100 W Class Output Power Transmission for High Data Rate, C-Band, WDM Free Space Optical Ground-to-Satellite Links

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Abstract *High power generation is an enabling technology for high capacity free space optical feeder links. We show the feasibility of optical transmission of WDM OOK / DPSK at high power based on 50 W amplifiers and their coherent combination to deliver up to 97 W power.©2023*

Introduction

Free Space Optical (FSO) Communications have huge potential in the field of telecommunications, and their use is expanding rapidly, however significant challenges still remain [1,2]. In particular, optical feeder links require enabling technologies to reach Terabits per second capacity [3] and overcome transmission losses close to 300 dB without any repeater. Even if telescope gain significantly higher than 100 dB can be provided at transmit and receive sides, there is a clear need for very high output power generation compatible with WDM telecom signals.

High power generation at 1064 nm is more readily attainable than in the C-band where multi-kW sources designed for material processing exist, a WDM 100W telecoms source has been recently demonstrated at this wavelength [4]. In the C-band reliable amplifiers up to 36 W [5] and WDM transmissions up to 50 W [6] have been demonstrated. The power of these sources can be scaled to higher levels using Coherent Beam Combining (CBC) [7,8] reaching up to tens of kW at 1064nm [9,10].

Besides, 1064 nm wavelength is not suitable for Tbps WDM applications. Up to now, to the best of our knowledge, neither VHPOA (Very High Power Optical Amplifier) nor have CBC techniques been evaluated on high data-rates C-band telecom transmissions using phase / amplitude modulations. Among the possible impairment sources, one can cite VHPOA non-linearities that could affect modulated signals, especially with wavelength multiplexing; Also, CBC of modulated optical signal requires a precise feedback loop to control in real time the phase and delay of the different paths that are combined, especially with wavelength multiplexing. Any residual phase/delay fluctuations could induce power penalties at the receiver.

In the frame of H2020 VERTIGO project, two 50 W VHPOA have been developed [11] and coherently combined [12]. In this paper, we present an assessment of both G&H 50 W VHPOA and of CBC techniques applied to 25 Gbps wavelength multiplexed modulated signals. Contribution of each building block and influence of the output power are characterized in terms of Received Optical Power (ROP) penalty for a given Bit Error Ratio (BER). We achieved very high power transmissions and prove the feasibility of 100 W class feeder links.

High Optical Power Generation Principle

VHPOA evaluated in this study are presented in reference [11]. We evaluated two units, named VHPOA A & VHPOA C. Tab. 1 shows their specifications and Fig. 1 (b) an output spectra.

Tab. 1: VHPOA Specifications.

Parameter	Value
Optimal Wavelength Range	~1557-1564 nm
Output power	50 W
Gain (at 1 mW input power)	47 dB
Output interface	End cap

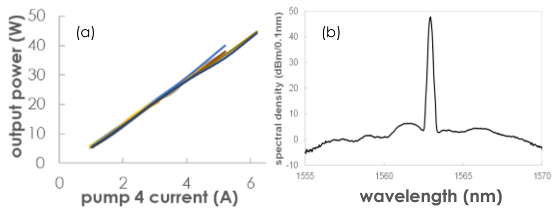

Fig. 1: VHPOA A output (a) power versus pump 4 current (10 measures) and (b) spectrum (output power: 25 W).

Note this test campaign gives a good idea of the reliability of VHPOA, which have been operating for an accumulated duration of 100-200 hours each, split over ~50 test sessions. Fig. 1 (a) gives the output power as a function of the 4th stage pump current. Deviation from one session to another is limited and, once established, typical output power deviation during a measurement is estimated around 1 % along 10 minutes for output powers above 20 W.

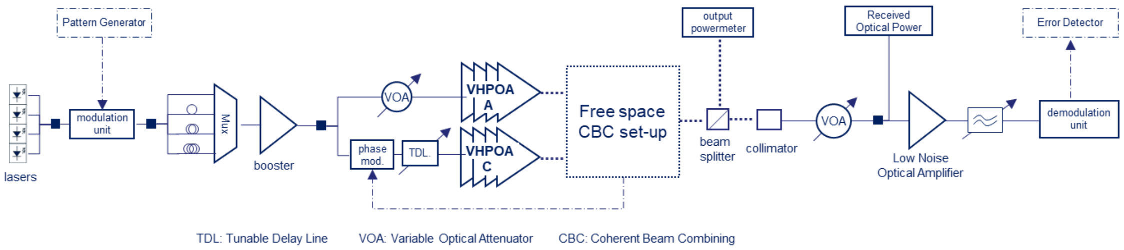

Fig. 2: Experimental transmission set-up

CBC assembly is described in detail in ref. [12]. It consists in two blocks. One block placed before the amplifiers splits the input signal into two paths and allows relative phase and delay control between the two paths. The second block, placed after the amplifiers, includes polarization and phase control loops and combines the two beams in free space. During all our experiments; including VHPOA standalone testing, the amplifiers were integrated to this bench.

