

Assessment of the performance of DPSK and OOK modulations at 25 Gb/s for satellite-based optical communications

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Abstract—Airbus Defence and Space developed with its partners iXBlue and CILAS an engineering breadboard (EBB) model of optical communication chain able to manage non-return to zero (NRZ) on-off-keying (OOK) and differential phase shift keying (DPSK) modulations at 10 Gb/s and 25 Gb/s. The EBB includes a digital processing unit (DPU), an optical transceiver (Tx/Rx) and a 5 W-optical booster. It uses wave-length division multiplexing (WDM) technology to increase the total data rate. This is a first step towards the development of an engineering model (EM) that will be developed in 2020-2021. This paper reports a part of measurements performed on the EBB, particularly the performance of NRZ-OOK and NRZ-DPSK modulations for 3 x 25 Gb/s channels. Measurements reveal that non-linear effects start to appear inside the 5 W-booster. Because of its constant envelope during bit time, NRZ-DPSK signal is less sensitive to power modulation-related non-linear effects than NRZ-OOK. The average sensitivity of the NRZ-OOK and NRZ-DPSK links at 25 Gb/s are respectively -36.8 dBm and -40.2 dBm for bit error ratio (BER) at 10^{-3} .

Keywords—Free space optical communication (FSOC), on-off keying (OOK), differential phase shift keying (DPSK), optical feeder, non-linear effects (NLE).

I. INTRODUCTION

Global internet traffic has been predicted to grow quickly in the next few years, driven mainly by the relentless increasing number of customers across the world (individuals and machines) and the streaming of high-definition videos [1]. Satellites will play a role for answering to this internet traffic demand in particular for underserved nations and individuals who reside in rural locations. The satellite communication industry historically-centered on geosynchronous earth orbit (GEO) has seen an influx of non-GEO high throughput satellite (HTS) constellation proposals in recent years which represents an upheaval in terms of technology and business case. The Federal Communications Commission (FCC) approved OneWeb, SpaceX, Telesat, LeoSat and

Kepler internet constellations [2]. These low earth orbit (LEO) constellations are creating new ways of providing satellite based broadband access. After years of fundraising and development, the first LEO satellites of the OneWeb constellation were launched early in 2019. New constellation announcements continue but the RF spectrum is a finite resource and is fast becoming congested, particularly in the Ku/Ka-bands. In this context, free space optical communications (FSOC) represent an attractive solution for satellite industry. The advantages offered by FSOC stem from the high frequency of the optical carrier. This property leads to large available modulation bandwidth and high beam directivity which makes unlikely the presence of interferences. As a consequence, there is no need for spectrum licensing and security against jamming is increased. As the optical wavelength is small, FSOC systems feature reduced overall size, weight and power consumption (SWaP) compared to RF systems. Several key programs and projects have demonstrated the viability of FSOC, like SILEX [3], LOLA [4], EDRS [5], JDRS [6], LCRD [7], SOTA [8], OICETS [9], OPALS [10], OSIRIS [11], and OPTEL μ [12]. Now the technology maturity, the data rates and the availability versus atmospheric impairment have to be improved.

Airbus Defence and Space, already established on the inter-satellite link (ISL) market, is putting strong research and development efforts to offer bidirectional optical links to the GEO and LEO feeder market as well as low complexity optical downlink for the Earth observation market. The FOLC project (Feeder Optical Link for Constellations) is one piece of this effort. It consists in manufacturing and testing in laboratory environment an engineering breadboard (EBB) of an optical communication chain implementing the on-off keying (OOK) and differential phase shift keying (DPSK) modulation formats pushed by the Consultative Committee for Space Data Systems (CCSDS).

The two first sections of the paper present respectively the FOLC project and the breadboard that has been developed. The third and last sections report a part of breadboard measurements and draw conclusions.

II. FOLC PROJECT

The vision of Airbus Defence and Space is to develop a versatile and scalable optical communication chain capable to meet the requirements of the different missions (GEO and LEO feeders; Earth observation). FOLC project aims at manufacturing and testing in laboratory environment an EBB model of the optical communication chain using mainly parts selected for their future usage in space. It is a technological phase which consists in reducing the technical and technological risks associated with the development of a space-qualified optical communication chain.

