A 100 W Output Power Coherent Transmission Link for Future High Data Rate Earth-to-Satellite Communication

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Abstract: An optical coherent transmission link with 100Watt output power is tested for satellite communications. Modulation formats are tested for transmission of the highest data-rates despite of nonlinear amplifier impairments across a linear, low-SNR free-space link.

1. Introduction

Satellite Internet access is nowadays a highly prevalent topic. Commercial satellite networks, such as SpaceX Starlink and Telesat LightspeedTM, aim to provide high-speed Internet to remote and rural areas where traditional communication technologies are not available. A major challenge is the transfer at large data rates between satellites and ground-stations from earth. Radio frequency links have spectral bandwidth limitations, whereas free-space (FS) optical communication constitutes a promising solution by using its inherent low divergence and vast optical bandwidth. So far there have been only a few on-flight demonstrations [1-4]: Recently, line rates of up to 200 Gbit/s utilizing polarization-multiplexed (PM) QPSK waveforms have been demonstrated in a LEO-satellite-to-earth downlink over FS distances of up to 930 km [2]. Even higher distance could be overcome in a Moon-to-Earth transmission by using pulse-position modulation (PPM) waveforms with data rates of up to 622 Mbit/s [1]. Nonetheless, higher data rates and/or higher distances are anticipated. To reach the improved performance, one has to overcome the very high FS losses and be able to receive data at low signal-to-noise ratios (SNR).

There exist two possibilities to solve these problems: First, the utilization of power-efficient coherent modulation such as QPSK, PS-QPSK [5] and 4D-BPSK [6] can decrease the required SNR, resulting in very high sensitivities of up to 5.9, 5.1 and 4.3 photons-per-bit at a data rate of 100 Gbit/s with BER $\leq 10^{-3}$. These modulation formats, despite their lower spectral efficiencies, show at higher speeds a higher sensitivity than high-order modulation formats[6, 7].

Secondly, one can overcome the free-space losses by using higher powers. Contrary to fiber optical channels where high optical powers lead to non-linearities, the free-space channels is essentially linear. Therefore, future optical feeder links are anticipated to work with output powers beyond tens of Watts [8, 9]. However, the high optical power target is hindered by the ongoing difficulty in developing high-power optical sources, especially in the C- and L-bands. While multi-kW sources have been achieved at 1064 nm [10], amplifiers in the C- or L-band lag behind. Recent progress includes reliable amplifiers up to 36 W [11], wavelength division multiplexing transmissions up to 50 W [12] and amplifiers with even higher powers of up to a few hundred Watts demonstrated [13, 14]. However, these sources are often unsuitable for FS optical transmitters like optical ground stations due to compromised beam quality, sensitivity to stimulated Brillouin scattering, and degradation from heat and photodarkening effects [14, 15]. Coherent beam combining (CBC) [16], enables high power generation while reducing the required output power of the optical amplifiers by a factor 1/N by coherent phase combining N independent amplified laser beams. Recently with such a system, the first successful transmission of 25 GBaud OOK and DSPK signals in C-band [17] with output powers of up 97 Watts was shown by the combination of two 50 W amplifiers [18, 19]. However, the data rates were limited to 25 Gbit/s/λ, while future optical feeder links aim for data rates in the order of 100's Gbit/s/λ [9].

In this work, we test the coherent beam combining system to transmit high data rates at high powers up to 100W. The effect on the signal quality of these very-high power optical amplifiers with coherent modulation formats is investigated. It was observed that the link is mainly impaired by the self-phase modulation originating from the amplifier, resulting into SNR penalties of up to 12 dB for 16QAM at low symbol rates. However, this high degradation can be mitigated by nonlinear (NL) equalizers, reducing the penalty to as low as 1 dB. Moving towards higher speeds, applying NL equalization, successful transmission and reception of 509 Gbit/s and 705 Gbit/s were achieved utilizing dual-polarization 128 GBaud 4QAM and 100 GBaud 16QAM. Furthermore, we test which modulation format can transmit the highest data rates under lowest SNR conditions. It is found that a power-efficient modulation format such as 128 GBaud 4QAM excels in that it permits data communication below the SD-FEC limit at received optical powers with as little as 0.391 µW (-34 dBm). This translates into a >8.5 dB sensitivity advantage over 16QAM modulation despite of applying the nonlinear SPM compensation to both formats (in theory there should only be a 3 dB advantage). The study shows the viability for future high-power long-range free-space optical links with high data rates.

