

Nonlinear Optical Effects in Ultra High Power Amplifiers: analysis, possible mitigations and impact on the FSO system design

E. Ciaramella^{*a}, G. Cossu^a

^a Scuola Superiore Sant'Anna, Via G. Moruzzi, 1, Pisa, Italy

ABSTRACT

High-speed Free Space Optics (FSO) communications for intersatellite and feeder (Earth-satellite) links will suffer from high power losses, especially in uplink where diffraction combines with beam wandering and scintillation effects. To guarantee proper link margins, much higher power levels than those in terrestrial links are required, e.g. up to 100 W. The fact that free-space has a negligible nonlinear coefficient suggests that nonlinear effects can be neglected in FSO: however, due to short pieces of fiber, nonlinear impairment was observed in ultra-high power amplifiers and will be relevant in FSO communications. Indeed, an optical booster amplifier having very high optical output power can produce nonlinear effects in the active fiber and, most importantly, it should be connected to the transmitting telescope by a short fiber. We critically review and characterize the impact of the nonlinear fiber effects, by means of numerical simulations considering both Nx10 Gbit/s IM-DD and Nx100 Gbit/s DP-QPSK signals. The obtained results clearly indicate that, in these conditions, the nonlinear effects appear, because the huge power values compensate for the small lengths of the involved fibers. We investigate the impairments in various system conditions by means of numerical simulations, showing the relative importance of the various nonlinear effects: among them, the most relevant impairments are due to Four Wave Mixing (FWM). Actually, IM-DD signals are only affected by FWM, which can partly be mitigated by alternate polarization of the signals and, possibly, unequal channel spacing (UCS) when the number of channels is not very high. On the other side, DP-QPSK signals are also strongly affected by FWM; however, even using UCS, it is found that they are also affected by Cross Phase Modulation (XPM) and Cross Polarization Modulation (XPoM). Building on this, we present a general framework to describe the effects in terms of all amplifier parameters. We finally provide few examples of system design and power budget in typical conditions, highlighting the consequences of nonlinear effects on the total acceptable loss, i.e. the total power budget. These findings can be used as a guideline to control this type of impairment in high-power FSO systems for satellite links or to design alternative types of optical amplifiers.

Keywords: nonlinear optical effects, free-space communications, satellite communications, nonlinear optical amplifiers

1. INTRODUCTION

Future space communications will largely rely on Free Space Optics (FSO), in order to implement high capacity links that could also realize the seamless extension of fiber networks realizing a 3D network [1]-[4]. In this scenario, three types of optical links should be deployed: intersatellite, satellite-to-ground (downlink) and ground-to-satellite (uplink). Today, intersatellite FSO links are operating in private constellations [5] and high-speed FSO downlinks from satellite are currently demonstrated [6]. Conversely, optical uplinks have the lowest maturity level, as atmospheric propagation introduces severe degradations, which ask for more complex developments (e.g. pre-compensation of turbulence effects), and inherently higher power losses [3].

A key common element of these links is their high total link losses; although optical Gaussian beams spread much less than RF signals, high-speed data transmission requires higher receiver sensitivity. Thus, the design of high speed FSO links includes a power budget where the total free space loss can be very high and, moreover, it combines with margins [7] that must be allocated to cope with the statistical effects (scintillation, beam wander and pointing errors) [3].

*: e.ciaramella@santannapisa.it; phone:+39 050 882156, www.santannapisa.it

Therefore, in the design of many links, the power budget calculations clearly indicate the need for high power transmitters [7]-[9]. Since this can only be achieved by means of ultra high-power optical amplifiers (UHPOAs), the development of these UHPOAs is now being actively pursued for space applications [10]. Of course, based on the loss estimations, the highest power values are required in uplink [7]; in those cases, UHPOAs should be deployed at the optical ground station (OGS), where the expected practical issues (power consumption, space, cooling etc.) can be managed with acceptable difficulty. Noteworthy, such huge power values (100 W and beyond [8]) are never needed in the fiber communications, mostly because of the nonlinear effects in traditional fibers. Indeed, the maximum output power of commercial C-band amplifiers is typically limited to few watts. This technology gap has driven research towards the realization of dedicated UHPOA for space FSO [11]-[13], to reach 100 W output power, as a minimum. To this aim, various design solutions were recently demonstrated that achieve very high output power, e.g., 50 W in [13] and [14], 40 W in [15].

