# Real-Time 100 Gbit/s/λ PAM-4 Fiber Link supporting 4λ Operation with a Common Fiber Amplifier for Future Mobile X-haul and Point to Point Access Networks

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**Abstract** *We demonstrate a real time and DSP-free 100 Gbit/s/λ fiber link supporting 4λ operation for future generation mobile X-haul reaching 16.15 dB of channel insertion losses and 30 km, with the use of a common O-band fiber amplifier and transmitter analog pre-equalization. ©2022 The Author(s)*

## Introduction

After the commercial deployment of the 5th generation of mobile network (5G), the work on the 6th generation (6G) has begun. To handle new usages unlocked by future 6G networks, the future optical access network needs to be capable to transport the great amount of data that 6G will lever. Mobile Back/Mid/Fronthaul optical links capable to transport 100 Gbit/s to up to 1 Tbit/s are required [1] on a point-to-point topology (PtP). New usages such as industry 4.0 and metaverse should also benefit from these future high bitrate fiber links. The current PtP standards [2] used for mobile X-haul use intensity modulation and direct detection (IM/DD) with the Non-Return to Zero On-Off Keying (NRZ-OOK) modulation format and provide up to 25 Gbit/s per wavelength. Coherent technologies intend to meet the requirements for such transmission systems [3] but the added complexity and cost compared to an IM/DD system remains a drawback. Standardisation bodies like the Institute of Electrical and Electronics Engineers (IEEE) have already edited specification on 100 Gbit/s links [4]. For these links, the targeted channel insertion losses must be above 15 dB and the optical budget (OB) must reach to 21.5 dB. These requirements are defined for a reach of 30 km of the 100GBASE-ER4-30 [4] specification.

In this paper, we experimentally assess the use of a common optical fiber amplifier on a 4-levels pulse amplitude modulation (PAM-4) 100 Gbit/s/λ. This link supports 4λ operation with the wavelength plan of the multi-source agreement (MSA) specifying optical link at 4λx100 Gbit/s for 30 km reach (400G-ER4-30) [5]. We used a Praseodymium Doped Fiber Amplifier (PDFA) which is a fiber amplifier fabricated in fluoride glass and amplifying in the O band thanks to the stimulated emission of $Pr^{3+}$ ions pumped at 1000 nm. We assess the wavelength amplification range of our PDFA and its capacity to amplify linearly 4 channels based on the Local Area Network-WDM (LWDM) wavelength plan used for the MSA 400G-ER4-30. Finally, we assess the performances of our system to transmit 100Gbit/s/λ PAM-4 signal in back-to-back (BtB) and through 30 km propagation in standard single mode fiber (SSMF).

## Experimental setup

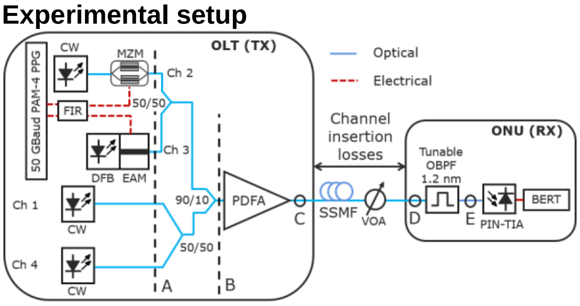


**Fig. 1:** Experimental setup.

The experimental setup is depicted on Fig.1. The 100Gbit/s (50 GBaud) real time PAM-4 signal is generated by a PPG which generates two pseudo random bit sequence of length $2^{15}$-1 (PRBS15) and PAM-4 encoded thanks to a 2-bit DAC. The electrical modulation signal passes through an analog 6-taps finite impulse response filter (FIR) with a time spacing of 7.5 ps and an electrical bandwidth of 64 GHz for analog pre-equalization [6]. The electrical modulation signal is then sent to two optical transmitters (Tx). The Tx called “Channel 2” (Ch 2) is composed of an external cavity laser (ECL) with a wavelength which can be tuned between 1260 nm and 1360 nm, and a Mach-Zehnder modulator (MZM) with a -3-dB electro-optical bandwidth (EO-BW) of 40 GHz. The MZM is driven at 4.0 Vpp leading to an extinction ratio (ER) of 8 dB. The second Tx called “Ch 3” is a distributed feedback laser (DFB) and an electro-absorption modulator (EAM) integrated on the same chip which forms an externally modulated laser (EML) emitting at