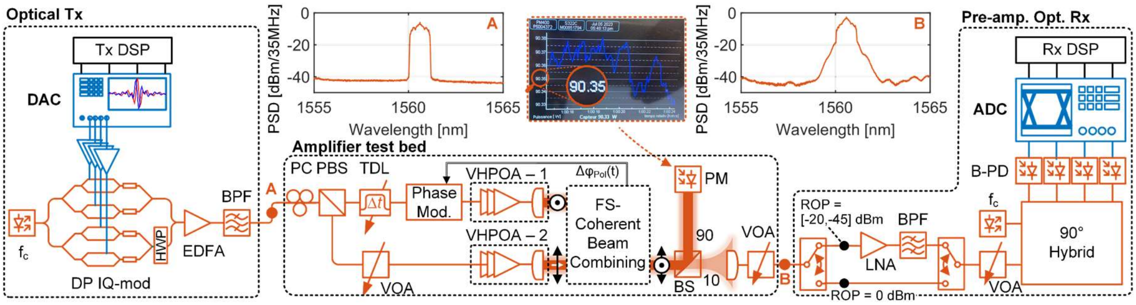

Fig. 1: **100W Optical Transmission Link**. The experimental setup involves encoding a data signal onto a 1560.5 nm optical carrier using a 35 GHz dual-polarized inphase-quadrature modulator. At the amplifier test bed, the signal is split into orthogonal polarizations, amplified to 50 Watts, and time-coherent and polarization-orthogonal recombined in the FS coherent beam combing (CBC) setup. The optical signal propagates over 2 m FS distance and couples to a standard single mode fiber (SSMF). After variable attenuation to simulate low received optical power scenarios, the signal is brought to baseband by using heterodyne mixing in the pre-amplified optical coherent receiver (Pre-amp. Opt. Rx).

2. Experimental configuration

The total experimental configuration is shown in Fig. 1. In the optical transmitter (Opt. Tx) a data signal is encoded onto an optical carrier (fc = 1560.5 nm) by means of 35 GHz dual-polarised (DP) inphase-quadrature (IQ) modulator. The complex-modulated baseband signal was generated by a 128 GSa/s digital-to-analog converter (DAC) with 65 GHz bandwidth and 8 bit vertical resolution. Afterwards, the optical data signal is amplified to 15 dBm and band-pass-filtered. At the amplifier test bed, a polarisation beam splitter (PBS) splits the signal into two orthogonal polarisations and feds the two single-polarised signals to the very high power optical amplifiers (VPHOA) 1 and 2. The VHPOA have an operating wavelength range of 1557 – 1564 nm, a gain of >50 dB and saturated output powers ≥ 47 dBm. Then, the two single-polarised optical signals are amplified by the VHPOAs and polarization-orthogonal and time-coherent re-added in the free-space (FS) coherent beam combining (CBC) bench. For the time coherence, in one amplifier arm a tunable delay line (TDL) and phase modulator (Phase Mod.) compensate the constant time skew and the fast-varying (~ kHz) phase difference $\Delta\varphi_{Pol}(t)$ between the two arms/polarisations. The CBC bench is described in more detail in ref [19]. The 100 W optical signal propagates through a beam splitter, where 90% of the power is used for power monitoring and 10% is coupled back to SSMF. In a next step, a variable optical attenuator (VOA) attenuates the optical signals to powers of 0 or [-20, -45 dBm] to emulate low received optical power (ROP) scenarios. In the latter case, a low-noise amplifier (LNA) amplifies the optical signal and feeds it to a coherent optical receiver (Opt. Rx). Here the optical signal is mixed to baseband by a local oscillator and balanced photodetectors (B-PD) and thus, converted to the digital domain by 256 GSa/s analog-to-digital converter (ADC) with 70 GHz bandwidth and a 10 bit vertical resolution. Finally, the signal is evaluated by an offline digital signal processing (DSP) stage consisting of matched filtering, timing recovery, constant modulus algorithm for polarization demultiplexing, a T/2-spaced feed-forward equalization, a 3-symbol pattern nonlinear equalization and a T-spaced feed-forward equalization.

3. Experimental results and discussion

This section is structured as follows: Firstly, we assess the performance of the VHPOAs in conjunction with coherent data transmission. Secondly, we present the experimental results detailing the highest achievable symbol rates and the performance of the data transmission link under low received optical powers (ROP).

Fig. 2(a) shows the signal-to-noise-ratio (SNR) as a function of ROP of a single-polarised (SP) 64 GBaud-16QAM rate for VHPOA-1 (green), VHPOA-2 (blue), and without VHPOA / back-to-back (b2b) in red. The quality of both VHPOA-1 and -2 is comparable, with VHPOA-1 having a marginal average SNR-advantage of 0.4 dB over VHPOA-2. More over, operating at the highest output powers will result in a constant 2.5 dB SNR penalty across the entire power range due to nonlinear impairments – mainly self-phase modulation introduced by the VHPOA. Alternatively, the CBC setup provides the option to use the N=2 amplifiers in parallel and reduce the output power by a factor N=2 (i.e. each VHPOA output power is 25 Watt). This approach allows the mitigation of impairments that scale with outpower, enabling us to approach the b2b-performance by 1.1 dB (average) additionally. Scaling of CBC with a higher number of VHPOAs at lower output power can yield to similar output powers with limited nonlinearities.