However, these UHPOAs were initially proposed assuming that FSO links are immune to nonlinear effects (NLEs). Unfortunately, although the largest portion of the FSO signal path is in free-space, the system design studies should still carefully consider the nonlinear impairments related to the UHPOA: it is known that NLEs can take place inside the amplifier itself, either in the active fiber and in short pigtailed of the passive components (e.g. isolators) [15]. Moreover, NLEs can also arise immediately after the UHPOA, because this should be connected to the transmitter telescope by a dedicated delivery fiber [11]. The occurrence of NLEs was observed experimentally in the first UHPOA realizations [13]-[15].

Recently, our numerical simulations demonstrated that Four Wave Mixing (FWM) severely degrades 10x10 Gbit/s WDM IM-DD systems: as these impairments limit the total available power at the transmitter (P_{out}), they constrain the available power budget [16]. It was also shown that alternate state of polarization (SoP) among the channels can help reduce the impact. Alternative modulation formats are proposed for FSO in space; among them, the most promising alternative to IM-DD is the Dual Polarization Quadrature Phase Shift Keying (DP-QPSK) with coherent detection and digital signal processing (DSP): first introduced in fiber networks around 20 years ago [17], [18], DP-QPSK is now considered for feeder links to/from LEO and GEO satellites [1], and was recently tested by NASA in downlink transmission [19]. This interest is driven by commercial DP-QPSK transceivers that typically have better sensitivity in terms of photons/bit at input of the optical preamplifier, thanks to the combined effect of the modulation format and enhanced Forward Error Correction (FEC).

In this paper, we investigate and compare the nonlinear impairments affecting WDM IM-DD and DP-QPSK signals propagating in the delivery fiber, i.e., a short fiber placed just after the UHPOA [11]; following the methodology introduced in [16], we focus on the delivery fiber while providing a framework to extend these results to nonlinearities occurring within the UHPOA itself or its connecting pigtailed. We first analyze the case of 4 channels, then extend it to higher number of channels. The results allow, for the first time, to obtain a benchmark between the two types of system.

2. MODEL

We note that NLEs can take place within the UHPOA itself, either in the active fiber and in short pigtailed of the passive components (e.g. isolators) [15], as well as in the delivery fiber that connects the UHPOA to the transmitter telescope [10]. To quantify this impairment, we define the nonlinear phase shift Φ , by extending the definition used in optical fibers:

$$\Phi = \sum_{i=1}^M \gamma_i \int_0^L P_{in}^i e^{G_i z} dz + \gamma_f P_{out} L_f \quad (1)$$

where the index i runs over the different M sections of UHPOA, each characterized by a given nonlinear coefficient γ_i , an input power P_i , and constant gain coefficient G_i . The last term accounts for the delivery fiber, which has no gain, assuming negligible losses) and it is characterized by a nonlinear coefficient γ_f and a length L_f . Noteworthy, NLEs depend on many implementation details, such as the number and characteristics of the M sections. However, for the sake of simplicity, we can see that, in the usual conditions, the last term of the sum ($i=M$) is largely higher than all the preceding others. By simple algebraic manipulations, we can thus write

$$\Phi \cong \gamma_M P_{out} / G_M + \gamma_f P_{out} L_f \quad (2)$$

As said, in the following, we will consider NLEs in the delivery fiber only, characterized by a fixed nonlinear coefficient γ_f and length L_f at given P_{out} . It can be simply seen that, whenever the first contribution in Eq. 2 is not negligible, all results should be rescaled

$$L_{eq} \cong L_f + \gamma_M / (\gamma_f G_M) \quad (3).$$

We highlight that, in all cases, the value of L_{eq} (few meters) is expected to be much lower than the effective length L_{eff} typical of terrestrial optical fibers. However, this is effectively counter-balanced by the huge power levels [11]. As an example, in standard fiber links, the role of nonlinear effects is typically estimated by the product PL_{eff} , where P is the launch power and L_{eff} includes the effect of fiber attenuation (L_{eff} is usually around 20 km). In our case, L_{eq} is so short (few meters) that the attenuation can be neglected, and then we can simply use the value of PL_{eq} . This product value can be comparable to those found in terrestrial links. Indeed, if we assume $P=200$ W, and $L_{eq}=3$ m, the above figure is close to the one that we get in a fiber link with 30 mW input power and $L_{eff}=20$ km.