The design trade-off phase led to consider an optical feeder based on digital transparent architecture. Under this assumption, data rates of 176 Gb/s and 120 Gb/s were considered respectively for uplink and downlink. With a target data rate per channel of 25 Gb/s, the breadboard was designed with 7 channels for uplink and 5 channels for downlink. The design trade-off performed on the two optical amplifiers (high power and low noise) leads to consider the uplink in the lower part of the C-band (called blue band) and the downlink in the upper part (called red band). This initial design trade-off based on digital transparent solution can also be considered with a digital regenerative optical modem or a regenerative payload with then much more capacity available (typically 3x to 5x more useful data).

The FOLC project is focusing on the communication chain development which is a part of a more global Airbus Defence and Space roadmap aiming at developing the key technologies for the optical feeder links. Other building blocks such as the laser terminal focal plane, control electronic, pointing mechanism and telescope are also under development with one common objective to achieve a first in-flight demonstration of the feeder link in GEO by 2022. For the specific FOLC elements, the next step aiming at

developing and qualifying the future flight product is already engaged through the FOLC2 project.

III. FOLC BREADBOARD

The breadboard developed by Airbus Defence and Space and its partners iXBlue and CILAS is capable to manage non-return to zero OOK and DPSK modulations at 10 Gb/s and 25 Gb/s. It is composed of three main elements: the digital processing unit (DPU), the optical transceiver (Tx/Rx) and the optical booster, also known as high power optical amplifier (HPOA). The breadboard block diagram is presented on Fig. 1.

A. Digital processing unit (DPU)

The DPU generates pseudo-random binary sequences (PRBS) and analyzes them after the transmission to compute the bit error rate (BER). Forward error code (FEC) and bit-level interleaver will be implemented in a next step. FEC based on low-density parity-check (LDPC) codes are under definition to reach best performance while minimizing the power consumption on-board [13]. Both DPU-Tx and DPU-Rx subsystems are based on a Virtex UltraScale board (XC7VU095-2FFVA2104E device). This device has been chosen because: it can manage several channels at 25 Gb/s through GTY 30.5 Gb/s transceiver, it has various in/out connectors (Bullseye, QSFP28 and CFP2) and it has sufficient DDR4 memory to manage interleaving over large blocks. In addition, the 20 nm UltraScale technology used for this FPGA is the same as the one currently in space qualification phase by Xilinx (Kintex 60).

For the breadboard implementation, DPU manages simultaneously up to 3 lines at either 10 Gb/s or 25 Gb/s. The DPU features also a 2-taps pre-equalizer that allows tuning slightly the eye diagram shape at the emission. An optimization based on BER has been made to find the best tap coefficients. The insets of Fig. 2 show the electrical eye diagram at the DPU-Tx output for optimized pre-equalization. The overshoots on 0-1-0 transitions helps to increase signal to noise ratio at the output of the optical modulator.

