

# Demonstration of an ultra-compact radiation-resistant high-gain EDFA pre-amplifier for long-range satellite communication

A. Osman<sup>\*a</sup>, G. Psyllakis<sup>a</sup>, I. Sourikopoulos<sup>a</sup>, T. M. Triantis<sup>b</sup> and L. Stampoulidis<sup>a</sup>

<sup>a</sup>LEO Space Photonics R&D, Lefkippos Tech. Park, 27 Neapoleos Str., Ag. Paraskevi, 15341, Athens, Greece: ao@leo-space.sprd;

<sup>b</sup>Institute of Nanoscience and Nanotechnology, NCSR Demokritos, 27 Neapoleos Str., Ag. Paraskevi, 15341, Athens, Greece.

## ABSTRACT

We report an ultra-compact two-stage erbium-doped fiber amplifier (EDFA) pre-amplifier for satellite laser communication receivers. The design combines two reduced-cladding erbium-doped fibers (RC-EDFs), 980-nm pumping, pump/signal combining and isolation functions and delivers >40 dB small signal gain and ~5 dB noise figure (NF). The radiation response of the two RC-EDFs was assessed by passive gamma irradiation to total ionizing doses of 20, 60 and 100 krad at 4.83 krad/h, followed by amplifier-level characterization. The measurements show sub-1 dB radiation-induced gain degradation at 20 krad and progressive increase up to ~8 dB at 100 krad. Pump current margin provides effective recovery: in a dedicated compensation measurement at 20 krad, an increase of pump current by 20% compensated the radiation induced degradation whereas at 100 krad increasing the pump operating point by 60% reduced the gain drop from 8.18 to 3.05 dB. Finally, the complete two-stage architecture was integrated into a  $42 \times 30 \times 15$  mm engineering model with a mass < 35 g. The packaged amplifier retained > 40 dB gain and approximately 5 dB NF, demonstrating the feasibility of compact, radiation-tolerant optical pre-amplification for inter-satellite and optical feeder links.

Keywords: erbium-doped fiber amplifier, EDFA, optical pre-amplifier, satellite laser communications, reduced-cladding fiber, radiation-induced attenuation, optical feeder link, inter-satellite link

## 1. INTRODUCTION

Optical pre-amplification with erbium-doped fiber amplifiers (EDFAs) is an effective approach for improving receiver sensitivity in long-range optical inter-satellite links (OISLs) and optical feeder links (OFLs). By amplifying a weak received signal before photodetection, an EDFA can increase the optical power presented to the receiver and relax the required link margin. Unlike booster amplifiers, which are primarily optimized for saturated output power, receiver pre-amplifiers operate in the small-signal regime and must provide high gain with low added noise. Two-stage architectures are therefore attractive, but the required pump lasers, wavelength-division multiplexers (WDMs), isolators and lengths of erbium-doped fiber challenge the reduction of size, mass and power (SWaP).

Miniaturization of optical amplifiers and laser communication terminals has received increasing attention for small satellites and highly integrated payloads [1]-[6]. A state-of-the-art, small form factor space pre-amplifier [6] occupies a 110 mm x 70 mm footprint and weighs < 250 g. Reduced-cladding erbium-doped fibers (RC-EDFs) are attractive for further size and weight reduction. For space deployment compact packaging has to be accommodated with radiation resistance. Ionizing radiation generates defects in the silica host that increase attenuation at the pump and signal wavelengths and can reduce gain and degrade noise performance [7]-[10]. The magnitude of the effect depends on glass composition, dopant concentration, irradiation conditions and accumulated total ionizing dose (TID), making fiber-specific characterization essential.

In previous work, we evaluated reduced-cladding EDFs and used them to realize an ultra-compact 20-dBm booster EDFA for space laser communication terminals [11], [12]. A receiver pre-amplifier poses a different design problem: substantially higher small-signal gain is required and the additional optical components of a multi-stage amplifier must still fit within a severely constrained package.