Moreover, these extremely short fiber lengths produce a key difference from terrestrial links, i.e., all the dispersion effects are negligible. Indeed, the well-known quantities, usually referred as walk-off length [20] and phase matching length [20], would be much longer than the fiber length itself. Thus, we expect various significant issues due to Cross-Phase Modulation (XPM), Cross-Polarization Modulation (XPoM) and Four Wave Mixing (FWM) [20]. Self-Phase Modulation (SPM) could also take place, but we expect to see more significant multi-channel NLEs, i.e. those due to the propagation of WDM channels, as in common terrestrial fiber links.

We highlight that, in all the previous cases, the length of the involved fiber L (few meters) is much lower than the effective length L_{eff} in terrestrial optical fibers; however, this is effectively counter-balanced by the huge power levels [11]. As an example, in a fiber link the role of nonlinear effects is typically estimated by the product PL_{eff} , where P is the total transmitter power and L_{eff} includes the effect of fiber attenuation (L_{eff} is around 20 km, i.e. much shorter than the link itself). In our case, L is so short (few meters) that we can neglect loss, and then simply use the value of PL : this can be of the same order of magnitude as in terrestrial links. Indeed, if we assume $P=200$ W, and $L=3$ m, the above figure is close to the one that we get in a fiber link with 30 mW input power and $L_{eff}=20$ km.

Finally, this paper concerns only NLEs of Kerr type. As known, other nonlinear effects can take place in the optical fibers., namely, Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS) [20]: simple calculations indicate that neither SBS nor SRS are an issue at the power levels indicated in the following sections for IM-DD and DP-QPSK, respectively.

3. METHODOLOGY OF NUMERICAL SIMULATIONS

In the following, we simulate the nonlinear propagation over a common single-mode delivery fiber (SMF) of 3 m length, having nonlinear coefficient $\gamma=1.3$ (W km)⁻¹ (average polarization).

We used a home-made tool to extensively investigate the impact of NLEs on the transmission performance in two types of WDM FSO systems aligned with ESTOL specifications: $N_{ch} \times 10$ Gbit/s IM-DD and $N_{ch} \times 100$ Gbit/s DP-QPSK [21]. The first type of system has direct detection and a FEC threshold of around 10^{-3} , whereas the second system implements coherent detection with digital signal processing and a more performing FEC, with a threshold of around 10^{-2} [22].

The system design of each WDM-FSO links follows the schematics given in . Every WDM channel is generated by modulating an independent bit/symbol sequence. Each channel is then randomly time-shifted and WDM-multiplexed (MUX) with the others. They can be allocated with equal channel spacing (ECS) or unequal channel spacing (UCS). For the sake of generality, we consider a grid with channel spacing ($\Delta\nu$) of 100 GHz, although it was shown that the effects do not depend on absolute frequency separation [16]. We assume that the total output power of the UHPOA (P_{out}) is equally distributed over the N_{ch} channels, which means that the amplifier, in its operation, has negligible gain tilt.

In the delivery fiber, the nonlinear propagation is modeled using the coupled Schoedinger equations for the two circular polarization components [16]. All propagation effects are considered as a variable loss, which include FSO path loss, all margins for statistical effects, and coupling loss. The system performance can be determined by the power at the input of

a low-noise amplifier (LNA), or, equivalently, by the optical signal to noise ratio (OSNR) at its output (see Figure 1). LNA is assumed to have a noise figure of 4 dB and flat gain. The signals are then demultiplexed (DEMUX) and each is received by a receiver (RX) implementing the usual detection scheme for the corresponding format.

By directly comparing the transmitted and received bit sequences, we estimate the bit error rate (BER) before FEC, provided that a properly high number of bits is transmitted. The OSNR sensitivity is obtained as the OSNR value where each format has the pre-FEC BER equal to the FEC threshold. Variation of the sensitivity, due to NLEs, is indicated as penalty. As a common first step, for each format, we consider a four-channel system.