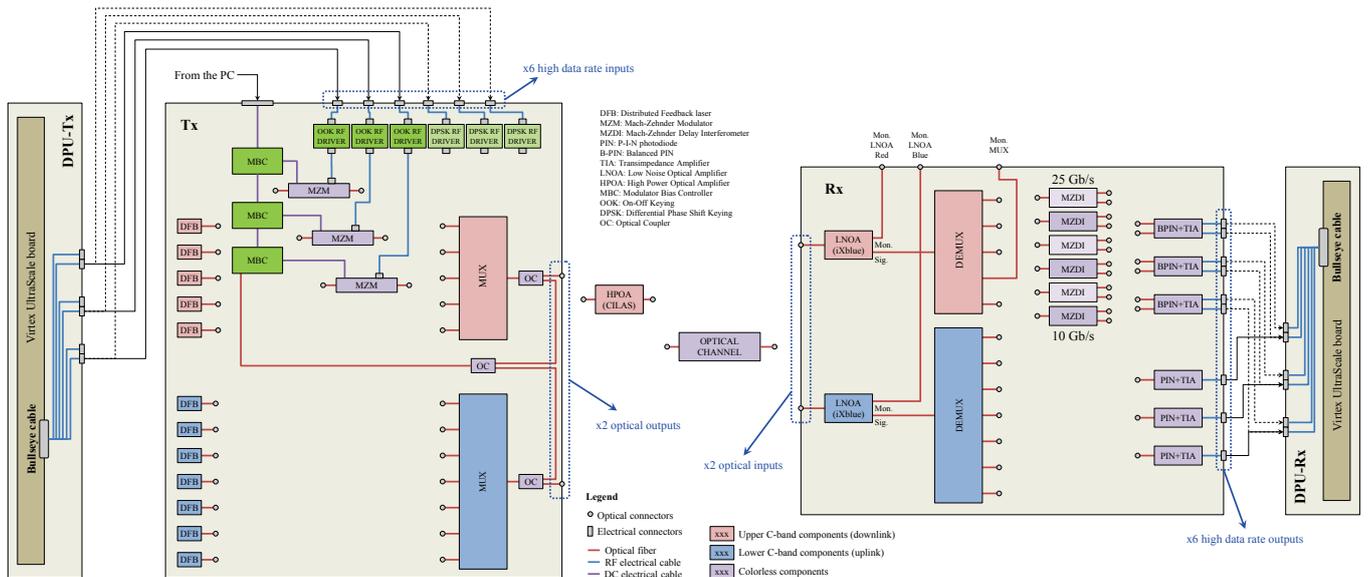


Fig. 1. Block diagram of the breadboard. The breadboard has been designed in a flexible way in order to test several configurations. It can manage 10 Gb/s and 25 Gb/s data rates, OOK and DPSK modulations, uplink and downlink bands.

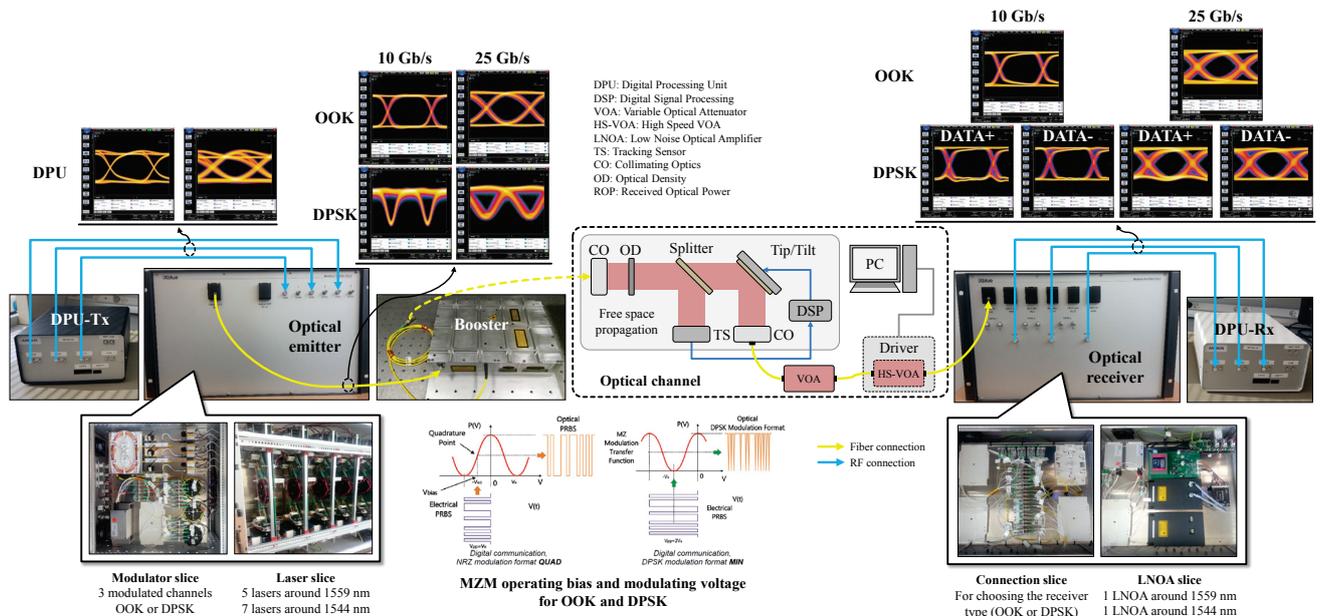


Fig. 2. Pictures of the breadboard and block diagram of the optical channel emulator. Measurements of eye diagrams are also presented at each key point of the link for error free operation.