1309.1 nm. The DFB and EAM are respectively biased at 92 mA and -2.2 V leading to an ER of 6 dB. The chip is kept at 21.3 °C with the help of a thermo-electric cooler (TEC). The EML shows an EO-BW of 46 GHz. Since no LWDM multiplexer/demultiplexer (MUX/DEMUX) is available in our lab, the two optical signals which come from the two Tx are then combined in a 50/50 optical coupler. Our experimental setup does not allow to modulate 4 wavelengths at the same time, so two wavelengths are modulated at the same time and two others are added in the experimental setup without modulation. Two continuous wave (CW) sources called Ch 1 and Ch 4 are added and combined in another 50/50 optical coupler to complete the wavelength plan. The resulting signals coming from the two 50/50 coupler are combined in a 90/10 coupler, and we balance its output launch power for the 4 channels. Then, the 4 signals are amplified by a single PDFA with 26 dB small signal gain, 5 dB noise figure (NF) and a maximum output power of 15 dBm. The optical signal propagates through 0 or 30 km of standard single mode fiber (SSMF) and reaches a variable optical attenuator (VOA). The optical signal is demultiplexed with an optical bandpass filter (OBPF) which presents 1.2 nm bandwidth and insertion losses $\alpha_{OBPF}$ equal to 1.8 dB, and the optical signal is detected with a 42 GHz PIN photodiode (PD) coupled with an electrical transimpedance amplifier (PIN-TIA). The detected electrical signal is sent to a bit error rate (BER) detector (BERT) for symbol error rate (SER) evaluation. The BER is measured on each of the three eyes corresponding to $BER_1$, $BER_2$ and $BER_3$ of the PAM-4 signal by adjusting the amplitude decision threshold [6]. The SER is calculated by the following equation [7]:

$$SER = {}^{1}/_{2}\,BER_1 + BER_2 + {}^{1}/_{2}\,BER_3.$$

## Results and discussion

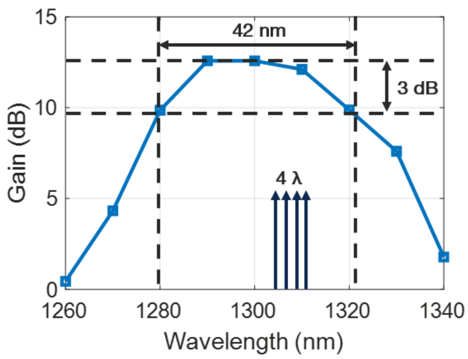


**Fig. 2:** PDFA gain versus signal wavelength for a total mean power of 0 dBm input power.

Fig. 2 presents the gain of the PDFA at emitter's side (booster) with a signal input power of 0 dBm versus the single input wavelength. The amplification bandwidth at -3 dB is equal to 42 nm. The positions of the 4 wavelengths are materialized by the four arrows on Fig. 2. PDFA is a good candidate for multiwavelength amplification in the O-band due to its low noise figure (5 dB) and the absence of cross gain modulation and non-linear gain compression due to its slow dynamics [8].

To assess the capability of the PDFA to amplify multi-wavelength signals and reach the performance standard's requirements, we first assess our amplified link in a single wavelength tunable configuration. Fig. 3 presents the sensitivity and the optical budget versus the wavelength of the Tx in BtB. For this experiment, the optical budget (OB) is defined as $P_{TX}(at\ point\ C) - P_{RX}(at\ point\ E)$ (between the PDFA output and the OBPF output). To obtain these results, only Ch 2 is turned on. The emitting wavelength of the ECL is tuned from 1270 nm to 1340 nm with a 10 nm step.