This paper extends that work to a high-gain two-stage EDFA pre-amplifier. The main contribution is twofold. First, we demonstrate bread-board level, radiation evaluation of RC-EDFs in a pre-amplifier configuration at 20, 60 and 100 krad

to quantify radiation-induced gain (RIGD) and NF degradation as well as pump-power compensation. Secondly, the complete optical architecture is integrated into a  $42 \times 30 \times 15$  mm engineering model (EM) with a mass below 35 g. The packaged EDFA delivers  $> 40$  dB of small signal gain at  $\sim 5$  dB NF and with sufficient pump current head room to compensate radiation and lifetime effects.

## 2. EDFA PRE-AMPLIFIER ARCHITECTURE

Figure 1 shows the two-stage optical architecture. Pump/signal WDM functions and optical isolation are distributed at the input, inter-stage and output interfaces. Both stages employ highly absorbing RC-EDFs, enabling the required gain to be obtained with short active-fiber lengths. This is particularly advantageous for a spaceborne pre-amplifier, as it facilitates compact packaging while limiting the accumulated impact of radiation-induced attenuation. The high erbium concentration required to achieve such strong pump absorption, introduces a trade-off with noise performance. Concentration-dependent ion-ion interactions can reduce population-inversion efficiency and make a low noise figure more difficult to achieve, particularly in the first stage under weak-signal operation. As such the fiber lengths and pump configuration were selected to balance high small-signal gain and NF performance.

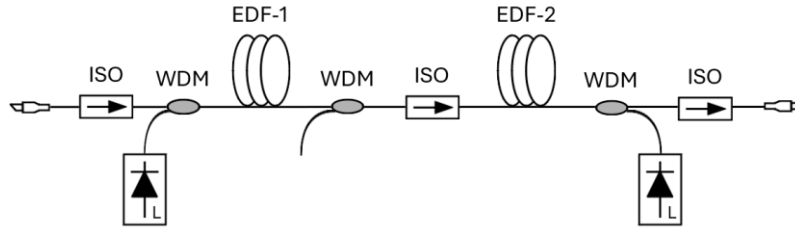


Figure 1. Schematic architecture of the two-stage EDFA pre-amplifier.

## 3. RC ERBIUM DOPED FIBER RADIATION EVALUATION

### 3.1 Pre-irradiation characterization

A two-stage EDFA breadboard was assembled according to Fig. 1 and characterized prior to irradiation. The optical spectra at the amplifier input and output were measured using an optical spectrum analyzer (OSA). Figure 2 shows representative pre-irradiation optical power and signal spectra for an input power of  $-30$  dBm, with the signal wavelength stepped across the C-band. The narrow spectral peaks correspond to the amplified input signal, superimposed on the amplified spontaneous-emission (ASE) background. At 1550 nm, the breadboard provides approximately 45 dB gain with a noise figure of about 5 dB, establishing the reference operating point for the subsequent radiation assessment. This performance was obtained with pump currents of 240 mA and 600 mA for the first and second stages, respectively. Since both pump lasers are rated for a maximum drive current of 1000 mA, substantial pump-current headroom remains available to compensate for radiation-induced degradation and potential performance loss over the operational lifetime.