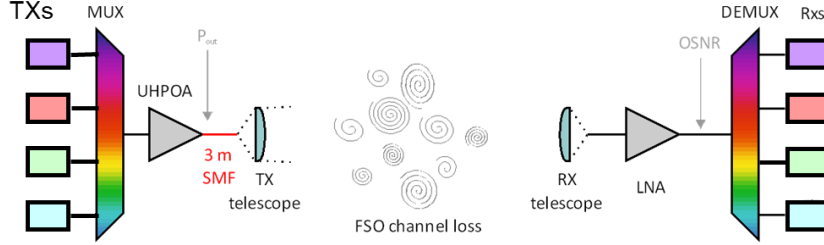


Figure 1. Schematic of the WDM-FSO link. The signals are wavelength-multiplexed (MUX), then they pass through an ultra-high power optical amplifier (UHPOA) with P_{out} output power. They then travel through a 3-m delivery fiber and are coupled to free-space by the TX telescope. At the RX, the signals are amplified by a Low Noise Amplifier (LNA), demultiplexed (DEMUX), and finally each of them is detected by an RX.

4. RESULTS

4.1 WDM IM-DD links

The system design of IM-DD links is performed in two steps. First, we analyze the performance of a 4-channel WDM system, assuming parallel polarization (the worst-case for NLEs) and equal channel spacing. Under these conditions, it is apparent that FWM can strongly affect the signal quality, as illustrated by the eye diagrams of the central channel in a 4x10 Gbit/s IM-DD system, operating at total power $P_{out}=1$ W (a) and 50 W (b) in . We can see the clear degradation of the signal, which reduces the benefits of the increased power.

As indicated in [16], we can reduce the impact of FWM using alternate SoPs, i.e., using adjacent (odd and even) channels with orthogonal polarizations. Figure 3(a) compares the penalty curves for parallel SoPs (red dots) and alternate SoPs (blue triangles) in a 4-channel system, as a function of total power P_{out} . Although alternating SoPs improve the system performance, higher-order FWM terms still impact the system quality.

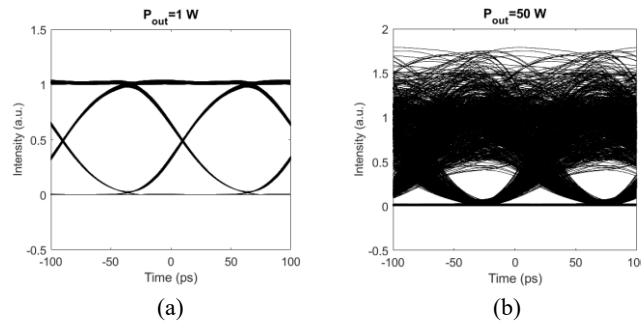


Figure 2. Eye diagrams of IM-DD 4x10 Gbit/s with parallel polarization and equal channel spacing, for total power $P_{out}=1$ and 50 W, respectively.

From these results, we derived the corresponding power budget, i.e. the maximum loss acceptable between TX output and LNA input. This is illustrated in Figure 3(b): to have a clear comparison, we report the power budget as function of the single-channel power (P_{ch}). In the worst case, the best power is around 37 dBm per channel (5W); yet even in the most favorable condition, the optimal power shifts to around 43 dBm per channel (20 W). The maximum power budget levels in the two cases are around 82 and 87 dB, respectively.

As a final step, we extend these results to an arbitrary number of channels (N_{ch}), operating a fixed power of 5W per channel, assuming only the best case, i.e. alternate SoPs. Figure 4 illustrates the estimated OSNR penalty, for a number of channels from 4 to 18. Although a single-channel power of 5 W can be considered safe in the 4-channel system, we clearly see that increasing the number of channels N_{ch} worsens nonlinear degradations, quickly increasing the penalty due to NLEs.