B. Optical transceiver (Tx/Rx)

The transceiver is composed of the electro-optic emitter (Tx) and the opto-electronic receiver (Rx). It allows the conversion of the electrical data into optical data and conversely.

In the emitter part, the laser slice includes 12 distributed feedback (DFB) lasers to generate 7 wavelengths for uplink (from 1539.77 nm to 1549.32 nm) and 5 wavelengths for downlink (from 1556.55 nm to 1563.05 nm). Up- and downlinks cannot be studied simultaneously but sequentially (not full-duplex). Wavelengths lie on 200 GHz-grid spacing of the International Telecommunication Union. The 3 dB bandwidth per channel is 96 GHz. It has been selected from a standard-products catalog taking into account optimal optical bandwidth for 25 Gb/s signal, MUX/DEMUX misalignment tolerance, DFB lasers thermal stability and Doppler effect for 1500 km-high LEO platform. Only 3 wavelengths are modulated simultaneously in order to study cross-talk. The modulator slice includes Mach-Zehnder modulators (MZM), RF drivers for OOK and DPSK, MUXs for red and blue bands and a rack for fiber interconnections. Both modulations are generated with the same MZM but

with different RF drivers and bias voltages (inset of Fig. 2 reminds OOK and DPSK operational bias and modulating setup). In the receiver part, a first slice includes low noise optical amplifiers (LNOA) and DEMUXs for red and blue bands. Blue and red LNOAs have been designed to operate respectively in 1539-1550 nm and 1556-1563 nm bands and use rad-hard doped fibers developed by iXBlue. Second slice is dedicated to the opto-electrical converters. Simple PIN photodiodes are used for OOK and Mach-Zehnder delay line interferometers (MZDI) with balanced PIN photodiodes are used for DPSK.

The transceiver has been designed in a flexible way in order to test several configurations. At the emitter the 3 MZMs can be connected to any of the blue or red band lasers. The optical signals are then multiplexed using the right MUX. For switching between OOK and DPSK modulations, MZMs are connected to the appropriate RF drivers. At the receiver, after demultiplexing the wavelengths, a fiber connector rack allows choosing the appropriate receiver. For OOK, PIN photodiodes are directly connected to the DEMUX output. For DPSK, the 10 GHz or 25 GHz free spectral range MZDIs are connected to the DEMUX output. The balance PIN photodiodes are then connected to the MZDI outputs. A first optimization step has been performed on the balanced PIN photodiode reverse bias voltage to get better performance. However, to reach the best performance in DPSK it is required to perfectly adjust the skew and the optical power between the two inputs of the balanced PIN. This additional optimization step has not been performed due to the flexibility requested for the breadboard.

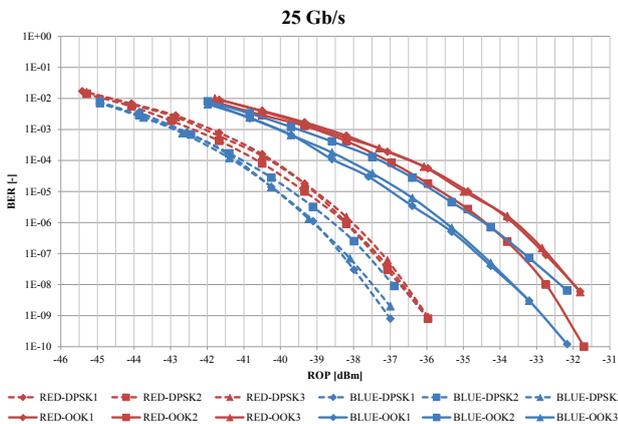


Fig. 3. Transceiver only performance for 25 Gb/s OOK and DPSK modulations in blue and red bands

C. Optical booster

The booster used for enabling transmissions over long free space distances is a 5 W polarization maintaining Erbium-Ytterbium doped fiber amplifier (EYDFA) designed to operate on 1556-1563 nm band. Double-amplification stage architecture has been chosen in order to offer flexibility over flatness setting. It is possible to compensate gain variations

