128GBd record QPSK transmission over 20 631 km and PCS16QAM transmission over 12 558 km using InP technology Platform

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Abstract: We experimentally demonstrate the generation, transmission, and detection of 128GBd QPSK and PCS16QAM signals in optical submarine systems. We have validated the transmission of 33 channels PCS16QAM along the C-band over 12 558 km with an average of 0.74 dB margin from 25% soft FEC threshold.

1. Introduction

The evolution of coherent transponders has always been distinguished for increasing channel capacity. The exponential growth of IP traffic demand, cloud datacenters, radio mobile stations require channel capacity at ever higher symbol rates. In the era of open cables systems, Subsea Line Terminating Equipment (SLTE) are likely to be equipped with the latest generation of coherent transponders. On one side, the advances in Application-Specific Integrated Circuit (ASIC) have brought improvements in the generation and reception of the digital channels, Probability Constellation Shaping (PCS), efficient pulse-shaping are some key aspects on this concern. On the other hand, InP-based Photonic Integrated Circuit (PIC) are becoming the dominant platform whose characteristics in terms of bandwidth, energy efficiency and footprint respond to the demands of the optical communication industry. These transponders should provide adequate transmission performance, reduced latency and reliability according to the boundaries of the system. New generation of coherent solutions are prone to replace present submarine transponders while maintaining quality and operation.

Increasing symbol rate in coherent transponders, besides lowering cost-per-bit of traffic, it allows to upgrade per-channel capacity for a given distance transmission. This is particularly interesting for existing submarine networks where the upgrading of transponders brings some extra terabits of additional capacity to the network. High Baud rate transmissions has already been demonstrated for short-haul and metro applications [1-9]. Few works deal with long-haul subsea transmission [10-13]. In 2020 Carbo *et al.* have demonstrated more than 100GBd transmission rate over 9 500 km distance [12], later Benyahya *et al.* have shown 120GBd PCS16QAM transmission over 10 890 km [13]. Transmission in ultra-long haul is a challenge when chromatic dispersion is highly predominant. In this paper we demonstrate record-distance submarine transmission of 128GBaud QPSK (20 631 km) and PCS16QAM (12 558 km) using InP integrated technology. To the best of our knowledge, this is the longest transmission above 100GBd reported so far (Figure 1a).

2. Prototype Transmitter

The experimental setup is showed on Figure 1b. It consists of two DAC (Digital-to-Analog Converter) modules interleaved to generate four differential output channels of 256 GSa/s. All the DACs are fully synchronized by a common source clock of 64 GHz, so timing skew between modules is less than 0.5 ps. We generate a pseudo-random sequence of 2^15 symbols with 2% of pilot tones. Sharp variations of the electrical signal are partially clipped in 2% to reduce distortion. At the output of the DAC, we use an InP coherent driver modulator (CDM) compliant to the Optical Interworking Forum (OIF). The co-packing of driver amplifier and I/Q modulators minimizes losses and reduces mismatch impedance produced by electrical cables. This technology enables the operation at relatively low voltages (some hundreds of millivolts in swing voltage) avoiding the use of additional noisy amplifiers. In order to maintain the quality of the electrical modulated signal, we developed a house-made interconnexion of RF cables to the CDM.

Pre-Distortion of DAC and MZM (Mach-Zehnder Modulator) are compensated separately, firstly by performing back-to-back electrical calibration which accounts for the overall time delay of interleavers, cables and connectors. Then, adjusting modulator substrate bias of the CDM to hold on constant V_π during transmission.

