output	SMF	PMF
Total Power consumption	< 3W	< 12W
Volume	< 80 cm^3	< 150 cm^3
Mass	< 100 g	< 200 g
Lifetime	> 15 years	

SMF= Single Mode Fiber
PMF= Polarization Maintaining Fiber

Table 2: Major target performance requirements

3. REVIEW OF OPTICAL AMPLIFIER TECHNOLOGIES

Although the Erbium Doped Fiber Amplifier is the amplifier of primary interest, because of its superior performance and higher maturity, all optical amplifier technologies have been considered including the Erbium-doped Waveguide Amplifier, and Semiconductor Optical Amplifier. The following paragraphs summarize the optical amplifiers technologies analyzed.

3.1 Optical Fiber Amplifiers

Doped Fiber Amplifiers (DFAs) use a doped optical fiber as a gain medium. The optical signal to be amplified and an optical pump are multiplexed into the doped fibre, and amplification is achieved by stimulated emission of photons from the dopant ions. The pump light excites electrons into a higher energy level, from where they decay via stimulated emission of a photon back to a lower energy level. The energy levels form a three or four level system, and include a non-radiative transition either from the highest energy level and/or back to the bottom energy level.

The amplification window is the range of optical wavelengths for which the amplifier provides usable gain. It is imposed by the dopant ions, the glass structure of the fibre and the pump wavelength. The fiber is doped with rare-earth ions such as Erbium (Er3+), Neodymium (Nd3+), Ytterbium (Yb3+), Praseodymium (Pr3+), or Thulium (Tm3+). The common rare earth used to dope the fiber is Erbium (Er) that has a radiative transition around 1.55 µm. The amplifier gain bandwidth is given by the energy separation of the upper and lower sub-levels of the rare earth ions. Although the electronic transitions of a single ion are very well defined, electron level broadening occurs when the ions are incorporated into the fibreglass, and thus the range of wavelengths that can be amplified is also broadened. This leads to a gain spectrum that is not uniform against wavelength.

The principal source of noise in DFAs is Amplified Spontaneous Emission (ASE), which has approximately the same spectrum as the gain. Electrons in the upper energy level can decay by spontaneous emission, which occurs randomly, depending upon the glass structure and inversion level. Photons are emitted spontaneously in all directions, but a portion of them is captured and guided along the fibre. Those photons may interact with dopant ions, and thus be amplified by stimulated emission. ASE is emitted in both the forward and reverse directions; co-propagating ASE noise has a direct impact on system performance. Counter-propagating ASE can lead to performance degradation, by depleting the inversion level and thereby reducing the gain.

3.1.1 EDFA

The Erbium-Doped Fibre Amplifier (EDFA) is the most commonly used amplifier in telecommunication networks because its amplification window coincides with the third transmission window of silica-based optical fibre. It has become an essential building block in WDM applications. The Erbium is excited into population inversion by pumping with laser diodes at either 980 nm or 1480 nm, or both. Indeed, a combination of 980nm and 1480nm pumping is also utilised in EDFA’s.

EDFA’s can be pumped in forward direction (i.e. with pump wave co-propagating with the signal wave), or in backward direction. The direction of the pump wave does not influence the small-signal gain, but the power efficiency of the saturated amplifier as well as the noise characteristics. Bidirectional pumping enables not only to provide high output power, but also to achieve a low noise figure at the same time. High gain optical amplifiers also need to be protected from any parasitic reflections, because these could lead to laser oscillation or fiber damage. EDFA’s are typically equipped with optical isolators at the output and possibly at the input.

The resistance to radiation of such doped fibers might be critical, and therefore it had to be assessed.

3.1.2 Cladding-pumped, Erbium-doped fibre amplifiers (CP-EDFA)

For applications requiring high optical powers, novel amplifier designs had to be developed, as this can not be using a conventional EDFA. Three factors limit the power efficiency and the output level of a single-mode fiber EDFA:

- The coupling between the pump laser and the doped core of the FA
- The rare-earth material concentration, and
- The maximum power density in the fiber core

Clad-pumping technology solves the first and third limitation. The second can be dealt with by selecting the base material (glass) appropriately and introducing Ytterbium (Yb) together with Erbium.

Clad-pumping is based on special fibers with two concentric cores (or clads). The pump is launched into a large multimode internal cladding (about 50 to 100 µm) surrounding the single mode, Erbium-Ytterbium co-doped core. As the pump propagates along the fibre, Yb absorbs it in the core. The amount of power absorbed by Yb is then transferred to Er ions leading to an efficient coupling between the pump beam and Er ions, even if their overlapping factor is rather poor.

