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9.6Tb/s CP-QPSK Transmission Over 6500 km of NZ-DSF With Commercial Hybrid Amplifiers

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Abstract—We experimentally demonstrate, for the first time to the best of our knowledge, an ultralong-haul dense wavelength division multiplexed transmission of $96 \times 100\text{Gb/s}$ coherent polarization multiplexed quadrature phase-shifted keying transponders over ITU-T G.655 nonzero dispersion-shifted large effective area fibers (NZ-DSF) with an effective core area of $72 \mu\text{m}^2$, employing both commercial erbium-doped fiber amplifiers (EDFA) and hybrid EDFA + Raman amplification systems. Using the state-of-the-art digital pulse shaping and digital preemphasis algorithms, we report $\sim 1.5\text{dB}$ back-to-back optical signal-to-noise ratio penalty at pre forward error correction (FEC) bit error rate (BER) threshold (3.8×10^{-2}), with respect to theoretical performance. In particular, we demonstrate $\sim 6500\text{km}$ transmission across the entire C-band, at pre-FEC BER of 3.8×10^{-2} , employing EDFA + backward Raman amplification—where the central channel (1552.2nm) had sufficient margin to enable transmission of up to $\sim 8000\text{km}$. Furthermore, we report that hybrid amplification enables up to $\sim 60\%$ improvement in maximum transmission reach, compared to EDFA based links. To the best of our knowledge, a record capacity-distance product of $\sim 62.4 \text{ Pb/s} \cdot \text{km}$ is achieved for NZ-DSF—an 11-fold increase, compared with the previous literature.

Index Terms—Optical fiber communication, digital filters, Kerr effect, digital signal processing.

I. INTRODUCTION

IN RECENT years coherently detected polarization multiplexed quadrature phase shifted keying (CP-QPSK) has emerged as a de-facto modulation format for commercial products, addressing applications ranging from metro to ultra long-haul transmission systems [1]–[3]. In order to further fuel the insatiable capacity demands, digital-to-analog converter (DAC) based flexible transponders are currently developed, allowing switchable modulation

formats including CP-QPSK, coherently detected polarization multiplexed quadrature amplitude modulation (CP-8QAM) and (CP-16QAM) [4]–[8]. One of the key concerns with the introduction of spectrally-efficient network traffic is the limited transmission reach due increased optical signal-to-noise ratio (OSNR) requirements. For instance, CP-16QAM doubles the network capacity, compared to CP-QPSK, however at the cost of $>70\%$ reach reduction over standard single mode fiber (SSMF) [9]. In order to alleviate such limits, distributed signal amplification [10], [11], and advanced digital signal processing (DSP) techniques [12], [13], are expected to become increasingly important. However, even with such niche configurations, the maximum reach for higher order formats remains limited in practical link topologies [14]. Consequently, CP-QPSK is still considered to be the sweet spot for long-haul and ultra long-haul transmission applications.

In recent years, numerous transmission experiments and field trials have been carried out, using commercial products and lab prototypes, demonstrating progress in high capacity long distance transmission [15]–[17]. However, the majority of these trials were either conducted on SSMF or ultra large effective area fibers (ULAF), employing short span lengths, adaptive forward error correction (FEC) codes, fiber nonlinearity compensation, etc., which represents rather optimistic transmission characteristics. In practice, commercial networks operate in non-ideal conditions with high span loss, conventional DSP algorithms, and employ a wide range of fiber types, including, SSMF, non-zero dispersion shifted fibers (NZ-DSF), large effective area fibers (LEAF), dispersion shifted fibers, formerly deployed to support legacy traffic operating at 10Gb/s and 40Gb/s [18]. One of the most common NZ-DSF fiber with $>30\text{Mkm}$ deployed worldwide is ITU-T G.655 LEAF [19], [20], with challenging characteristics of lower dispersion coefficient, higher loss per km, and higher nonlinear coefficient, compared to the SSMF. Note that LEAF is considered one of the best fibers in G.655 in ITU-T G.655 recommendation, however, its transmission performance is significantly worst, compared to G.652 SSMF [21]. These fiber design parameters make long distance transmission increasingly challenging with state-of-the-art industry-ready communication systems, even with a robust modulation format like CP-QPSK.

In this letter, we report on record transmission of dense wavelength division multiplexed (DWDM) $96 \times 100\text{Gb/s}$ CP-QPSK over G.655 LEAF in a recirculating loop experiment. We employ digital pre-emphasis (DPE) and root raised cosine (RRC) pulse shaping to enable a semi-Nyquist

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Fig. 1. Experimental setup for dispersion uncompensated G.655 NZ-DSF LEAF transmission of $96 \times 100\text{Gb/s}$ CP-QPSK. WSS: wavelength selective switch, PS: polarization scrambler, ASE: amplified spontaneous emission, BPF: band pass filter, ADC: analog-to-digital converter.