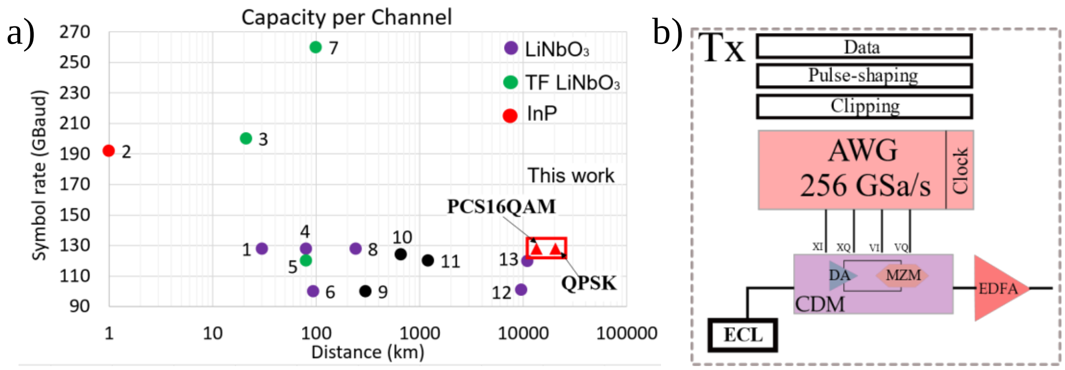

Figure 1. a) Summary of single-channel transmission over distance for recent record experiments (>100 GBd). b) Coherent prototype transmitter for 128GBd. AWG: Arbitrary Wave Generator. CDM: Coherent Driver Modulator. DA: Driver Amplifier. MZM: Mach-Zehnder Modulator. ECL: External-Cavity Laser. EDFA: Erbium-Doped Fiber Amplifier.

3. Jitter characterization and Pulse-shaping

For 128GBd transmission, half of symbol period (T_p) is 3.9 ps, tiny differences in the electrical cables or sudden variations in temperature may introduce loss or skew delay between channels. Figure 2a,b show the eye patterns for QPSK and PCS16QAM format reconstructed after 200 acquisitions. We have used a Raised Cosine (RC) filter with 0.3 roll-off-factor. We can estimate 3.7 ps of average jitter p-p, this is less than the half of symbol period T_p.

Time domain pulse shape is a crucial parameter in regard of spectral efficiency. It is well-known that reducing roll-off factor will produce narrower spectral bandwidth, allowing to increase the number of optical channels. In Figure 2c we show the dependence of jitter p-p as a function of roll-off factor. We have simultaneously tested the cases of RC and Root Raise Cosine (RRC) filters for: 0.3, 0.2, 0.1 and 0.01 roll-off factors. From the curve we observe how the jitter rapidly increases attaining 5.28 ps for the most efficient filter. This degradation of jitter brings challenges in the precision of sampling timing. In order to minimize this problem, we have generated our digital signal taking into account the reference source clock. We have decreased until RRC =0.01 without major degradation of our signal at reception. It turns out that while keeping accurate sampling rate during generation, efficient pulse-shaping can be applied without additional penalties. Figure 2d shows the optical power spectra for RRC filter, roll-off factor 0.1 and 0.01. Using this technical approach we observe a very good stability and less than 0.2% of acquisition-failure (Figure 2e).

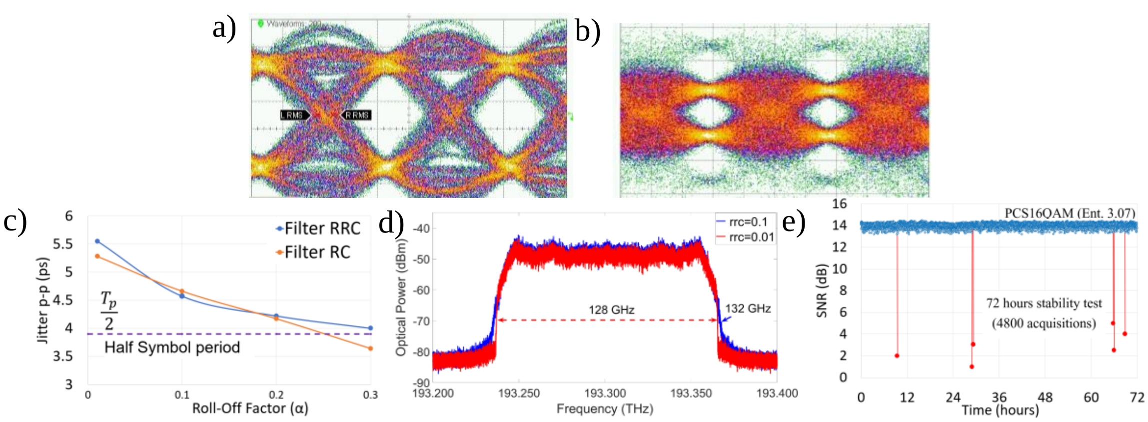

Figure 2. a,b) Eye-pattern of QPSK (left) and PCS16QAM (right). Time scale: 2.0ps/div. c) Jitter p-p of our DAC as a function of roll-off factor for RRC and RC shape filters. d) Optical power spectra for RRC pulse-shape filter with 0.1 and 0.01. e) Long-term stability test (72 hours) for PCS16QAM (Ent. 3.07).