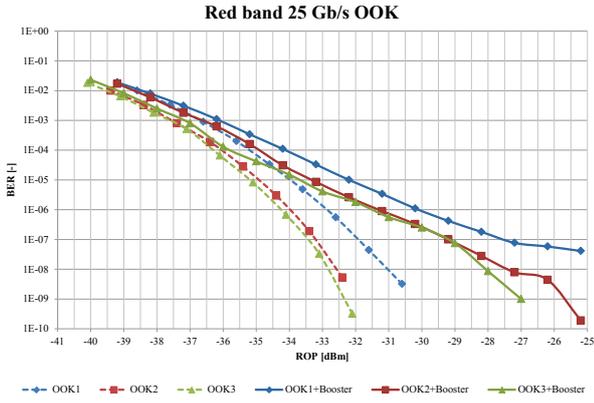


Fig. 4. Full breadboard performance with and without booster for 25 Gb/s OOK modulation in the red band

of each amplification stage when the booster is used in a non-nominal output power range, or after components ageing. It has been designed with rad-hard doped fibers developed by iXBlue. It features an average noise factor around 8.5 dB. The booster output is connected to collimator giving a 1.4 mm beam diameter.

IV. EXPERIMENTAL RESULTS

Fig. 2 presents pictures of the breadboard and a block diagram of the optical channel emulator. The booster output is connected to the optical channel emulator through the collimator. The 5 W-collimated beam is attenuated by a factor 100 using optical densities in order to manage reasonable optical power on the rest of the free-space bench. A part of the optical beam is picked up for spotting on a tracking sensor that gives feedback information for the tip-tilt mirror that maintains the fiber injection. After injection, a variable optical attenuator (VOA) is used to vary the power that reaches the optical receiver. In addition, a high speed variable optical attenuator (HS-VOA) can be used to emulate attenuation time series that represent turbulence effects after fiber injection. The assessment of the link performance with FEC and interleaver over a turbulent channel emulated by the HS-VOA will come in 2020.

Measurement is split into several steps. First the transceiver is tested alone. Then the DPU and the transceiver performance are evaluated. Finally the booster is added in the link. This test sequence allows evaluating the contribution of each part to the final performance. The performance

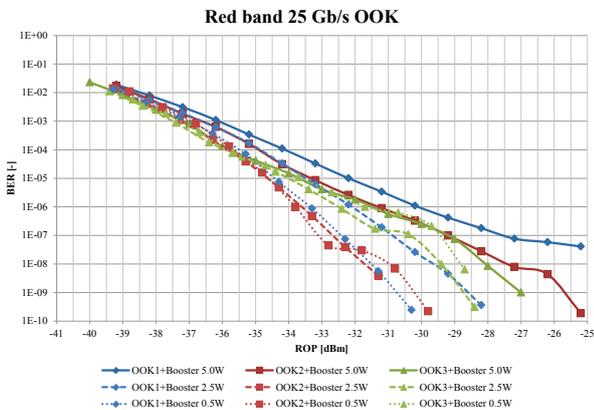


Fig. 6. Full breadboard performance with various booster powers for 25 Gb/s OOK modulation in the red band

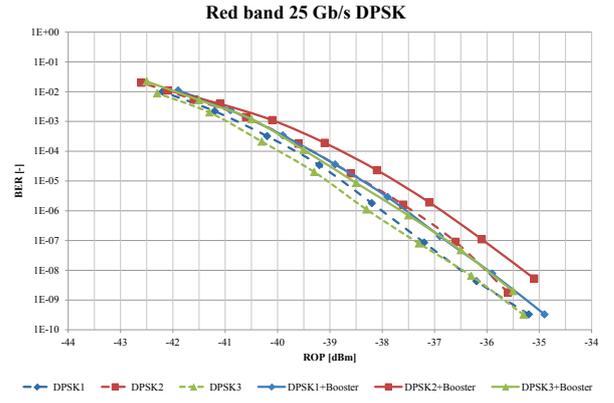


Fig. 5. Full breadboard performance with and without booster for 25 Gb/s DPSK modulation in the red band

of the link is evaluated by the BER versus received optical power (ROP) curves. The ROP is defined as the mean optical power per wavelength measured at the input of the receiver (before the LNOA). These curves are used to derive the required ROP for a target BER, also called the link sensitivity. This sensitivity is used to define the link budget and to size the system.