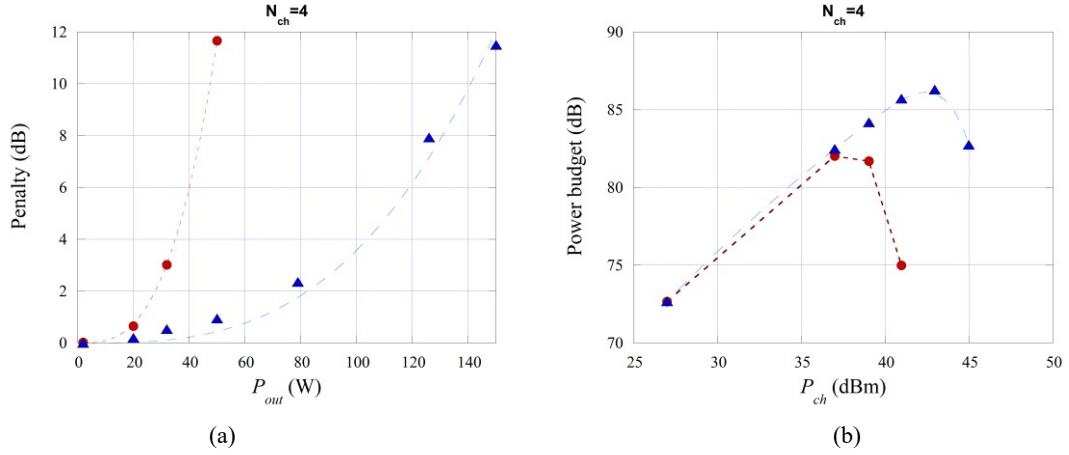


Figure 3. (a) OSNR penalty vs P_{out} in case of parallel (red dots) and alternate polarizations (blue triangles) in IM-DD 4x10 Gbit/s. (b) The corresponding power budget curves are reported as function of power/channel P_{ch} .

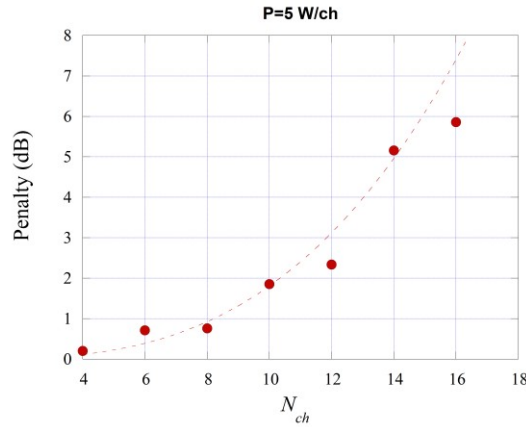


Figure 4. OSNR penalty vs N_{ch} in IM-DD N_{ch} x 10 Gbit/s FSO system, assuming alternate polarizations and fixed power/channel $P_{ch} = 5$ W

3.2 WDM DP-QPSK links

The system study of DP-QPSK links is also done in two steps. First, we investigate a 4-channel system, under both worst-case and best-case conditions. Noteworthy, here there is no possibility to manage the SoP of the channels, since they are made of two orthogonal SoPs, which eventually produce a continuously varying SoP.

We initially considered four channels with ECS. Again, we find that FWM can strongly affect the signal quality. This degradation is shown by the constellation diagrams of the one central channel in a 4x10 Gbit/s DP-QPSK for total power $P_{out}=2$ W (a) and 100 W (b) in Figure 5, under a fixed OSNR=15 dB.

To mitigate FWM, we evaluate UCS as potential countermeasure [23]. Figure 6(a) reports BER curves for linear condition, 100 W total power with ECS and UCS. It clearly indicates that DP-QPSK can benefit from UCS, although the improvement does not completely remove the NLE impairments. This is attributed to existence of XPM and XPolM, which can affect the specific DP-QPSK format, even if FWM is largely reduced. As shown in Figure 6(b), where we see that using UCS allows to increase the total power by around 2 dB, at fixed penalty value.

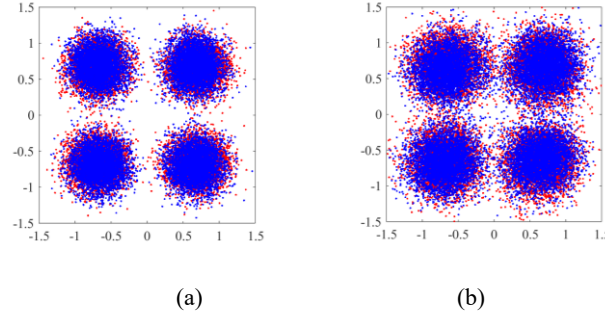


Figure 5. Constellation of the central channel in 4x100 Gbit/s with equal channel spacing (ECS); blue and red points indicate to the two PM-channels. Results are obtained for OSNR=15 dB and $P_{out}=10$ W, linear regime, (a) and 100 W (b).