Double-clad fibre has enabled efficient capture of the output of high-power multimode diodes. With the commercialisation of high-power, broad-area lasers with stripe width as large as the multimode core diameter, clad-pumping has become the technique of predilection for high-power amplifiers. Such a technique allows for pumping powers in excess of a few Watts, and optical amplifiers with output powers greater than +30 dBm (Ref [5]).

There are several technology and design options that can be used to improve the CP-EDFA as use of co-dopants (Yb3+), multimode pumping and pump to fiber coupling techniques.

3.1.3 Erbium-Doped Tellurite Fiber Amplifiers (EDTFA)

Tellurite oxide (TeO2)-based glasses are of interest based on their properties when used for the fabrication of Er3+ optical amplifiers. EDTFAs present a large bandwidth gain covering C and L bands, with large gain per unit length, which allows the fabrication of under-meter amplifiers. The power efficiency is lower than standard silica amplifiers, and the NF is higher than 4 dB, typically in the 5-6 dB range. A serious alternative is the Al-silica fibers which allow higher Er3+ concentrations reducing the gain threshold, but high aluminium concentrations can be a problem under radiation (see Ref [6]).

3.1.4 Photonic Crystal Fiber Amplifiers

PCFs are optical fibers for which the wave-guiding core not necessarily exhibits a refractive index higher than that of the cladding. The light guidance is obtained with the help of suitable arrays of air holes extending along the fiber propagation direction. Fig. 3 below shows an example of a photonic fiber cross-section.

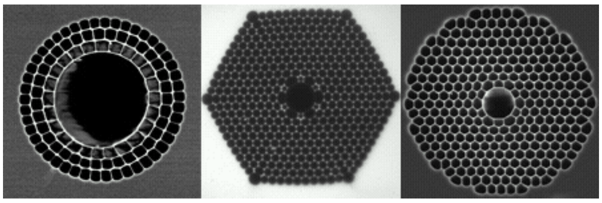


Figure 3: Photonic crystal fiber examples
(from www.crystal-fiber.com)

The unique properties of PCFs make them very attractive candidates for future on-board applications. However, present research trends in PCF active devices are not trying to compete with standard fiber EDFAs used in telecom, but are rather addressed to very high power applications (LIDAR, remote sensing) (Ref [7]).

3.2 SOA

Semiconductor Optical Amplifiers (SOAs) are based on the same technology as Fabry-Perot (FP) laser diodes but with anti-reflection coatings on their end mirrors (to avoid laser oscillation) and with fibre attached to both ends. They are considered as a potential alternative to EDFAs in applications where the requirements on performance are less stringent, and factors like integration or the need for amplification in an extended range of wavelengths, like in coarse WDM, come into the picture.

Motivation for Semiconductor Optical amplifiers includes their small size and potentials for further integration with other active functions on semiconductor substrate. They can be less expensive than EDFA and their reduced size allow them to be integrated with semiconductor lasers, modulators and other components. But their actual performances are still not equivalent with those of EDFAs. The optical gain of such devices at small signal operation varies from +15 to +30 dB, being thus comparable with the typical values of EDFAs. Unfortunately, SOAs exhibit many drawbacks:

- High coupling losses (around 3 dB).
- High noise figure (NF), partly resulting from poor coupling. Typically, a 2-3 dB difference exists between the NF of SOAs and EDFAs. The typical value of NF is about 7 dB.
- Medium sensitivity to polarisation.
- A high non-lineary response, which is the most severe problem in optical communications.

Nevertheless, recent research, such as for example Gain-Clampled SOAs and the use of Quantum Dots, has increased the possibilities of SOAs.

3.3 EDWA

The principle of Erbium-Doped-Waveguide-Amplifier (EDWA) is in essence equivalent to Erbium-doped fibre amplifiers (EDFA). The difference is that the optical amplification takes place inside an optical waveguide integrated on a planar substrate rather than inside an optical fibre. An EDWA consists of a waveguide embedded in an amorphous erbium-doped glass substrate. Two main classes of technologies have emerged to manufacture PLCs (Planar Lightwave Circuit), namely the Ion-Exchange technology on glass substrate, and the so-called Silica-on-Silicon technology with various deposition processes. Both technologies can incorporate Erbium atoms into the waveguides in order to provide the glass with optical gain in the 1550 nm window.