Next, we investigate the performance of nonlinear equalization vs. back-to-back (b2b) measurements. Fig. 2(b) displays the normalized generalize mutual information – NGMI – (above) and SNR penalty (below), plotted against symbol-rate for single-polarised 4QAM and 16QAM modulation at 50 Watt. The graph demonstrates a decrease in NGMI and an increase in SNR penalty with higher symbol rates. Notably, nonlinear (NL) post-equalization is crucial; reducing the DSP to linear equalization results in additional SNR penalties of up to 10 dB More importantly, the lower-order modulation format, 4QAM, seems to be less affected by the self-phase modulation (SPM) as 16QAM, resulting in lower penalties at higher speeds. This raises the question whether this advantage persists at different output powers. In the subsequent analysis, we explore the performance of polarization-multiplexed 128 GBaud signal for

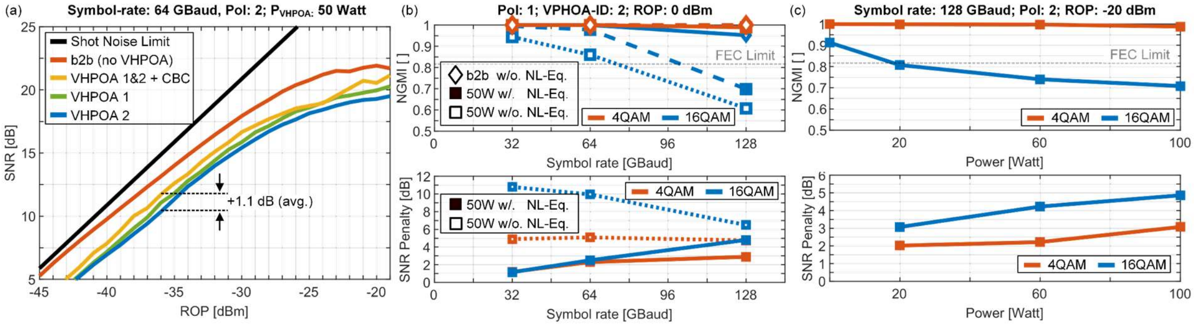

Fig. 2: **Performance investigation of VHPOA**. (a) SNR vs. received optical power at single-polarised 64 GBaud-16QAM for different amplifier configurations: VHPOA-1 (green), VHPOA-2 (blue), VHPOA 1&2 w./ CBC (yellow) and no VHPOA (red) measurements. (b) Normalized mutual generalized mutual information (NGMI) and signal-to-noise-ratio (SNR) penalty versus symbol rate for a single-polarised 4 QAM and 16 QAM signals at 50 W output power. (c) NGMI and SNR penalty vs. output power for polarization-multiplexed 128 GBaud QAM modulation formats.

output powers ranging between 20 and 100 Watt with ROP of -20 dBm, as despicted in Fig.2 (c). Our findings reveal that for 4QAM modulation, the SNR penalty remains limited to a maximum of 3 dB across all output powers, providing lower SNR penalties over 16QAM of up to 2 dB.

In the final experiment, we investigate highest achievable symbol and information rates for PM-128GBaud-16QAM, PM-128GBaud-4QAM and PM-100GBaud-16QAM, see Fig. 3. The constellation diagrams, line-rate, and achievable information rate (AIR) with and without the 100W-VHPOAs at a ROP of 0 dBm are shown in Fig. 3(a). Utilizing high symbol rates of 128 GBaud and high-order modulation 16QAM with polarization multiplexing allows for a high AIR of up to 0.788 Tbit/s, despite the 3.8 dB penalty in SNR. However, ROP of 0 dBm are improbable due to expected high path losses, estimated to be around 80 - 90 dB in a real-case satellite feeder link scenario. This results in low ROP of ~-35 dBm and leading to low SNR conditions. Therefore, in the subsequent step, we investigate which of these modulation formats can transmit at highest capacities for low ROP, see Fig. 3(b). To account for different line rates and spectral efficiencies, the x-axis was normalised to photons-per-bit (PPB). Remarkably, 4QAM, despite operating at highest bandwidth, exhibits the highest sensitivity: It has a sensitivity advantage of > 8.5 dB in ROP over 100 GBaud-16QAM and 128 GBaud-16QAM, even after applying the nonlinear SPM compensation to all formats. This enables 512 Gbit/s transmission above the 0.75 FEC rate [20] at PPB as low as 7.9 dB (≙ ROP of −34 dBm). This finding is intriguing as in theory 4QAM was expected to provide only a 3 dB sensitivity advantage over 16QAM. Thus, 4QAM features a >5 dB higher robustness against NL impairments such as self-phase modulation at low ROP.