A. Measurement with the transceiver only

For these measurements, the emitter is modulated by a commercial pulse pattern generator (PPG) which generates high quality electrical signal. It is connected to the receiver through the VOA. The receiver is connected to an error detector (ED) for BER computation. All lasers are turned ON but only one channel is modulated at the same time because the PPG has only one output.

Fig. 3 presents the BER versus ROP for both downlink (red) and uplink (blue) in OOK and DPSK at 25 Gb/s. Blue LNOA mean noise factor is around 4 dB whereas red one is around 4.5 dB. This explains why the blue band transmission gives slightly better performance than the red one. Table 1 summarizes the transceiver sensitivity for a target BER at 10^{-3} , chosen under the assumption of FEC that can improve the BER up to quasi-error free operation.

TABLE 1. TRANSCIEVER SENSITIVITY AT 25 GB/S FOR BER AT 10^{-3}

ROP for BER at 10^{-3} [dBm]	OOK		DPSK	
	Red	Blue	Red	Blue
Transceiver	-39.0 (± 0.1)	-39.8 (± 0.2)	-42.2 (± 0.2)	-42.7 (± 0.1)

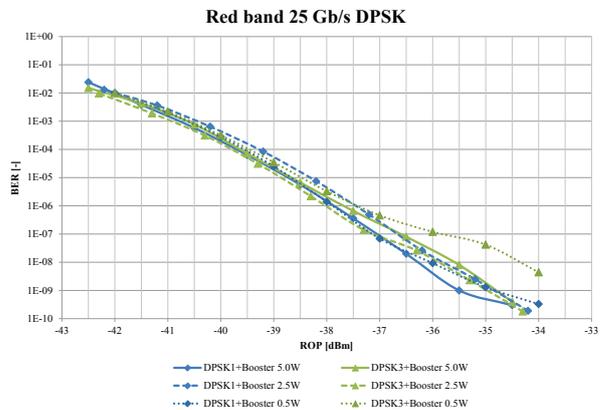


Fig. 7. Full breadboard performance with various booster powers for 25 Gb/s DPSK modulation in the red band

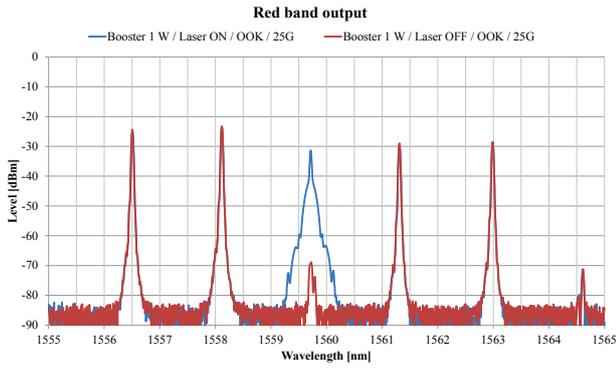


Fig. 8. Optical spectrum at the 1 W-booster output. Only the center channel is modulated. Blue curve: all lasers are turned ON; red curve: the central laser is turned OFF.

B. Measurement with the full breadboard

The emitter is now modulated by the DPU-Tx. The booster is inserted (or not) in the link. The receiver is connected to the DPU-Rx for BER computation. The three modulated channels are measured at the same time so as to take into account possible cross-talk.

Fig. 4 and Fig. 5 report BER versus ROP curves with and without 5 W-booster for OOK and DPSK modulations at 25 Gb/s in the red band. The DPU has a significant impact on the transmission performance at 25 Gb/s. Average power penalties of around 2 dB and 1.5 dB are observed respectively for OOK and DPSK compared with the curves of Fig. 3. The signal quality at the DPU-Tx output, the DPU-Rx electrical bandwidth as well as the intrinsic sensitivity of the DPU-Rx (ability to choose the best sampling instant and the best decision threshold for deciding a bit) explain this impact as channel cross-talk is low without booster. DPU-Rx design is optimized for differential input while OOK receiver is single ended contrary to DPSK. This can explain why performance degradation is more pronounced for OOK.