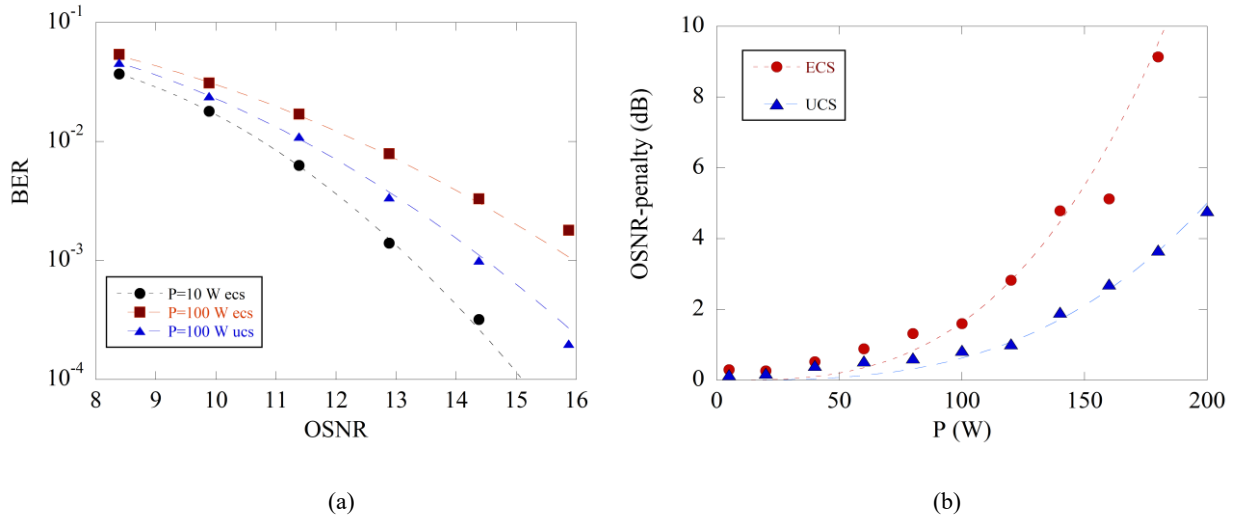


Figure 6. BER curves for 10 W, 100 W ECS and 100 W USC (a); OSNR penalty (at pre-FEC level of 10^{-2}) vs total output power of the UHOPA (b).

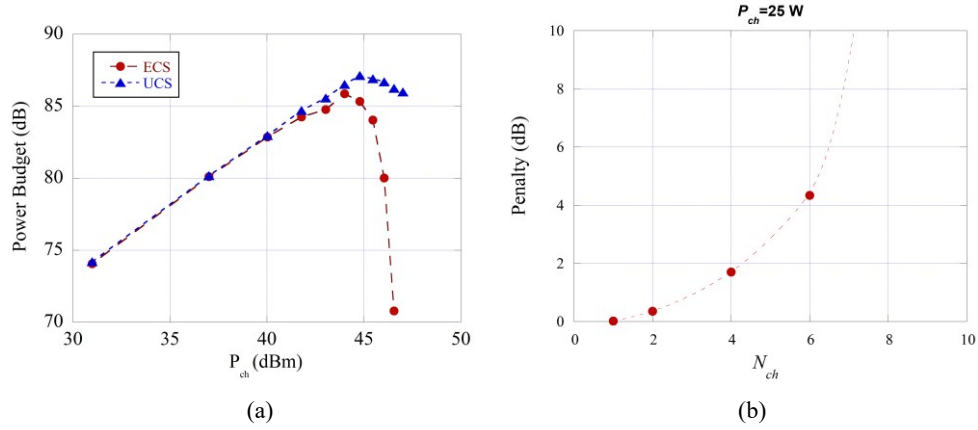


Figure 7. Power budget curves for 4x100 Gbit/s DP-QPSK system, reported as function of P_{ch} . (a), and penalty as function of number of channels N_{ch} (b), with $P_{ch}=25$ W.

From above results, we then estimated the power budget as function of P_{ch} , which is presented in Figure 7 (a), for ECS and UCS. When compared to Figure 4 b, these curves reveal that Kerr effects have much lower impact than in IM-DD. There are various explanations: first, NLEs are influenced by the peak power, which in IM-DD systems is around +100% higher than the average power. Second, DP-QPSK benefits from a more powerful FEC, which allows to accept a higher level of NLE impairments. Finally, it may be that the tolerance to FWM in DP-QPSK signals are different than in IM-DD, thanks to the different detection scheme. On the other side, adopting UCS yields a modest power budget increase of less than 2 dB, as This is ascribed to XPM and XPolM. Presently, there is no way to reduce their effects.