3.4 Comparison of characteristics of different types of Optical Amplifiers.

In addition to the standard parameters (maximum output power, noise figure, small-signal gain …), the following criteria have been considered for comparison of commercial Optical Amplifiers:

Wall Plug Efficiency: WPE (in %) = Optical output power / Electrical power consumption, where the electrical power consumption includes the consumption of the pump laser diodes and of the thermoelectric coolers if any. The higher the WPE, the better. Fig. 4 below compares the wall plug efficiency of commercial optical amplifiers grouped by technology (data taken from datsheets).

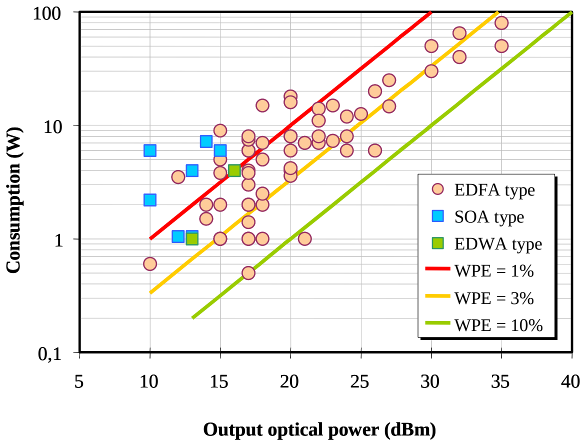


Figure 4: Comparative wall-plug efficiency (WPE) of OA products

Volumic Optical Power (VOP): As mass and volume are of special interest for space applications, it was found relevant to define another figure of merit, so-called volumic optical power (VOP), that takes into account the mass and that can be expressed as follows: VOP (in mW / cm3) = Optical output power / Volume. Again the higher , the better.

Fig. 5 below compares the volumic optical power (VOP) of commercial optical amplifiers grouped by technology.

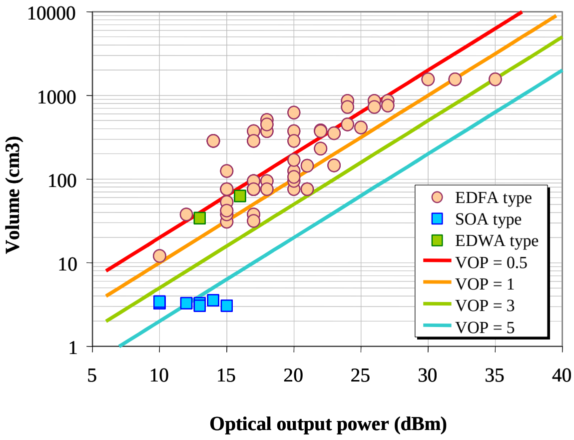


Figure 5: Comparative volumic optical power (VOP) of OA products

From this review and trade-off analysis, it is possible to extract the following conclusions:

- Commercially available EDFAs can provide any output power in the range of interest (+15 to +30 dBm) with the lowest noise figure.
- SOAs and EDWAs may be used for +18 dBm optical output amplifiers, especially if output power is substantially increased as expected, or requirements relaxed, or if integration of several optical amplifier channels, or integration with passive optical functions such as splitters become of prime interest.
- Both SOAs and EDFAs still pay some penalty in noise figure.
- Linearity requirement is well met by EDFAs and EDWAs, but might be a critical issue that is to be assessed with SOA.
- All OA technologies can be designed, either for polarisation maintaining, or polarisation independent operation.
- EDFAs present best performance in terms of power consumption and wall-plug efficiency, in particular in uncooled versions.
- SOA present best performance in terms of volume.

The selection of the samples to be tested was based on these conclusions and, due to the availability of commercial devices, it was focused on types A and B.

4. TESTING OF AMPLIFIER SAMPLES

4.1 Selection of components

Taking into account the previous review and analysis of the current status of optical amplifier products, technologies and R&D trends, the intention of testing the most promising devices and devices from the main technologies, and also the limited budget, optical amplifier products were selected and proposed for procurement and further evaluation through testing.

The selection of optical amplifiers was as follows:

- +17dBm output power uncooled EDFA for intensive testing (6 units),
- +17dBm output power uncooled EDFA for comparison (1 unit),
- +24dBm output power uncooled EDFA with cladding-pumped fiber for intensive testing (6 units) ,
- +13dBm output power EDWA on glass for comparison (1 unit),
- +11dBm output power EDWA on Silica-on-Silicon for comparison (1 unit),
- +14dBm output power SOA for comparison (1 unit).

Note that the limited number of samples available implied some risks as the failure of one sample could lead to a non-completion of the entire foreseen test plan.

4.2 Test Plan

The test plan was defined considering the test related to space environmental mainly. Note that all the selected amplifiers were commercial devices not designed for space applications but with Telcordia qualification.