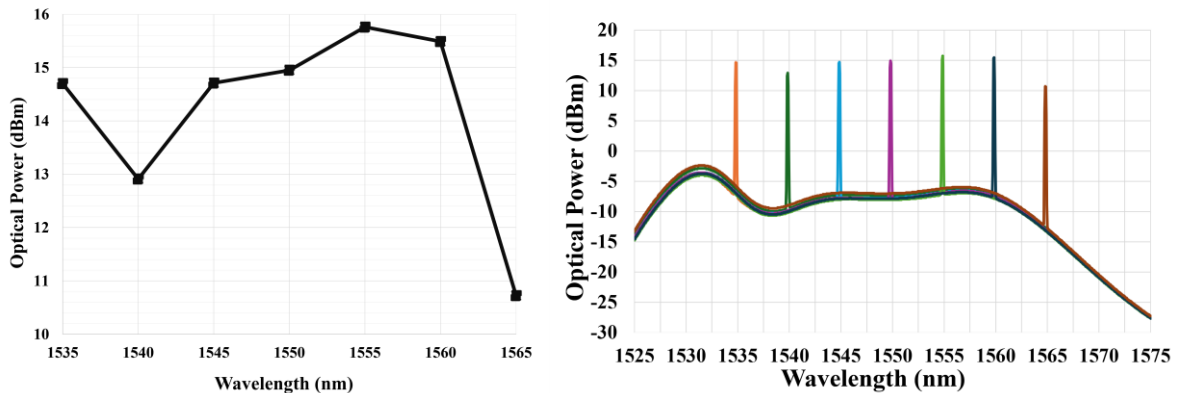


Figure 2. Measured pre-irradiation output power (left) and signal spectra (right) of the two-stage EDFA for a  $-30$  dBm input. Seven single-wavelength measurements are superimposed, with the input wavelength stepped from 1535 to 1565 nm in 5-nm increments.

**Table 1: Pre-irradiation Gain and NF as a function of input signal wavelength**

| Wavelength (nm) | Gain at -30 dBm input (dB) | Noise Figure (dB) |
|-----------------|----------------------------|-------------------|
| 1535            | 44.99                      | 5.39              |
| 1540            | 42.94                      | 5.44              |
| 1545            | 44.74                      | 5.29              |
| 1550            | 44.93                      | 5.14              |
| 1555            | 45.86                      | 4.9               |
| 1560            | 45.38                      | 4.87              |
| 1565            | 40.63                      | 4.96              |

### 3.2 Gamma radiation testing

The radiation response of the two RC-EDFs was evaluated by passive gamma irradiation to accumulated TID levels of 20, 60 and 100 krad at a dose rate of 4.83 krad/h. The fibers were not optically pumped during irradiation. After each dose step, the irradiated fibers were spliced in the same two-stage breadboard and characterized using the pre-irradiation measurement procedure. This approach isolates the contribution of the active fibers to the amplifier degradation since pump lasers, WDM couplers and isolators are not irradiated.

Radiation-induced gain degradation (RIGD) was determined relative to the corresponding pre-irradiation reference. At 20 krad the output power penalty was 0.78 dB and the amplifier delivers a small signal gain of 44.15 dB at 1550 nm. Figure 3 (left) shows the progressive reduction in output power as the TID increases as a function of signal wavelength. At the reference wavelength of 1550 nm, the penalty increases to 3.24 dB at 60 krad and 8.18 dB at 100 krad. The corresponding small signal gain is 41.68 dB and 36.73 dB at 60 and 100 krad respectively. Figure 3 (right) shows the NF evolution as a function of TID. The measured NF degradation remains below 0.15 dB at 20 krad and increases to 0.79 dB at 60 krad and 2.24 dB at 100 krad. At 1550 nm the NF is 5.27 dB at 20 krad, increasing to 5.93 dB at 60 krad and 7.38 dB at 100 krad TID.