Finally, in Figure 7 (b) we present the expected trend when the number of DP-QPSK channels is increased. As said above, DP-QPSK have higher tolerance to NLEs, thus in this case, we assume a higher P_{ch} value (25 W). Again, we observe that higher number of channels give higher penalties.

5. CONCLUSION

We investigated the nonlinear impairments induced by an optical booster amplifier operating at ultra-high optical output power, where nonlinear effects can emerge within the active fiber and, most importantly, in the delivery fiber to the transmitter telescope. We critically review and explain the impact of the nonlinear fiber effects, by means of numerical simulations: we first considered a 4-channel system, in two cases, i.e., 4x10 Gbit/s IM-DD and 4x100 Gbit/s DP QPSK signals. The obtained results clearly indicate that the nonlinear effects appear under these conditions because ultra-high power values counterbalance the short fiber lengths.

Noteworthy, IM-DD signals are more affected than DP-QPSK signals: in the worst condition, four IM-DD signals with ECS and all SoP's parallel are effectively impaired even at total power of around 20 W. At the same total power, even in the worst case condition, DP-QPSK signals are not significantly influenced. Yet, in both cases, we found that some solutions can be found to mitigate the impact of NLEs.

Actually, IM-DD signals are only affected by FWM, which can be partly reduced by alternate SoP of the signals and, possibly UCS, when the number of channels is not very high [4]. On the other side, DP-QPSK signals are also affected by FWM, but at higher power values; however, even using UCS, we found that they are also affected by XPM and XPolM. Moreover, the impact of FWM in IM-DD signals is largely higher: this clearly affects the power budget, even using alternate polarizations.

On the other hand, when DP-QPSK signals start to suffer from NLEs, the contribution due to FWM is only one out of various. Therefore, to further increase the power budget, new analysis must be performed to explore alternative solutions.

To the best of our knowledge, the presented results are the first to indicate a complete benchmark between the two most relevant modulation formats for the FSO WDM systems that could be used in future high-capacity uplinks. They also provide some initial design guidelines to control these types of impairments in high-power FSO systems for satellite links or to design alternative types of optical amplifiers. Other alternative strategies to further boost the power budget could also be investigated in the future.

ACKNOWLEDGEMENTS

This work was partially supported by the European Union -Next Generation EU under the Italian National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.3, CUP J53C22003120001, partnership on “Telecommunications of the Future” (PE000000001 - program “RESTART”). The authors gratefully acknowledge stimulating discussions with Stefano Trillo.

