

Transmission of 1.15 Tb/s NGI-CO-OFDM DP-QPSK Superchannel over 4520 km of PSCF with EDFA-only amplification

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Abstract—The development of coherent optical transmission technologies is impacting the design of the future optical networks. The increase in coherent transmission spectral efficiency (SE) in wavelength division multiplexing (WDM) systems is a strong research topic. High order quadrature amplitude modulation (QAM), Nyquist pulse-shaping and forward error correction coding are among digital transmission techniques being tested in optical coherent systems. Also, different optical implementations of orthogonal frequency division multiplexing (OFDM) were proposed for the next generation systems. In this paper, we investigated the performance of a 1.15-Tb/s (23x50-Gb/s DP-QPSK) superchannel with 3.75 b/s/Hz, using no-guard-interval orthogonal frequency division multiplexing (NGI-CO-OFDM), over pure silica core fiber (PSCF) and using erbium doped fiber amplifiers (EDFAs) only. A maximum reach of 4520 km was obtained. This result demonstrates reliability of these systems on fibers with regular effective area, unlike majority of related works that used large effective area fibers to demonstrate long haul performance.

Index Terms—Coherent Systems, CO-OFDM, Spectral Efficiency, Superchannel, Terabit transmission.

I. INTRODUCTION

Optical transmission technology has evolved rapidly in the last decades to meet the rising demands of a worldwide telecommunications services. Optical transport networks are now deploying 100 Gb/s WDM coherent transponders [1], which bring the total capacity per fiber to around 20 Tb/s, considering only C-band transmission. However, in a few years, this capacity will need to increase again to sustain the network functionality [2]. Since it is highly expensive to deploy new fiber links and make it operational, the development of coherent optical systems may bring advantageous solutions to overcome capacity bottlenecks. Today most indicators point out that the next optical transmission technology to hit the market will be 400 Gb/s per channel [3], with Tb/s superchannels being the most likely follow up solutions. One of the main challenges in this evolution is how to use network's resources (bandwidth, power, etc.) in an efficiently way. Approaches such as flexible grid channel allocation and elastic and cognitive optical networks are under consideration [4]. In fact, even

in 400 Gb/s transmission technology architectures proposals, flexible grid deployment is already being considered in a great number of papers with state-of-the-art technology [5-7]. In the flexible optical networks scenario, superchannels are strongly promising alternatives for efficient flexible adaptive transponders implementation. These transponders will have capability to operate with adjustable number of subcarriers, bandwidth, modulation formats, spectral efficiency (SE) and data rates [2]. These features are required in order to explore all physical degrees of freedom to maximize the network resources. Considering these facts and assumptions, orthogonal frequency division multiplexing (OFDM) is a strong alternative to be considered for the next generations of optical transmission systems. In this paper, we describe and analyze a proposal to achieve 1.15 Tb/s channel transmission with spectral efficiency of 3.75 b/s/Hz using NGI-CO-OFDM with dual polarization quadrature phase shift keying (DP-QPSK) as modulation format. Long-haul transmission reach was demonstrated without the benefits of large effective area fibers and Raman amplification.

II. ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OFDM)

OFDM is a multi-carrier digital transmission technique that can achieve high spectral efficiency by dividing the data among a set of orthogonal carriers. This technique is more efficient than conventional frequency division multiplexing (FDM) approach because it allows, under specific orthogonality conditions, the subcarriers spectrum to overlap preserving carriers' separation properties without significant crosstalk interference. Once each carrier symbol duration is much longer compared to that of a single carrier system operating at same OFDM channel total rate, equalization of channel effects like frequency selective time dispersion and inter-symbol interference (ISI) is easier, since it can take advantage of per carrier parallel processing strategies to overcome high channel frequency selectivity. In Fig.1, bandwidth occupation of OFDM is compared with corresponding FDM implementation.