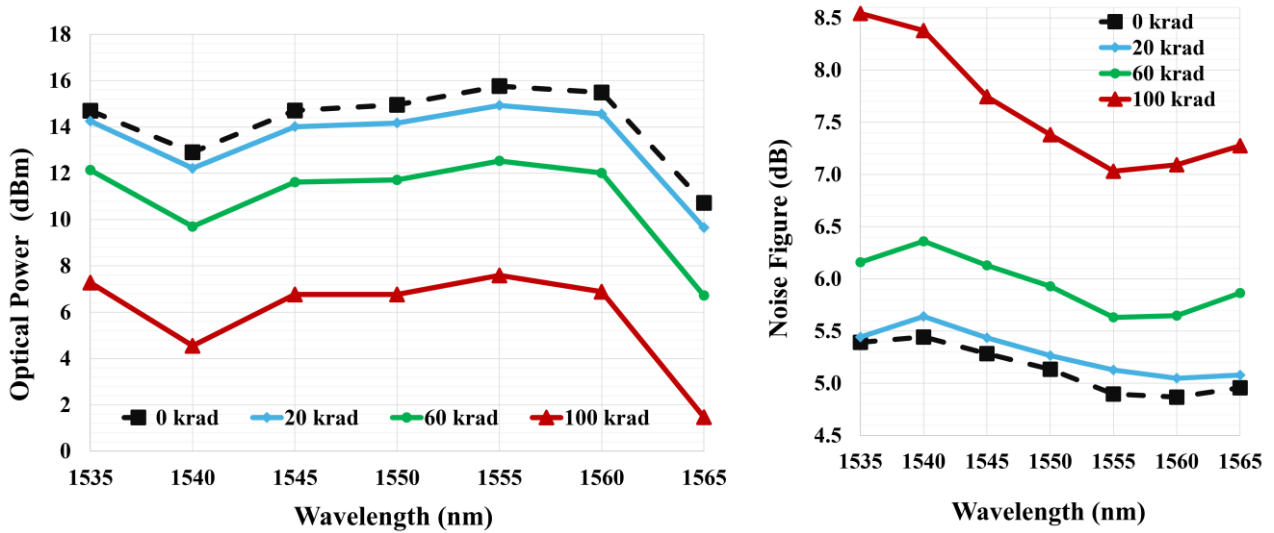


Figure 3. Pre and post 20, 60 and 100 krad TID radiation measurements: (left) EDFA output power and (right) NF.

### 3.3 Pump power compensation

Pump current margin was investigated as an active means of compensating radiation-induced degradations. As a reference, the pump lasers exhibit a maximum operating current of 1000 mA. The amplifier was characterized at the nominal pump current setting, i.e. 240 mA and 600 mA for the first and second stage pump respectively and at 10%, 20%, 40% and 60% increases above that operating point after the 20, 60 and 100 krad irradiation steps. As shown in Figure 4 (left) Increasing the pump current reduces the output optical power penalty at all investigated doses. At 20 krad, a 20% pump current increase is sufficient to fully compensate the RIGD and further pump current injection increases the output optical beyond its nominal value. At 60 krad, the drop is suppressed from 3.24 dB at nominal pump current to 0.39 dB at +60% pump current, corresponding to 2.85 dB recovery. At 100 krad and 60% pump current increase, the drop decreases from 8.18 to 3.05 dB, corresponding to 5.13 dB recovery.