REFERENCES

- [1] Chan, Vincent WS. "Optical satellite network architecture." *Journal of Optical Communications and Networking* 16.1 (2024): A53-A67
- [2] M. M.Saad, M. A.Tariq, M. T. R., Khan, D. Kim, “Non-terrestrial networks: An overview of 3gpp release 17 & 18” *IEEE Internet of Things magazine*, 7(1), pp. 20-26 (2024), doi: 10.1109/IOTM.001.2300154.
- [3] L. C. Andrews, M.K. Beason, “Laser beam propagation in random media: new and advanced topics”, SPIE Press, 2023. doi: 10.1117/3.2643989
- [4] E. Ciaramella, Y. Arimoto, G. Contestabile, M. Presi, A. D'Errico, V. Guarino and M. Matsumoto, "1.28 terabit/s (32x40 Gbit/s) WDM transmission system for free space optical communications." *IEEE Journal on Selected Areas in Communications* vol. 27, n. 9, pp. 1639-1645 (2009), doi: 10.1109/JSAC.2009.091213.
- [5] T. R. Brashears, "Achieving 99% link uptime on a fleet of 100G space laser inter-satellite links in LEO," *Proc. SPIE 12877, Free-Space Laser Communications XXXVI*, 1287702 (13 March 2024); doi: 10.1117/12.3005057.
- [6] B. S. Robinson, D. M. Boroson, C. M. Schieler, F. I. Khatri, O. Guldner, S. Constantine, T. Shih, J. W. Burnside, B. C. Bilyeu, F. Hakimi, A. Garg, G. Allen, E. Clements, and D. M. Cornwell "TeraByte InfraRed Delivery (TBIRD): a demonstration of large-volume direct-to-Earth data transfer from low-Earth orbit ", *Proc. SPIE 10524, Free-Space Laser Communication and Atmospheric Propagation XXX*, 105240V (15 February 2018); doi: 10.1117/12.2295023.
- [7] V. Spirito, E. Ciaramella, G. Cossu. "E2E Physical Layer and Link Analysis for High-Throughput Satellite Optical Communication." *IEEE J. Selected Areas Communications* (2025).
- [8] L. Canuet, "Coherent optical feeder links for very high throughput satellite systems," *Proc. SPIE 12877, Free-Space Laser Communications XXXVI*, 128770E (12 March 2024);
- [9] V. Spirito, G. Cossu, E. Ciaramella, “Feasibility study of a Terabit/s GEO-to-Ground WDM Optical Communication Link”, *Proc. SPIE, International Conference on Space Optics - ICSO 2022*,
- [10] K. G. Petrillo, et al. "Optical Fiber Amplifiers for Satellite Communications," *IEEE J. Selected Topics Quantum Electronics*, 32, pp. 1-13, 2026
- [11] K. G. Petrillo, J. Cook, D. Engin, A. Sincore and A. M. Schober, "Optical Fiber Amplifiers for Satellite Communications," in *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 32, no. 1, pp. 1-13, Jan.-Feb. 2026
- [12] H. Kobayashi, R. Kano, T. Seo, Y. Suzuki, E. Mizuta, Y. Hashimoto, T. Araki, Y. Takada, “Development of a continuous wave single transverse mode polarization-maintaining 10 W Er/Yb-codoped fiber amplifier for space communications”, *SPIE Photonics West 2023*.
- [13] D. Engin, S. Litvinovitch, C. Gilman, H. Cao, T. Wysocki, B. McIntosh, J. Rudd, J. Hwang, D. Pachowicz, K. Petrillo, N. Sawruk, A. Schober, M. Storm, "50W, 1.5 μ m, 8 WDM (25nm) channels PPM downlink Tx for deep space lasercom” *Proc. SPIE 11678, Free-Space Laser Communications XXXIII*, 116780K, 5 March 2021
- [14] D. Engin; J. Hwang; P. Olmstead; D. Pachowicz; T. Wysocki; M. Storm, “Experimental and theoretical study of TDM based FWM mitigation with 8 channel 50W WDM PPM Tx for slot sizes 0.5 and 1nsec”, *SPIE Photonics West*, 2023, Paper 12413-14.
- [15] F. Maes et al. “100 Gbps data transmission with 40 W optical power amplifier validation for GEO-to-GEO data relay”, *Proc. International Conf. on Space Optics (ICSO 2024)*, paper 083

- [16] E. Ciaramella, and G. Cossu. "Nonlinear fiber effects in ultra-high power 10×10 Gbit/s WDM-IM free-space systems for satellite links." *Optics Express* 32.5 (2024): 7959-7968.
- [17] P. J. Winzer, and R.-J. Essiambre. "Advanced optical modulation formats." *Optical Fiber Telecommunications VB*. Academic Press, 2008. 23-93.
- [18] M. G. Taylor, "Coherent detection method using DSP for demodulation of signal and subsequent equalization of propagation impairments," *IEEE Photon. Technol. Lett.*, vol. 16, no. 2, pp. 674–676, Feb. 2004.
- [19] C. M. Schieler et al., "Recent on-orbit results and arq performance analysis for the third 200-gbps mission," in 2023 IEEE International Conference on Space Optical Systems and Applications (ICSOS), 2023, pp. 49–55.
- [20] G. P. Agrawal, *Nonlinear fiber optics*, Academic Press (2001)
- [21] "ESA Specification for Terabit/sec Optical Links (ESTOL)," ESA-CSC-T-SP-0001, Issue 2.2, 2024. [Online]. Available: https://connectivity.esa.int/sites/default/files/2024-09/ESTOL_air_interface_v2.2.pdf
- [22] OpenZR+ Multi-Source Agreement (MSA) Group, OpenZR+ Specifications, Version 3.0, Sep.12, 2023. Accessed: Mar.5, 2025. [Online]. Available: <https://openzrplus.org/resources/openzr-specifications-v-3-0/>
- [23] F. Forghieri, R. W. Tkach and A. R. Chraplyvy, "WDM systems with unequally spaced channels," in *Journal of Lightwave Technology*, vol. 13, no. 5, pp. 889-897, May 1995