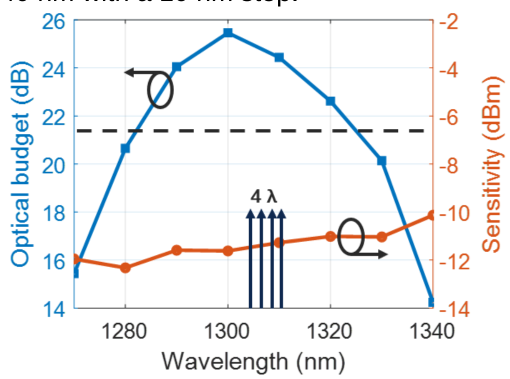


**Fig. 3:** Optical budget (blue square curve) and sensitivity at FEC threshold (red circle curve) of the Rx versus the wavelength of Ch 2.

The sensitivity of the receiver at the forward error correction (FEC) threshold is defined at SER=$10^{-2}$ based on the FEC threshold of SD-FEC [9]. The sensitivity of the receiver stays in a range of 2.2 dB for all the wavelength range. It is not the case for the OB which depends on the launch power at the output of the PDFA ($P_{launch}$) and so depends on the gain of the amplifier at the Tx wavelength. With only one signal in the PDFA, the wavelength range to obtain 21.5 dB or more OB is from 1282 nm to 1325 nm giving a wavelength tunability of 43 nm.

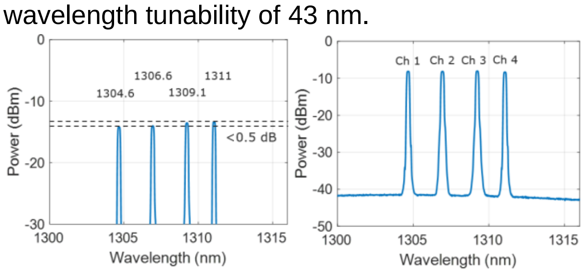


**Fig. 4:** Optical spectrum of the WDM comb signal at the input of the PDFA (a)) and at the output (b)) with a flatness better than 0.5 dB.

Based on the MSA 400G-ER4-30 in the context of transport networks, the WDM wavelength plan is with channel centered at: 1304.6 nm, 1306.9 nm, 1309.1 nm and 1311 nm with 400 GHz channel frequency spacing. Fig. 4 presents the optical spectrum of the signal at the input (Fig. 4 a)) and at the output (Fig. 4 b)) of the PDFA. The input signals are set to present a flatness better than 0.5 dB. On the signal at the output of the PDFA, the signal is not distorted and the flatness of the signal stays better than 0.5 dB. Between the 4 wavelengths transmitted in our experimental setup, 2 are modulated and 2 are continuous wave (CW) signals. The 1st modulated signal is Ch 3 coming from the DFB-EAM and emitting at 1309.1 nm and the 2nd modulated signal is alternatively each other three values of the wavelength plan for analysis of Ch 1, Ch 2 and Ch 4.

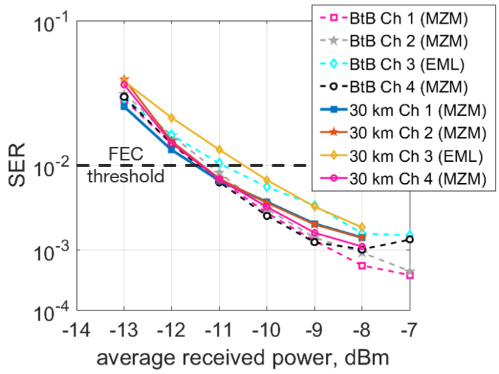


**Fig. 5:** SER versus average received optical power measured on point E in BtB (dash curve) and after 30 km of SSMF (full curve) for Ch 1, Ch 2 and Ch 4 (MZM) and Ch 3 (EML).