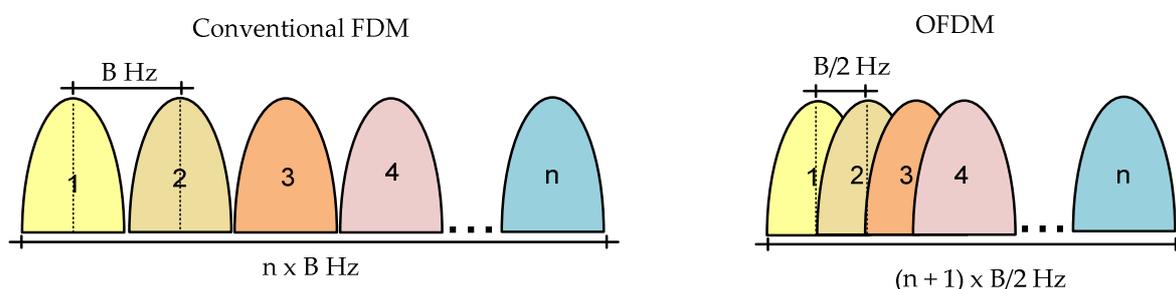


Fig. 1. Frequency multiplexing techniques. (a) Conventional FDM; (b) OFDM.

In Fig. 1, the OFDM superchannel uses less bandwidth to transmit the same data rate, increasing the overall system SE. In fact, when the number of OFDM subcarriers (n) increases, the SE approaches the Nyquist pulse shaping limits, when considering the same number of carriers, modulation format

and baud rate in a FDM equivalent system. OFDM is a very successful technique in wireless and wireline communication systems. Due to performance characteristics, it is currently being considered for optical transmission in large capacity optical networks. The original concept of CO-OFDM was proposed in [8]. Experimental results of NGI-CO-OFDM transmission were showed in [9-14]. Particularly, no-guard-interval coherent optical OFDM (NGI-CO-OFDM) is considered as a solution for optical transmission systems at data rates beyond 100 Gb/s. In NGI-CO-OFDM subcarriers must be generated with a phase and frequency locking technique to guarantee orthogonality. In this case, a comb of harmonic subcarriers can be generated from a CW laser and each carrier is modulated individually observing the OFDM orthogonality conditions. At the receiver, the OFDM signal is mixed with a local oscillator using a polarization diverse coherent receiver, and converted to the digital domain DSP algorithms are then employed to estimate the transmitted data streams after performing clock recovery, equalization and carrier recovery.

III. SUBCARRIERS: COMB GENERATION

In this work it was employed the comb carriers generation method described in [15-16]. This method uses a CW laser as seed to generate harmonic optical subcarriers, followed by cascaded amplitude (AM) and phase (PM) modulators driven by sinusoidal signals with a frequency of 12.5 GHz. This will determine the subcarriers spacing.

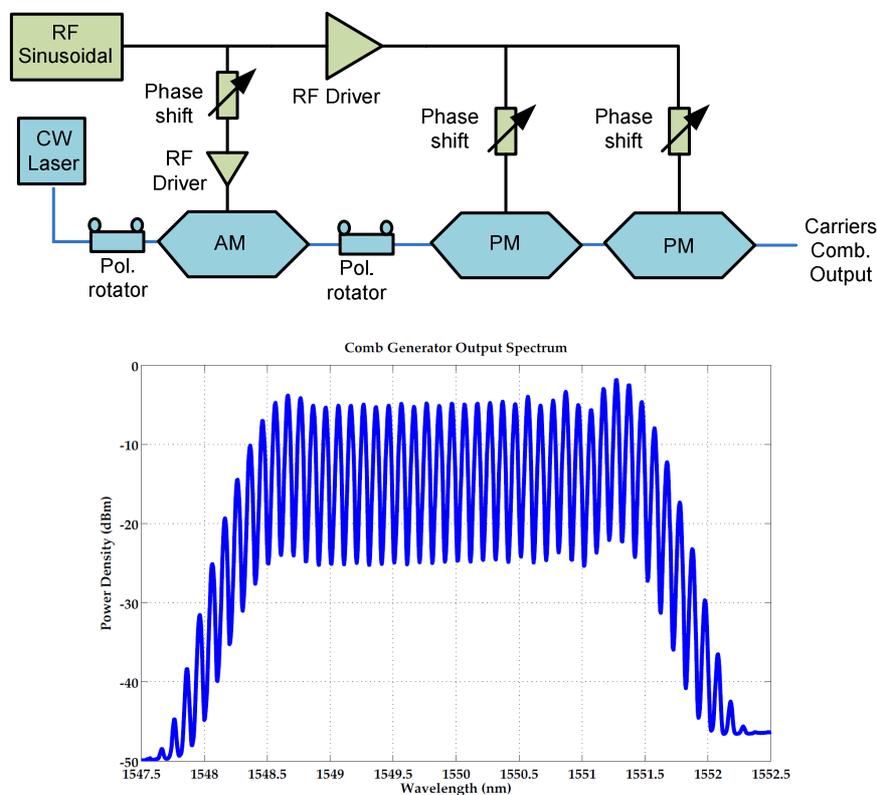


Fig.2: Harmonic comb generation setup (top) and generated comb spectrum (bottom).