The introduction of the booster into the link brings around 0.5 dB additional penalty for a BER at 10^{-3} due to the degradation of signal to noise ratio (SNR). In addition for OOK modulation, we observe a beginning of error floor for low BER. When reducing the booster power (see Fig. 6 and Fig. 7) the error floor disappears for OOK modulation. In fact this error floor is due to non-linear effects (NLE) that arise in the booster fiber.

NLE in optical fibers occur due to change in the medium refractive index with optical power density and inelastic

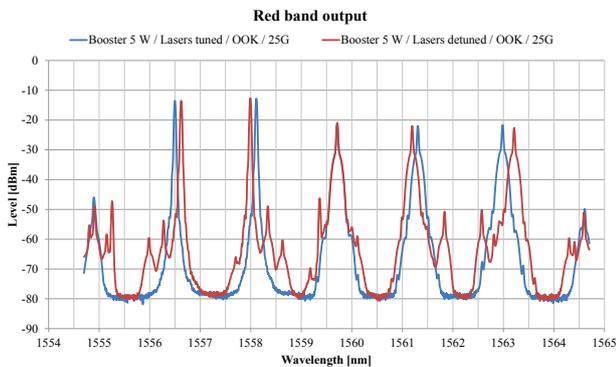


Fig. 10. Optical spectrum at the booster output when lasers are equally spaced (blue curve) and not equally spaced (red curve)

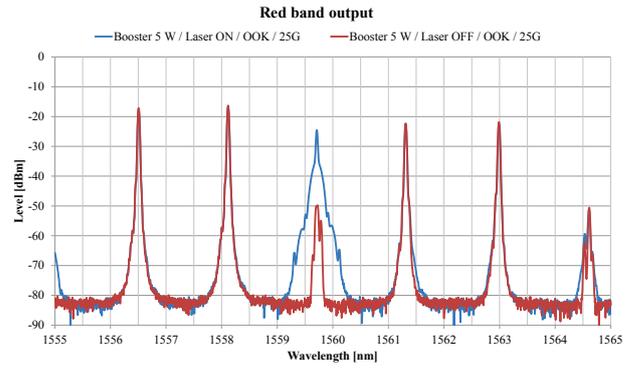


Fig. 9. Optical spectrum at the 5 W-booster output. Only the center channel is modulated. Blue curve: all lasers are turned ON; red curve: the central laser is turned OFF.

scattering phenomenon [14]. The power dependence of the refractive index is responsible for the Kerr-effect. Depending on the input signal type, the Kerr-nonlinearity manifests itself in three different effects such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM). At high power level, the inelastic scattering phenomenon can induce stimulated effects such as stimulated Brillouin-scattering (SBS) and stimulated Raman-scattering (SRS). The NLE strength depends on the optical power launched in the fiber, the fiber length and the ratio n_2/A_{eff} , where n_2 is the nonlinear refractive index of the fiber and A_{eff} the light-mode effective area. The non-linear effect that will interest us most is the FWM. It occurs when light of two or more different wavelengths are launched into a fiber giving rise to spurious wavelengths generated by linear combinations of the others. This effect can be devastating for WDM signals with equally spaced channels as the generated frequencies coincides with transmission channels, leading to bit dependent interferences which degrade the transmitted signal.

Fig. 8 and Fig. 9 illustrate the FWM effect for 1 W and 5 W booster powers. Blue curves correspond to the optical spectrum at the booster output for the 5 optical channels of the red band with only the centered channel modulated by 25 Gb/s OOK signal. For red curves, the center channel has been turned OFF so as to measure the FWM spurious generated at this wavelength. The more the booster power is, the higher the FWM spurious level is. For 1 W optical power the isolation between the useful signal and the FWM spurious is around 35 dB. For 5 W optical power the isolation is reduced to around 25 dB.