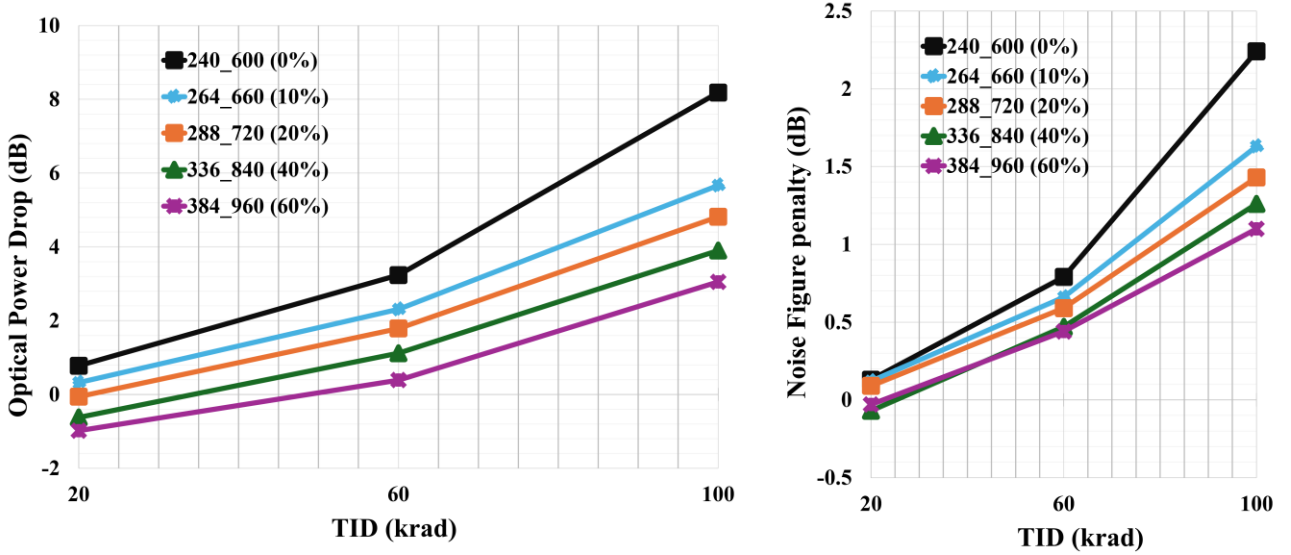


Figure 4. Effect of increased pump current operating point on radiation-induced gain degradation and noise figure at 1550 nm signal wavelength after 20, 60 and 100 krad TID. Results are shown for nominal pump current of 240-600 mA (0%), 264-660 mA (10% increase), 288-720 mA (20% increase), 336-840 mA (40% increase) and 384-960 mA (60% increase).

The radiation-induced NF penalty improves simultaneously as the pump operating point is increased. In the compensation data set shown in Figure 4 (right), the radiation-induced NF penalty of 0.13 dB at 20 krad is fully compensated with a 40% pump current increase. At 60 krad, the NF penalty is suppressed from 0.79 dB to 0.44 dB with +40% pump current increase. At 100 krad a +60% pump current increase leaves an uncompensated penalty of 1.1 dB from the initial 2.24 dB. Thus, pump current margin does not merely restore output level; it also reduces the radiation-induced NF penalty.

## 4. ENGINEERING MODEL ASSEMBLY, INTEGRATION AND TEST

Following breadboard validation, the complete two-stage optical architecture was assembled into a compact Engineering model (EM) EDFA. Figure 5 (left) shows the mechanical design which is the same as the one previously used to package a booster amplifier [12] verifying the design agility to host different amplifier types. The package measures  $42 \times 30 \times 15$  mm and has a mass below 35 g. Figure 5 (right) shows the assembled unit. It contains both RC-EDFs, the two 980-nm pump lasers, the WDM couplers and isolators and features a hi-rel micro-D connector as the electrical interface. The EM-EDFA was characterized from 1535 to 1565 nm with pump currents of 240 – 800 mA. Figure 6 (left) shows the measured output power for input powers of -35 to -20 dBm with a step of 5 dB. At 1550 nm, the plotted output powers correspond to approximate gains of 37.2, 39.55, 41.15 and 41.67 dB for input powers of -20, -25, -30 and -35 dBm, respectively. The increase in gain toward the weaker-input conditions is consistent with operation closer to the small-signal regime.