The comb of harmonics generated is based on the principle of time-to-frequency (TTF) conversion [15], which presents very good stability and flatness. More than thirty subcarriers with less than 5 dB flatness were generated, but the experiments presented here used a band-pass filter to select a set of 23 spectral lines, centered at 1550 nm wavelength.

IV. EXPERIMENTAL SETUP

In Fig.3 the experimental setup to generate, transmit and receive 1.15 Tb/s NGI-CO-OFDM DP-QPSK signal is shown. In Fig. 3 (a), a sinusoidal clock source of 6.25 GHz was used to configure the output of a pseudo random bits sequence (PRBS) generator for a baud rate of 12.5 Gbaud. A PRBS with length of $2^{15}-1$ was used. This signal was split into two copies. By mean of RF delay lines, different delays were applied to these copies in order to make then uncorrelated by an integer number of symbol periods. Each signal was amplified in order to guarantee the appropriate RF signal power required by the IQ modulator to generate a 25Gb/s QPSK signal. All 23 orthogonal carriers were directed modulated with the same data. The optical signal at modulator's output was amplified by a polarization maintaining EDFA with 24 dBm output power and passed through a polarization multiplexing stage, further increasing the bit rate to 50 Gb/s per subcarrier, as in Fig.3 (d).

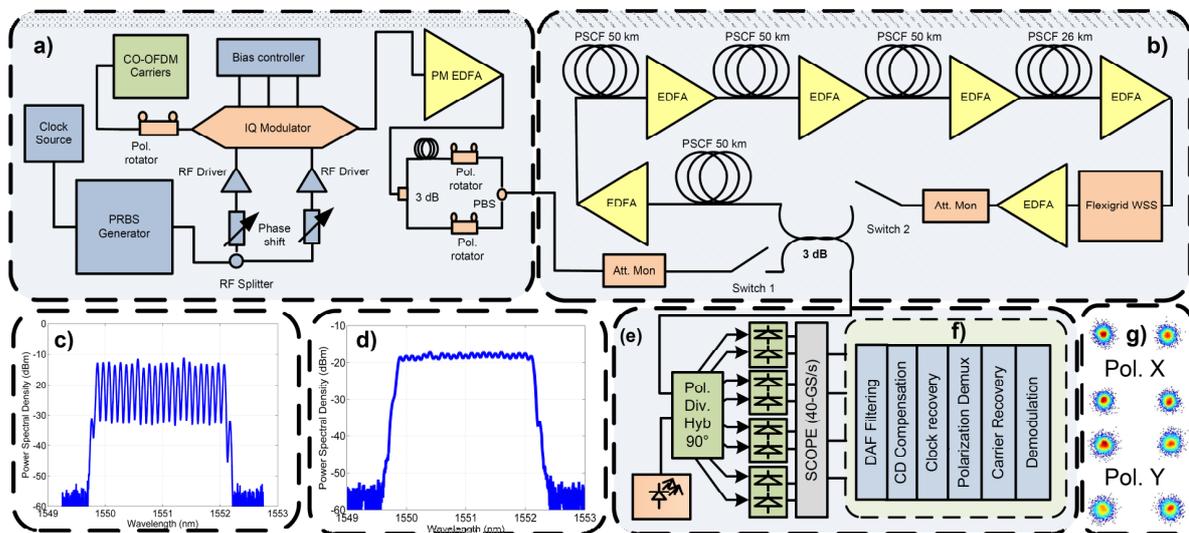


Fig.3: Experimental setup for 1.15 Tb/s NGI-CO-OFDM DP-QPSK generation, transmission and reception. (a) Transmitter; (b) Recirculation loop; (c) Comb of orthogonal carriers; (d) Modulated carriers spectrum; (e) Receiver front-end; (f) Offline DSP; (g) Recovered QPSK constellations.