3. Transmission experiments

We transmit our 128GBd signal in a recirculating loop system. The loop is composed of N=15 spans of nearly 60 km of 200-μm-diameter coating Pure Silica Core Fiber (PSCF). The characteristics of the optical fiber are: 0.15 dB/km of transmission loss, 21 ps/(nm·km) of chromatic dispersion and 115 μm^2 of effective area. The 128GBd channel is multiplexed with two adjacent channels of 74GBd and a continuous Amplified Spontaneous Emission

(ASE) noise source to fill up the 38 nm spectral bandwidth. All the three channels were sent to the recirculating loop where two Acousto-Optic Modulators (AOM) are fully synchronized with the input trigger signal of the Real-Time Oscilloscope (RTO). For each experimental condition (23 roundtrips for QPSK and 14 roundtrips for PCS), the recirculating loop was equalized to assure less than 1dB of OSNR difference between channels. The total output power of the amplifiers was 17.3 dBm. At the receiver side, Digital Signal Processing (DSP) is performed Off-Line. The DSP consist of chromatic dispersion compensator, time recovery, polarization demultiplexer, carrier frequency/phase correction, pilot-based cycle slip removal of 2% and post-equalizer. We apply spatial coupled Low Density Parity Check (LDPC) FEC decoding for error-free recovery of the signal [14]. Waveforms of 2 and 4 million points were processed for QPSK and PCS16QAM, respectively.

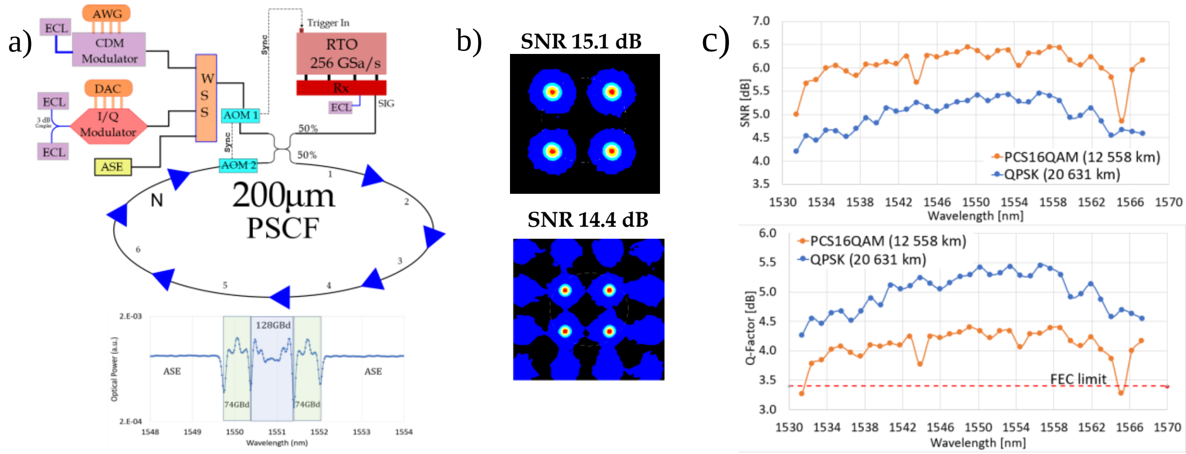

Figure 3. a) Recriculating Loop system, b) Constellation diagrams in Back-to-Back configuration with maximum SNR. c) Performance metrics of 128GBd QPSK over 20 631 km and PCS16QAM (H=3.07) over 12 558 km. AOM: Acousto-Optic Modulator. WSS: Wavelength Selective Switching. RTO: Real-Time Oscilloscope. PSCF: Pure Silica Core Fiber.

4. Results and conclusions

We performed the transmission of 35 channels which are fitted along the C-band with 132 GHz channel spacing. Figure 3c shows the performance metrics of QPSK over 20 Mm and PCS16QAM over 12 Mm. The average SNR for QPSK is 5.0 dB while PCS16QAM reaches around 6.0 dB. From 35 modulated channels in PCS, we recovered 33 error-free channels with margin above 0.74 dB from FEC threshold of 25% overhead. This is, to our knowledge, the longest transmission above 100 GBd reported so far.

5. References

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