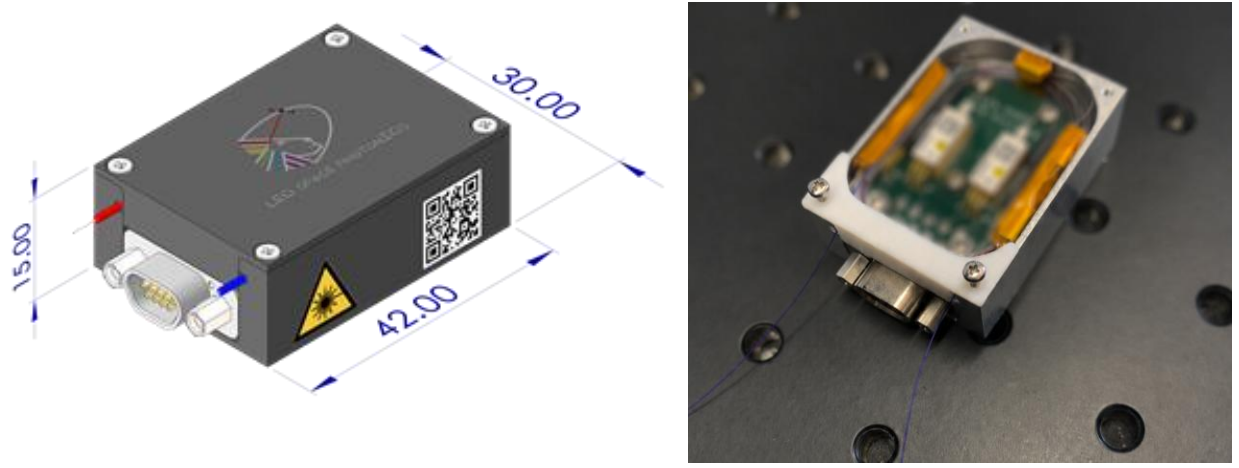


Figure 5. EDFA pre-amplifier engineering model; (left) CAD model, (right) assembled unit

Figure 6 (right) shows the corresponding optical output spectra captured at -30 dBm input power. For all investigated wavelengths, the amplified signal remains clearly above the local ASE background, demonstrating a substantial signal-to-ASE spectral contrast under -30 dBm input conditions. At -20 dBm input power the EM-EDFA NF ranges from 5.53 dB at 1535 nm to 4.68 dB at 1565 nm with 5.11 dB measured at 1550 nm.

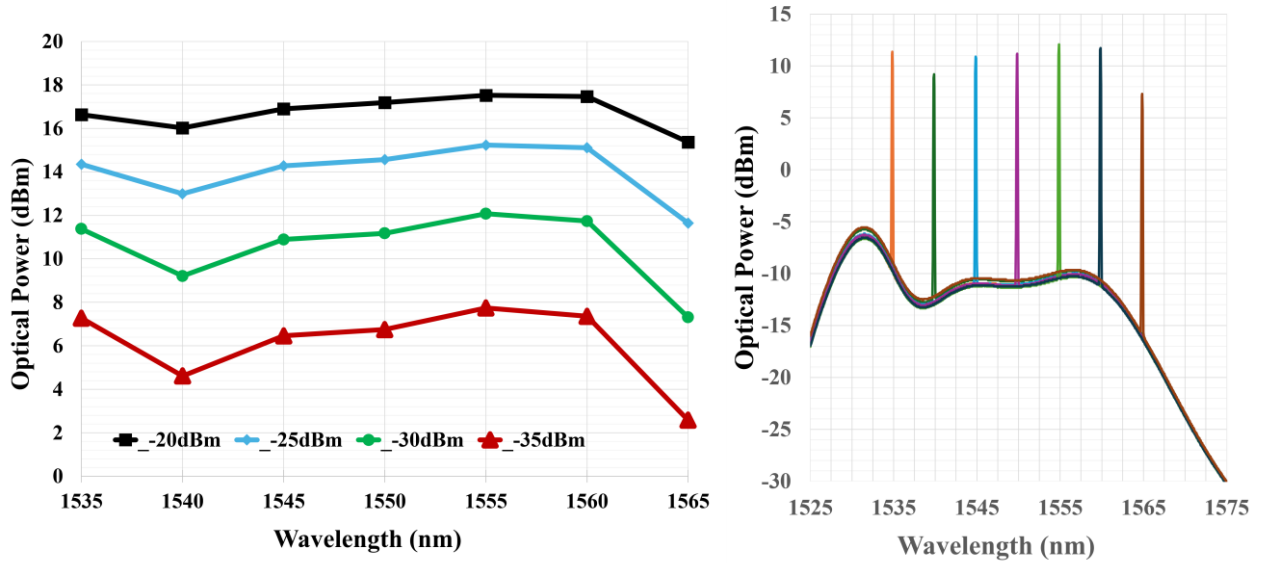


Figure 6. Measured performance of the packaged EDFA engineering model: (left) output power as a function of signal wavelength for input powers from -20 to -35 dBm; (right) superimposed single-wavelength output spectra for a -30 dBm input signal.