The 1.15Tb/s signal propagated through a recirculation loop consisted of four 50 km spans plus one 26 km span of pure silica core fiber (PSCF), totaling 226 km, and only EDFA amplification (Fig.3 (b)). A wavelength selective switch (WSS) was used as a filter and a spectrum equalizer. At the

receiver side, optical-to-electrical signal conversion was performed by a standard optical coherent receiver, comprised of a local oscillator, and polarization diverse hybrid and balanced photodiodes, as per Fig.3 (e). The local oscillator was tuned to perform the A/D conversion of each subcarrier information. The baseband electric signal A/D conversion was performed using a real-time scope operating with 40 Gsamples/s, allowing an oversampling of 3.2 samples/symbol. The digitized signal was processed offline by digital signal processing algorithms to process the subcarriers separation via delay and add filtering (DAF) [17] in order to compensate for chromatic dispersion, polarization mode dispersion, polarization dependent loss, imperfect construction of front-end devices, and deviations in frequency between carrier and local oscillator, amongst others [18].

V. RESULTS AND ANALYSIS

The back-to-back transmission was firstly conducted to evaluate the BER performance as function of OSNR at receiver. In this experiment, receiver’s local oscillator frequency was tuned to the central carrier of the modulated spectrum in order to acquire and evaluate its respective transmitted data. Fig.4 shows theoretical and experimental BER vs. OSNR (in 0.1 nm) curves for one DP-QPSK subcarrier at 12.5 Gbaud transmission. The forward error correction (FEC) limit of 3.8×10^{-3} is considered for a coding overhead of 7%. An OSNR of ~ 9.5 dB was measured for BER approaching the FEC limit, presenting a 1 dB implementation penalty when compared with theory. For higher OSNR values this penalty increases reflecting the not ideal characteristics of the experimental setup.

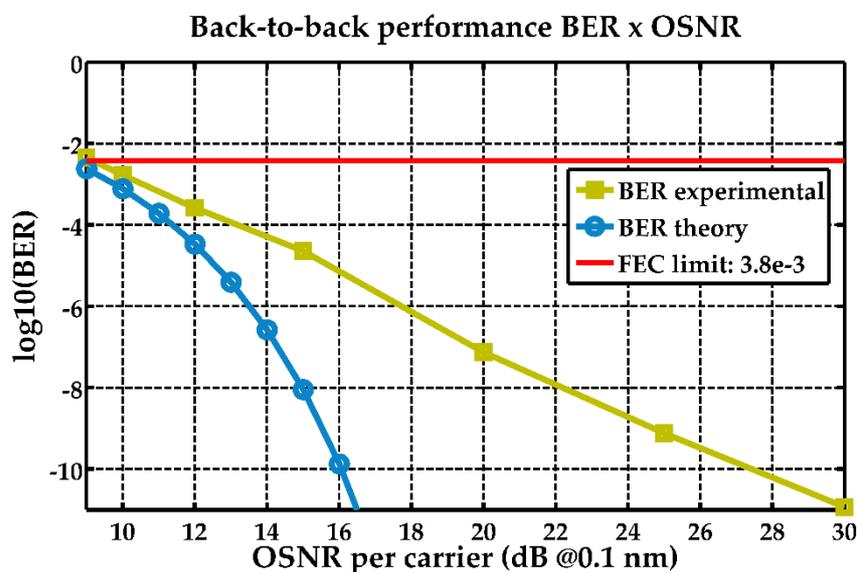


Fig. 4: Theoretical and experimental BER versus OSNR performance curve for one DP-QPSK carrier at 12.5Gbaud.

In Fig. 5, the fiber launched power for the 1.15 Tb/s CO-OFDM DP-QPSK was varied between 5 and 12 dBm for all fiber spools in the loop, after 4520km (or 20 recirculating turns). BER is calculated for

the center carrier, that must be the most affected by crosstalk and non-linear distortion, at each of the measured launch powers. A total power of 6 dBm was found as value that gave the best tradeoff between OSNR value and penalties due to non-linear effects.