DWDM transmission system, demonstrating a practical ultra long-haul solution for next-generation switchable transponders. In particular, we demonstrate $\sim 6500\text{km}$ transmission, at bit error rate (BER) below (or equal to) the pre-FEC BER threshold of 3.8×10^{-2} , across the entire C-band. It is worth mentioning that the central channel (1552.2nm) had enough margin to allow up to $\sim 8000\text{km}$ transmission. To achieve these results, we employ commercial hybrid amplification systems, including EDFA + backward Raman (quad pumped) amplifiers. Furthermore, we also establish that hybrid amplification systems allow up to $\sim 60\%$ reach improvement, compared to conventional EDFA only transmission links. This work records the highest capacity-distance product for widely deployed NZ-DSF fiber type, increasing from $5.2\text{Pb/s}\cdot\text{km}$ [17] to $62.4\text{Pb/s}\cdot\text{km}$ – an increase of $\sim 1100\%$.

II. EXPERIMENTAL SETUP DETAILS

Fig. 1 shows the experimental setup. DSP prior to DAC was performed offline, where a pseudo-random-bit-sequence of length 2^{15} was mapped to QPSK, followed by root-raised-cosine pulse shaping (RRC), and digital pre-emphasis (DPE). The RRC filter roll-off was chosen to be 0.2, based on a practical tradeoff between horizontal eye closure due to RRC pulse shaping and stability of clock recovery algorithm [22]. DPE was employed as a frequency domain filter with overlap-add length of 128 samples. The filter transfer function was optimized based on the given symbol rate and measured transfer functions. More details on DPE can be found in [23] and [24]. We employed two types of DPE filters, first considering transmitter pre-emphasis, including transfer functions of DAC, driver amplifier and Mach-Zehnder modulator (MZM), and second considering both transmitter and receiver (coherent front-end) pre-emphasis, where analog-to-digital converter transfer function was additionally considered. The waveform was uploaded on a DAC

(3dB bandwidth of $\sim 16\text{GHz}$ and 5.5 effective number of bits), followed up by driver amplifier. Laser assembly with $\sim 100\text{kHz}$ linewidth was used as a tunable source for in-phase quadrature-phase modulator. The overall analog 3dB transmitter bandwidth was measured to be $\sim 7\text{GHz}$. The modulated optical signal was fed to polarization multiplex emulation stage, resulting in a 100Gb/s CP-QPSK signal. The 34Gbaud test-channel included 25.5% FEC overhead, allowing a pre-FEC BER threshold of 3.8×10^{-2} , assuming irregular low density parity check code [14]. The test-channel was then multiplexed with $95 \times 100\text{Gb/s}$ CP-QPSK neighboring channels [1] on a 50GHz ITU grid, and the DWDM signals were EDFA boosted, before transmission.

The loop consisted of $81\text{km} \times 4$ spans of G.655 LEAF fiber with core area of $72\mu\text{m}^2$, dispersion and loss coefficients of $\sim 3\text{ps/nm/km}$, and $\sim 0.217\text{dB/km}$, respectively. Furthermore, $\sim 3\text{dB}$ additional attenuation was added per span to emulate worst-case end of life span loss of $\sim 20.5\text{dB}$, which was completely compensated by either commercial EDFA cards or commercial hybrid EDFA + Raman amplifiers. In the case of hybrid EDFA + Raman amplification, backward Raman pumping was used with four pump lasers at wavelengths 1424nm , 1435nm , 1455nm and 1472nm . The Raman on-off gain was set at $\sim 12\text{dB}$ per span. The loop also contained a polarization scrambler which was triggered by the loop switch to avoid polarization dependent degradations in loop.

After N circulations through the loop, the optical stream was pre-amplified, filtered by a 0.6nm tunable band-pass filter, and coherently detected using balanced photodetectors (3dB bandwidth of $\sim 22\text{GHz}$). In the case of back-to-back OSNR measurements, a broadband noise source, followed by an attenuator, was used to vary the received OSNR. The local oscillator frequency was adjusted in range of $\sim 100\text{MHz}$ of the transmitter laser. The electrical output signals were then sampled by a 50GS/s loop-triggered digital sampling oscilloscope (DSO) having an electrical bandwidth of $\sim 23\text{GHz}$. DSO traces of $\sim 2\text{million}$ samples were then post processed for semi real-time standard digital signal processing, including frequency-domain chromatic dispersion compensation, timing recovery, polarization de-multiplexing, carrier phase and frequency offset estimation, followed by BER count. Details of the algorithms can be found in [25] and [26].