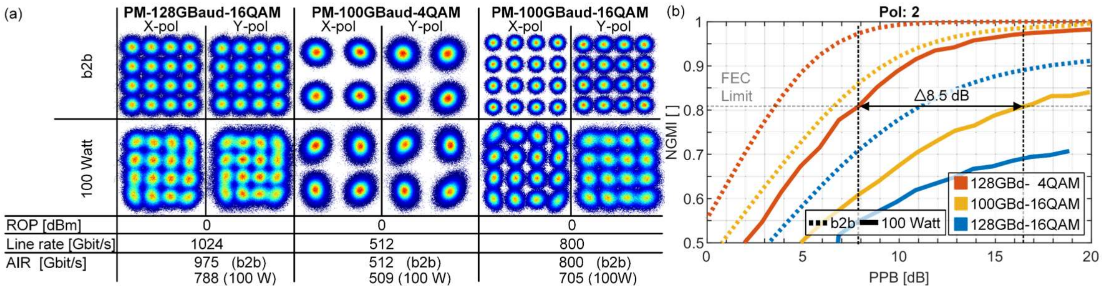

Fig. 3: **Results of the high-data rate transmission experiments at 100 Watt Tx power.** (a) Received constellation diagrams for 4QAM and 16QAM signals at 100 W transmit powers at highest speeds and received optical power (ROP) of 0 dBm, resulting in achievable information rates (AIR) of up to 778, 509 and 705 Gbit/s using 16QAM, 4QAM and 16QAM. (b) NGMI as a function of photons-per-bit (PPB) for QAM modulation formats at highest speeds in a b2b / no VHPOA (dashed) and 100Watt (solid curve) scenario. The grey line indicates a 25%-OH SD-FEC limit [20].

In conclusion, we investigated a coherent beam combining system that is capable to transmit high data-rate coherent modulation waveforms at high powers up to 100W. We found that at high speeds low-order modulation formats do give sensitivity advantages of > 8.5 dB over high-order modulation formats. Furthermore, this enables to successfully transmit and receive 512 Gbit/s at ROP as low as -34 dBm (7.9 dB PPB). The experiments verify that CBC with the correct modulation formats could enable next generation high data-rate Earth-to-satellite communication.

[1] D. M. Boroson *et al.*, SPIE LASE, 2014, vol. 8971, p. 89710S: SPIE.
[2] C. Schieler *et al.*, SPIE LASE, 2023, vol. 12413, p. 1241302: SPIE.
[3] M. Gregory *et al.*, ICSO, 2010, vol. 10565, pp. 324-329: SPIE.
[4] C. Fuchs *et al.*, ICSO 2018, vol. 11180, p. 111800I: SPIE.
[5] M. Karlsson *et al.*, *Optics Express,* 17, pp. 10814-10819, 2009.
[6] Y. Horst *et al.*, *Light: Science & Applications,* 12, p. 153, 2023.
[7] L. Kulmer *et al.*, OFC 2023, p. W3I.1: Optica Publishing Group.
[8] N. Perlot *et al.*, Future Network & Mobile Summit, 2012, pp. 1-8: IEEE.
[9] A. Le Kernec *et al.*, ICSO, 2021, vol. 11852, no. 1185217: SPIE.
[10] G. Nau *et al.*, SPIE LASE, 2022, vol. 11993, pp. 120-128: SPIE.
[11] K. Guesmi *et al.*, SPIE LASE, 2023, vol. 12400, pp. 198-202: SPIE.
[12] D. Engin *et al.*, SPIE LASE, 2021, vol. 11678, pp. 95-108: SPIE.
[13] H. Lin *et al.*, *Optics Letters,* 43, pp. 3080-3083, 2018.
[14] T. Matniyaz *et al.*, *Optics Letters,* 45, pp. 2910-2913, 2020.
[15] D. Creeden *et al.*, SPIE LASE, 2016, vol. 9728, p. 97282L SPIE.
[16] J. Bourderionnet *et al.*, *Optics Express,* 19, pp. 17053-17058, 2011.
[17] A. Maho *et al.*, ECOC, 2023, p. Tu.A.4.3.
[18] M. Welch *et al.*, SPIE LASE, 2022, vol. 11993, no. 119930B: SPIE.
[19] V. Billault *et al.*, *Optics Letters,* 48, pp. 3649-3652, 2023.
[20] Q. Hu *et al.*, ECOC, 2021, no. 9606060, p. 52684.