The following group of tests was proposed:

- Constructional analysis. One of the EDFAs with 6 devices available was used for initial constructional analysis in order to get a deep understanding of the technologies used.
- Electro-optical characterization at room, maximum and minimum operational temperature.
- Mechanical tests. Space level vibration (both sine and random) and SRS (Shock Response Spectrum) to simulate vibrations during launch and pyrotechnic shocks.
- Thermal vacuum cycling
- Radiation test. Both protons and gamma radiation campaigns.
- Final DPA (Destructive Physical Analysis)

4.3 Test results

The main results of the tests were the following:

+17dBm output power uncooled EDFA for intensive testing (6 units):

- Mechanical tests: Low degradation was observed, probably related to repeatability of the measurements.
- Thermal vacuum: No degradation.
- Proton radiation: Very little degradation.
- Gamma radiation: The test results show about 3dB optical gain degradation of each piece of Erbium-Doped Fibre used in the amplifiers, and no degradation for all other optical and electro-optical components.

+24dBm output power uncooled EDFA with cladding-pumped fiber (6 units):

- Mechanical tests: Low degradation, probably related to the variation of the geometry of the amplifier fiber which was not well fixed internally in the package.
- Thermal vacuum: No degradation.
- Proton radiation: Maximum degradation of 6 dB approximately in gain.
- Gamma radiation: Very high degradation leading to non-working samples. Fig. 6 below shows the gain spectra after gamma radiation steps of 0, 10, 20, 30, 60 and 100 Krads.

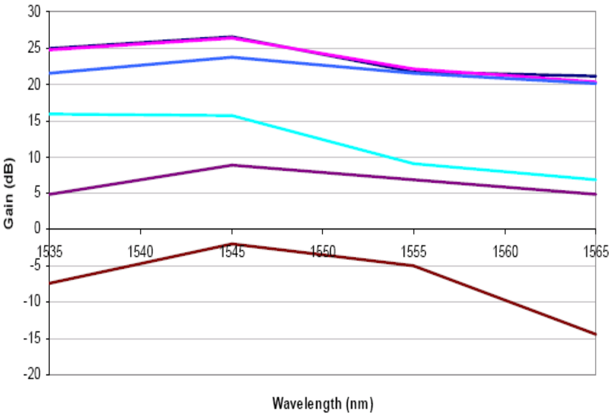


Figure 6: Gamma radiation-induced degradation of spectral gain

+17dBm output power uncooled EDFA for comparison (1 unit):

The component failed after vibration tests (only initial measurements at room, min and max temperatures had been previously performed). The internal visual inspection performed after the failure showed that the device had not been designed for supporting any mechanical tests.

+13dBm output power EDWA on glass for comparison (1 unit)

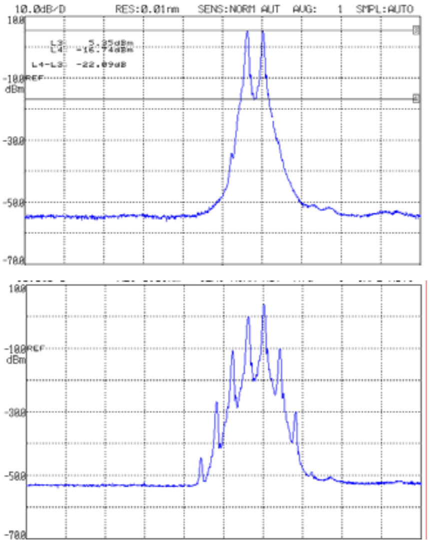
- Mechanical tests: Very low degradation of less than 1 dB in gain and noise figure.
- Thermal vacuum: Degradation of 1.4 dB in gain and no degradation in NF.
- Proton radiation: Degradation of 2.4 dB in gain and no degradation in NF.
- Gamma radiation: Degradation of around 7 dB in gain and no degradation in NF.

+11dBm output power EDWA on silicon insolator for comparison (1 unit):

Only one sample was tested and it failed during the initial measurements at 70ºC, therefore, no information about the behavior after mechanical tests, thermal vacuum or radiation has been obtained.

+14dBm output power SOA for comparison (1 unit)

The SOA was extensively tested in terms of linearity, in the RF and optical domain. As expected, the SOA does not provide fully linear amplification, and generates unwanted frequency-compounds through cross-gain saturation and Four-Wave Mixing processes. First, such frequency compounds were observed in the optical domain with LO-type signals. These non-linear effects increase as the input power increases and as the frequency separation decreases. Then, we observed non-linear effects in the RF domain with telecom-type signals. These effects increase as the optical input power increases, and as the RF signal modulation index increases. The sample was damaged at the end of these tests when higher optical power inputs were being tested. Fig. 7 shows as an example the non-linearity with 10 GHz LO-type signal at high modulation index with an optical input power of 0 dBm.