Experiment

Fig. 2 above shows the experimental set-up. It is composed of transmitters, a high power generation block and receivers. Transmitters consist in 4 low-linewidth C-band tunable lasers, two modulation units one for OOK and the other for DPSK. For WDM transmissions all the channels pass through the same modulator and are de-correlated by optical delays before entering in a wavelength tunable optical multiplexer. For OOK modulation, we broaden the optical carrier with a phase modulator to mitigate stimulated Brillouin scattering (SBS). A pre-amplifier is inserted at transmitter output to ensure a constant input power at VHPOA input. The output of each VHPOA is connected to the high power combining block described above. The free space output beam goes to a beam splitter which directs most of the signal to a powermeter while a small part is coupled into a Single Mode Fiber (SMF). The receiver is composed of a Low Noise Optical Amplifier (LNOA) (NF ~4 dB at -45 dBm), an optical filter and either a photoreceiver for OOK or a Delay Line Interferometer (DLI) connected to a Balanced Photoreceiver (BPD) for DPSK. Data modulation was performed at 25 Gbps with a PRBS of 2^{15}-1 bits.

In our experiment, we considered 3 configurations of transmission links:

- A reference configuration, without high power block, where the pre-amplifier output is directly connected to the receiver,
- a transmission link with one VHPOA only,
- a transmission link with coherent beam combining of the two VHPOA.

For a given configuration, measurement taken consist of output power and optical spectra and the Bit Error Ratio (BER) curve i.e. the BER as a function of the received optical power (ROP). OOK and DPSK references are shown in Fig. 3. Receiver sensitivity is defined as the ROP required for a given BER, here 10^{-4}. OOK and DPSK reference receiver sensitivity were found to be around -37.4 and -41.8 dBm respectively. Then, we calculate the optical budget link as the difference between the optical power at the high power block output and the receiver sensitivity.

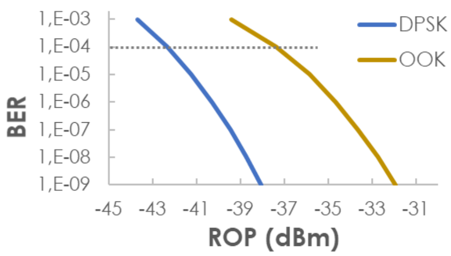

Fig. 3: BER curves of reference for DPSK and OOK

VHPOA and CBC assessment

We first assessed VHPOA behaviour with DPSK modulation. Fig. 4 shows the receiver sensitivity penalty compared to the reference transmission (without high power block) for BER of 10^{-4} as a function of output power. Results are given for 3 optical channels 192.2, 192.5 and 191.7 THz (respectively shortest and longest wavelengths of VHPOA optical bandwidth utilised). For all the channels, receiver sensitivity penalty was very limited and did not exceed 0.6 dB. Output power does not have a clear impact on the receiver sensitivity penalty whereas the boundaries of optical window seem to be more impaired. VHPOA A & C present similar results. Results repeatability is quite good with penalty offset deviation better than 0.2 dB.

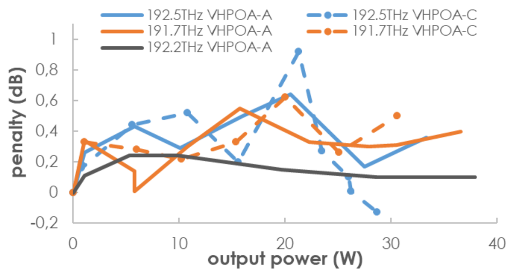

Fig. 4: DPSK sensitivity penalty for VHPOA A, VHPOA C and optical channels 192.5, 192.2 and 191.7 THz

Fig. 5 presents optical link budget for both OOK and DPSK modulation formats. It increases linearly with the output power, proving there is no significant degradation at high power. The figure also shows that the optical link budget for DPSK is more than 3 dB (theory) higher than for OOK which is attributed to the non-optimization of OOK photoreceiver. Indeed, DPSK receiver sensitivity of reference is 4.4 dB better than for OOK.