The sensitivity of the receiver is assessed through the SER measurements on the four channels. Fig. 5 presents the SER versus average received optical power at point E, in BtB and with 30 km of propagation in SSMF.

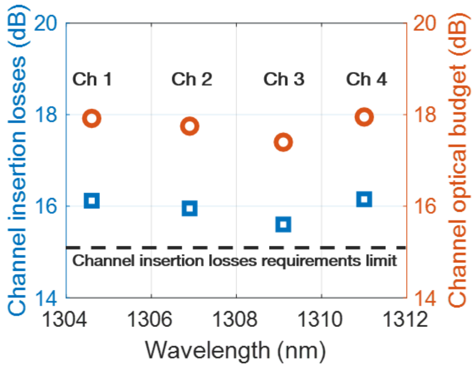


**Fig. 6:** Channel insertion losses (blue squares) and channel optical budgets (red circle) for the four channels in BtB.

Fig. 6 presents the channel insertion losses (blue square) and the OB (red circle) for the four wavelengths of the comb for each channel. Channel insertion losses are defined as $P_{TX}(at\ point\ C) - P_{RX}(at\ point\ E) - \alpha_{OBPF}$ for the four wavelengths of the comb. The output power of the PDFA ($P_{TX}$) is equal to 6.6 dBm on the three CW and 6.4 dBm for Ch 3. Channel insertion losses up to 16.15 dB are then obtained as depicted on Fig. 6. As mentioned before, the minimum requirement for channel insertion losses is 15 dB [6]. These performances in terms of channel insertion losses and OB can be improved by using a proper LWDM MUX/DEMUX instead of the combination of optical couplers we employed for practical reasons. The insertion losses of the combination of optical coupler are indeed 4.5 dB larger than a MUX/DEMUX (at least 6 dB for Ch 2 and 3 (measured between plan A and B on Fig. 1) compared to 1.5 dB typically for a commercial MUX/DEMUX). Another point is that the PDFA does not work in saturation regime due to a low input power (the balanced comb power is limited by one of our CW sources delivering low power).

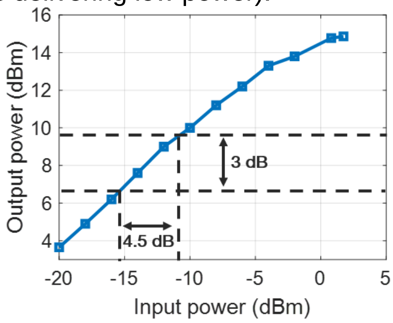


**Fig. 7:** PDFA output power versus input power.

As depicted on the output power versus input power curve (Fig. 7) of our PDFA at 1308 nm (middle of the comb), increasing the input power by 4.5 dB would increase the output by 3 dB. In these conditions, the channel insertion losses would reach up to 19.15 dB after 30 km fiber propagation.

## Conclusions

We assess the behaviour of a common praseodymium doped fiber amplifier in a multi-wavelengths real time and digital signal processing free 100Gbit/s/λ transmission with two modulated wavelengths over 30 km of standard single mode fiber with up to 16.15 dB of experimentally measured channel insertion losses. PDFA is still complex to be commercialized massively due to its cost and integration difficulties. However the PDFA can be replaced for example, by a bismuth doped fiber amplifier [10] which can be fabricated in silica fiber allowing an easier fabrication and integration than the fluoride glass used for PDFA. On the contrary, the use of a semiconductor optical amplifier instead of a fiber amplifier can be complicated in links supporting multi-wavelengths transmission mainly due to crosstalk issues and non-linear gain compression. This work sketches a possible IM/DD system working at 400 Gbit/s operation on 4λ with a single common O-band fiber amplifier.

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