## 5. CONCLUSIONS

An ultra-compact two-stage EDFA has been developed for satellite laser communication pre-amplified receivers. The EDFA architecture combines two different reduced-cladding EDFs with forward and backward 980-nm pumping. Passive gamma irradiation of the RC-EDFs resulted in limited gain degradation of 0.78 dB and negligible NF degradation at 20 krad, with both penalties increasing at higher accumulated doses. A dedicated pump current sweep demonstrated that operational pump head-room can recover a substantial fraction of both penalties. The complete two-stage optical architecture was subsequently integrated into a  $42 \times 30 \times 15$  mm, < 35 g EM and retained high gain with approximately 5 dB NF. The work demonstrates the suitability of reduced-cladding EDFs for EDFA miniaturization and establishes pump current head room as a practical mechanism for managing accumulated fiber radiation effects. Future

work should extend the assessment of addition RC-EDF fibers and environmental evaluation of the complete packaged amplifier.

## REFERENCES

- [1] A. Carrasco-Casado et al., "Development and environmental validation of a compact EDFA with integrated LNA + HPA for satellite optical communications," *Front. Phys.* 13, 1542043 (2025).
- [2] P. Martin-Pimentel et al., "Cube laser communication terminal (CubeLCT) state of the art," *Acta Astronaut.* 211, 326-332 (2023).
- [3] A. Carrasco-Casado et al., "Development and space-qualification of a miniaturized CubeSat's 2-W EDFA for space laser communications," *Electronics* 11, 2468 (2022).
- [4] A. Carrasco-Casado et al., "Optical communication on CubeSats - enabling the next era in space science," *Proc. 2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS)* (2017).
- [5] MPB Communications, "EOA-M ruggedized erbium-doped optical amplifier," product information, <https://www.mpbcommunications.com/telecom-products/ea-m-ruggedized>.
- [6] Exail, "Low-noise optical amplifiers," product information, <https://www.exail.com/product/low-noise-optical-amplifiers-photonics>.
- [7] T. S. Rose, D. Gunn, and G. C. Valley, "Gamma and proton radiation effects in erbium-doped fiber amplifiers: active and passive measurements," *J. Lightwave Technol.* 19(12), 1918 (2001).
- [8] S. Girard et al., "Radiation effects on silica-based optical fibers: recent advances and future challenges," *IEEE Trans. Nucl. Sci.* 60(3), 2015-2036 (2013).
- [9] G. M. Williams and E. J. Friebele, "Space radiation effects on erbium-doped fiber devices: sources, amplifiers, and passive measurements," *Proc. RADECS 97, Fourth European Conference on Radiation and its Effects on Components and Systems* (1997).
- [10] D. L. Griscom, M. E. Gingerich, and E. J. Friebele, "Radiation-induced defects in glasses: origin of power-law dependence of concentration on dose," *Phys. Rev. Lett.* 71(7), 1019 (1993).
- [11] G. Psyllakis et al., "Miniaturized, radiation-resistant booster EDFA for compact CubeSat lasercom terminals," *Proc. SPIE 13355, Free-Space Laser Communications XXXVII* (2025).
- [12] A. Osman et al., "Gamma radiation testing of reduced-clad erbium-doped fibers and demonstration of an ultra-compact EDFA for satellite laser communications," *Proc. 2025 IEEE International Conference on Space Optical Systems and Applications (ICSOS)* (2025).