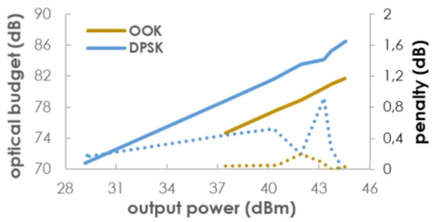

Fig. 5 OOK & DPSK Optical link budget (solid lines) and sensitivity penalty (dotted lines) with VHPOA C.

Coherent Beam Combining technique was then applied to VHPOA A & C. As we do not have access to each VHPOA output power, we plotted receiver sensitivity penalty as a function of the 4th pump current either from VHPOA A or C (Fig. 6 (a, b)). There is no major difference compared to VHPOA standalone mode. Logically, there is no impairment on the optical link budget of OOK and DPSK transmissions (Fig. 6 (c, d)).

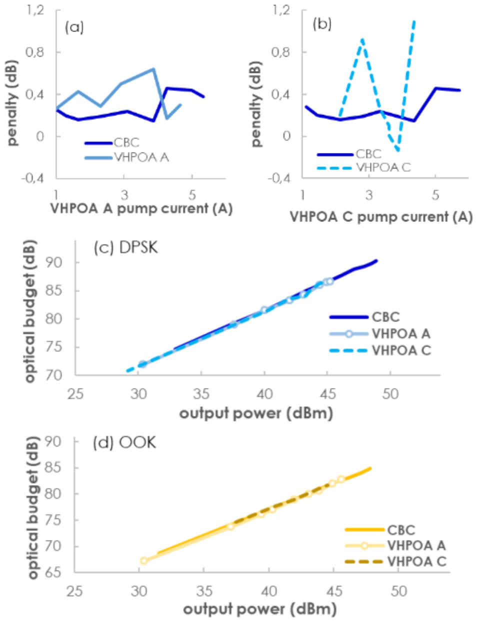

Fig. 6 VHPOA A, VHPOA C and CBC sensitivity penalty as a function of pump 4 current for DPSK (a, b) and optical link budget for DPSK (c) and OOK (d) obtained at 192.5 THz.

We did not test the maximum output power limit achievable with VHPOA. Yet we measured up to 45 W output power for VHPOA standalone testing and up to 97 W output power with a CBC technique. DPSK transmissions reached optical link budget ~87 dB for a BER of 10^{-4} with one VHPOA and ~90 dB with CBC. This shows that CBC technique enables to provide higher output power and higher optical link budget.

Wavelength multiplexing assessment

WDM assessment is important for system definition. We studied both the influence of the number of multiplexed optical channels and of their spacing. Fig. 7 presents receiver sensitivity penalty results for various spacing and number of channels through VHPOA A. There is no impairment for 2 channels, even with a spacing of 100 GHz. Transmissions with 4 channels are more affected, with ~1.2 dB penalty with 300 GHz spacing. Similar results in terms of sensitivity penalty are obtained with CBC, proving its compatibility with operation in WDM regime.

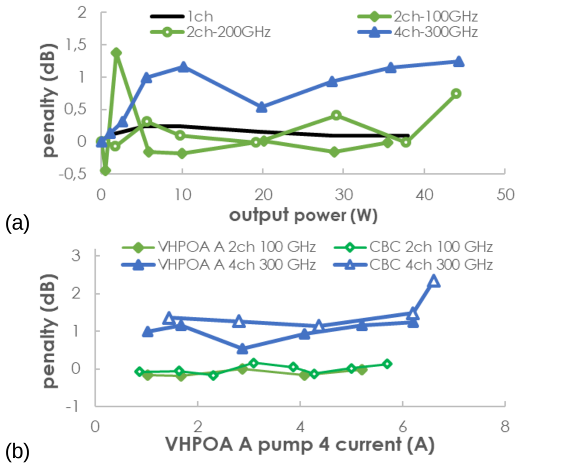

Fig. 7 DPSK sensitivity penalty vs. the output power for different channel numbers and spacing (a) and comparison between CBC and VHPOA (b).

Conclusions

In this paper, we have reported on the optical transmission of high data rate telecom signals in the C-band with output power in the 100 W class.

25 Gbps DPSK and OOK signals were first transmitted with Very High Power Optical Amplifiers up to 45 W and across an optical bandwidth of ~7 nm with almost no signal quality degradation leading to system penalties. Wavelength division multiplexing was also demonstrated with small penalty.

Then we proved the compatibility of Coherent Beam Combining technique with such signals, thus enabling to reach up to 97W output power and to offer 90 dB of optical link budget. CBC is shown to be usable when VHPOA output power is not sufficient. These results are considered as a major step in the system definition and development of high throughput Free Space Optical Ground-to-Satellite Links.

Acknowledgements

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