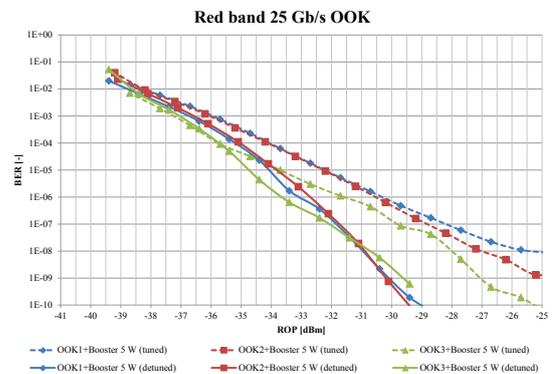


Fig. 11. Full breadboard performance when lasers are equally spaced (tuned) and not equally spaced (detuned) for 25 Gb/s OOK modulation

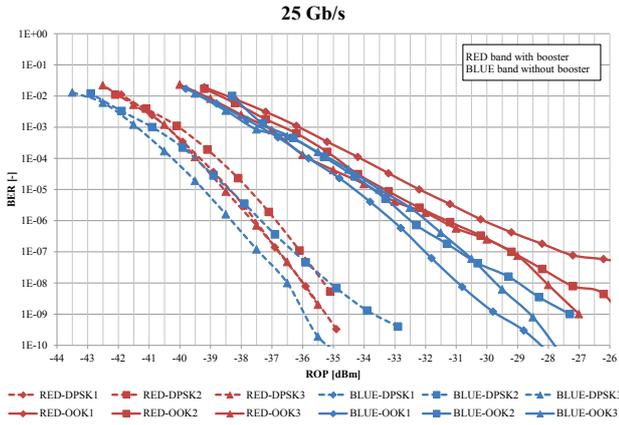


Fig. 12. Full breadboard performance for red and blue band in 25 Gb/s OOK modulation.

Because of its relatively constant envelope during low and high bit levels, DPSK signal is less sensitive to power modulation-related non-linear effects, such as SPM and XPM [15] [16]. This could explain why OOK modulation is more penalized by the booster nonlinearity for low BER.

To mitigate booster nonlinearity one can work on three axes: optimizing the ratio n_2/A_{eff} , breaking the spectral periodicity of WDM signal and/or reducing the number of optical channels per booster. In this paper, we propose preliminary results for the second solution. Fig. 10 shows the optical spectrum at the booster output when the optical channel spacing is uniform (laser tuned) and non-uniform (laser detuned). The center channel wavelength has not been changed. Detuning the lasers makes the FWM spurious to be generated at other frequencies than the channel frequencies. This will help to decrease the FWM spurious level that lies in the optical channel band and thus reduce interferences. BER versus ROP curves when lasers are tuned and detuned for a 5 W booster are presented on Fig. 11. By breaking the WDM periodicity, it is possible to cancel the error floor.

Fig. 12 presents a summary of BER versus ROP for the full breadboard in OOK and DPSK at 25 Gb/s (lasers tuned). Blue band has not been evaluated with the booster because the latter has been designed and optimized for the red band.

TABLE 2. SENSITIVITY SUMMARY FOR BER AT 10^{-3}

ROP for BER at 10^{-3} [dBm]	OOK		DPSK	
	Red	Blue	Red	Blue
DPU+ Transceiver	-37.1 (± 0.5)	-37.4 (± 0.2)	-40.7 (± 0.2)	-41.2 (± 0.2)
DPU+ Transceiver+ Booster	-36.8 (± 0.5)	-	-40.2 (± 0.2)	-

Table 2 summarizes the sensitivity for the configuration including only DPU and transceiver and for the full breadboard for a target BER at 10^{-3} .

V. CONCLUSIONS

FOLC breadboard was presented. It constitutes a first step towards the qualification of a versatile and scalable optical communication chain for direct to earth applications. NRZ-OOK and NRZ-DPSK performance have been assessed for simultaneous transmission of 3×25 Gb/s channels. The average sensitivity at 25 Gb/s of the full bread-

board is -36.8 dBm and -40.2 dBm respectively for OOK and DPSK considering a BER at 10^{-3} . Work has already been engaged to increase these sensitivities by improving the DPU characteristics and DPU to transceiver connections. Gain up to 2 dB and 1.5 dB should be accessible respectively for OOK and DPSK modulations. The DPSK sensitivity is around 3.4 dB better than OOK. Measurements reveal that non-linear effects start to appear inside the 5 W-booster. Because of its constant envelope during bit time, DPSK signal is less sensitive to power modulation-related non-linear effects than OOK. A solution based on unequally spaced WDM channels has been proposed to reduce the non-linear effects impact for low BER. The next step of the work on the EBB includes the integration of optimized FEC and interleaver to mitigate atmospheric turbulence.

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