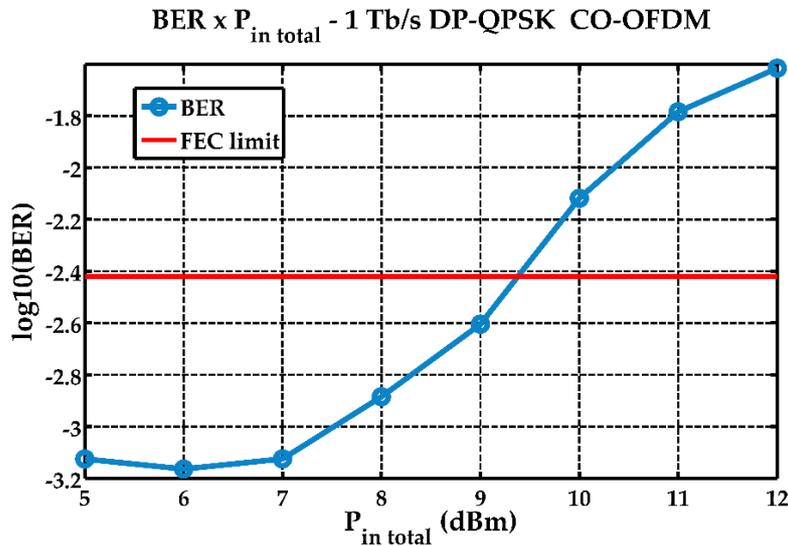


Fig.5: Performance of BER after 4520 km as function of total fiber launch power at recirculation loop.

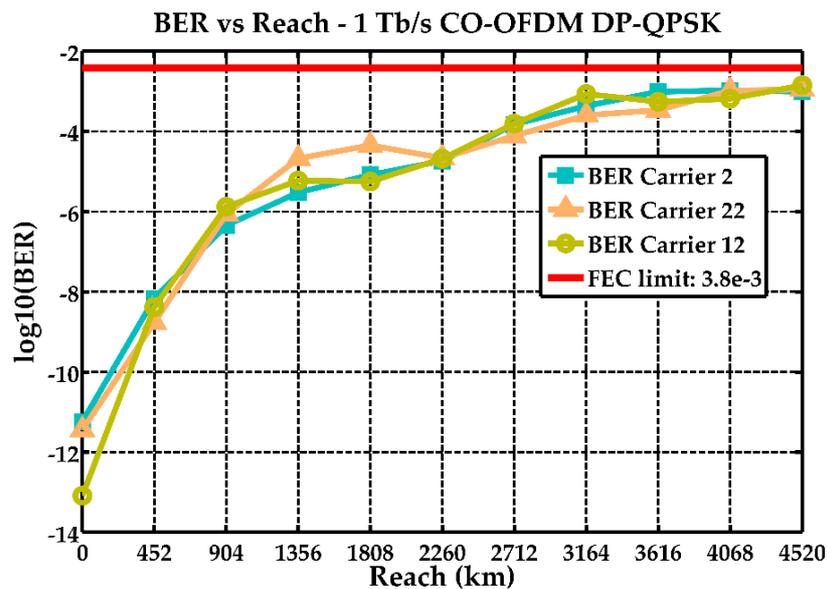


Fig.6: Performance BER versus reach in a 226 km PSCF plus EDFA recirculation loop.

The transmission performance against reach is shown in Fig 6. The BER was evaluated for central carrier and two neighbors to external carriers of the modulated spectrum. The other carriers did not showed worse performance than shown in Fig.6. This performance could be considered as overestimated, once all the subcarriers were modulated with the same information and they must interfere constructively at receiver input. However, based on results showed in [20], we believe that a

possible OSNR gain by inter-carriers constructive interference at the receiver probably will be counteracted by the increase of non-linear penalties due self-phase and cross-phase since the fiber has a regular core size. This is a topic for future investigation. With BERs below the stringent FEC limit, a maximum distance of 4520 km was reached using EDFA-only, suggesting that this approach may be suitable for long haul transmission, even without the use of Raman or hybrid amplification.

VI. CONCLUSION

We experimentally demonstrated 1.15 Tb/s CO-OFDM DP-QPSK superchannel transmission over 4520 km of pure silica core fiber and only EDFA amplification. This superchannel occupied a 287.5 GHz bandwidth, with a corresponding spectral efficiency of 3.75 b/s/Hz, reaching over 4000km without the aid of Raman amplification.

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