Optical spectrum at SOA input

Optical spectrum at SOA output, with Pin=0dBm

Figure 7: Non-linearity effects in SOA with a 10GHz LO signal

5. CONCLUSIONS AND PERSPECTIVES

Optical Amplifier (OA) products and technologies, including Optical fiber amplifiers (OFA), the popular EDFA (Erbium-doped Fibre Amplifier) and the Cladding-Pumped, Erbium-Doped Fibre Amplifier (CP-EDFA), Erbium-doped Waveguide Amplifiers (EDWA), and Semiconductor Optical Amplifiers (SOA), have been reviewed with respect to their capability to meet the requirements of on-board space applications.

The output optical power requirements lead to the main selection of OFAs, although devices from all the types were tested.

EDWAs may be used for medium-power amplifiers, provided that output power is substantially increased in the future, or requirements are relaxed, or if integration of multiple amplifiers or/and passive devices becomes of prime interest. Linearity requirement is well met by EDFAs and EDWAs, but was experimentally confirmed as a critical issue for SOAs.

Most of tests have concentrated on OFAs as these are the most mature and highest performance devices. Consistently, the most promising for space usage results were obtained for the EDFAs. The results obtained for the EDFAs show very good overall behaviour and resistance to the environmental constraints (mechanical and thermal vacuum), the main drawback being in the gamma radiation induced degradation of the gain.

This has prompted additional testing campaigns that will compare the behaviour under radiation of doped fibers from different suppliers in order to optimise the selection of these fibers for future space use in optical amplifiers. This will be done using the same optical amplifier unit and changing the doped fiber. Therefore not only attenuation will be measured but also the behaviour when mounted in an optical amplifier.

6. ACKNOWLEDGMENTS

The work presented in this paper has been performed in the frame of ESA ARTES-5 funded project (ESTEC contract n° 19871/06/NL/Sfe). The authors want to thank the support and collaboration of ESA during the entire project and especially to Nikos Karafolas who is the technical officer for this activities and who has contributed and given support during the entire project.

7. REFERENCES

[1] B. Bénazet, M. Sotom, M. Maignan, J. Berthon, "Optical distribution of local oscillators in future telecommunication satellite payloads", *ICSO 2004*, Toulouse, France, 2004, March 30 - April 2.

[2] Oshima, K. Nishiyama, K. Kurotori, and H. Hayakawa, "Compact Optical Fiber Amplifier", Furukawa Review, No. 23, pp. 71-75, 2003.

[3] C. Simmoneau, C. Moreau, L. Gasca, D. Bayart, "Alumino-silicate heavy-doped fibers for compact WDM-EDFAs", ECOC 2005, Vol. 4, paper Th 3.3.7, pp. 953-954, 2005.

[4] SINERGIA project. Si nanocrystals and erbium co-doped glasses for optical amplifiers. Project URL: http://www.padova.infm.it/sinergia.

[5] D. Bayart, L. Gasca, G. Gelly, "Cladding-Pumped Erbium-Doped Fiber Amplifiers for WDM Applications", Alcatel Telecommunications Review, 3rd Q 2001, pp. 179-180.

[6] A. Mori et al. "Broadband Amplification Characteristics of Tellutite-based EDFAs". ECOC-97. Proceedings of the Conference. September 1997. pg. 22-25.

[7] A. Bjarklev, J. Broeng, and A. S. Bjarklev, "Photonic crystal fibres" (Kluwer Academic Publishers, Boston, MA, 2003).

[8] M. Caussanel, O. Gilard, M. Sotom, P. Signoret and J. Gasiot, "Extrapolation of radiation induced EDFA gain degradation at space dose rate", Electronics Letters, Vol. 41, N°4, pp. 168-170, 17th Feb. 2005.

[9] Generic Reliability Assurance Requirements for Optoelectronic Devices Used In Telecommunications Equipment, Telcordia, GR-468-CORE, Issue 2, September 2004.

[10] M. Van Uffelen, S. Girard, F. Goutaland, A. Gousarov, B. Brichard, F. Berghmans, "Gamma radiation effects in Er-doped silica fibers", Proceedings of RADECS 2003: Radiation and its Effects on Components and Systems, Noordwijk, The Netherlands, 15-19 Sep. 2003.