III. RESULTS AND DISCUSSIONS

A. Back-to-Back Transmission

Prior to the transmission experiments, we characterized our two DPE approaches in back-to-back system configuration. Fig. 2 shows back-to-back pre-FEC BER as a function of measured OSNR, referenced to 0.1nm noise bandwidth. The results are shown without DPE, with transmitter only DPE (DPE_{TX}), and transmitter + receiver DPE ($\text{DPE}_{\text{TX+RX}}$). Also, theoretical performance is shown. The test-channel, at 1552.2nm , was multiplexed with a broadband noise source at the input of the booster amplifier, and OSNR was varied by varying the noise power at the input of the amplifier.

It can be seen that, compared to no DPE, both DPE_{TX} and $\text{DPE}_{\text{TX+RX}}$ enable $\sim 0.6\text{dB}$ OSNR improvement – at

Fig. 2. Pre-FEC BER vs. measured OSNR (0.1nm noise reference), for CP-QPSK test-channel. Black Line: Theoretical performance, Circles: no DPE, Up-triangle: Transmitter DPE, Down-triangle: Transmitter + Receiver DPE.

pre-FEC BER threshold, whereas slightly greater improvements are seen at lower bit error rates. The marginally worse performance after DPE_{TX+RX} , compared to DPE_{TX} only, may be attributed to enhanced DAC quantization noise when applying stronger DPE, essentially counteracting any receiver bandwidth limitation compensation. Nonetheless, even with DPE_{TX} , ~ 1.5 dB OSNR penalty is observed, at pre-FEC BER, with respect to theoretical performance, which may be attributed to extremely limited overall transmitter 3dB bandwidth of ~ 7 GHz (DAC + Driver Amplifier + MZM). The lower transmitter bandwidth necessitates stronger DPE, however at the cost of increased quantization noise which is not compensated in our simple DPE filter – see [27] for improved DPE algorithm including quantization effects. This penalty is increased to ~ 2.1 dB, for the case without DPE. These results ascertain the vital role of transmitter DSP in upcoming commercial products, and show that a simple DPE filter can enable appreciable improvements. Recently, it was also reported that DPE not only enables back-to-back improvements, but also mitigates fiber nonlinearities [28].

B. Recirculating Loop Experiment

Fig. 3 shows typical launch power optimization curves, where pre-FEC BER is plotted as a function of launch power per channel, both for EDFA only and EDFA + Raman hybrid amplifiers. The results are presented for the DWDM 100Gb/s CP-QPSK test-channel (1552.2nm) after ~ 2645 km of G.655 NZ-DSF LEAF. In case of hybrid amplification, Raman pump powers were optimized across C-band to ensure gain flatness.

As expected, the performance for the EDFA system is initially limited by OSNR, before reaching an optimum point, beyond which fiber nonlinearities limit the channel performance. On the other hand, with EDFA + Raman amplification, significant improvement can be observed in the low power region due to distributed backward Raman pumping. The optimum launch powers are found to be -2 dBm and -4 dBm, for EDFA and hybrid amplifiers, respectively.

Fig. 3. Pre-FEC BER as a function of launch power for CP-QPSK test-channel (1552.2nm), considering DPE_{TX} . Square: EDFA only links, Circles: Hybrid EDFA + Backward Raman amplification system.

Fig. 4. Pre-FEC BER vs. transmission distance [km] for CP-QPSK test-channel (1552.2nm), considering DPE_{TX} . Squares: EDFA only links, Circles: Hybrid EDFA + Backward Raman amplification system. Grey line shows pre-FEC BER threshold. Open: Single-channel (SC) transmission, Solid: WDM.

Fig. 4 shows pre-FEC BER versus transmission reach, where 96×100 Gb/s CP-QPSK DWDM traffic (measured at 1552.2nm) is transmitted over ~ 5000 km and ~ 8000 km of G.655 NZ-DSF LEAF, at pre-FEC BER threshold of 3.8×10^{-2} , for EDFA and EDFA + Raman amplifiers, respectively. The improved reach in case of hybrid amplification is attributed to lower linear and nonlinear effects per span due to lower launch power requirements, distributed amplification, and improved span noise figure [10]. Also, single-channel performances are reported for reference, allowing performance analysis based on channel count. These results show that if the traffic load is not full (96 channels), performance significantly beyond reported bounds can be achieved.

In order to demonstrate the feasibility of transoceanic DWDM transmission, measurements were carried out across the entire C-band, as shown in Fig. 5a and Fig. 5b. It can be seen that all the channels have BER below – or equal to the pre-FEC BER threshold, confirming error-free post-FEC

Fig. 5. (a) EDFA only, after ~4500km, (b) Hybrid amplifier, after ~6500km. Left axis: Channel Power vs. wavelength [nm], Right axis: Pre-FEC BER vs. wavelength [nm], for all the 96 channels in C-band transmission.

performance after ~4500km (Fig. 5a) and ~6500km (Fig. 5b) of G.655 NZ-DSF (LEAF) across the C-band – Also plotted is the received spectra at maximum reach. From these graphs it is clear that the better performing channels ($\sim > 60$) have enough margin to traverse up to ~5000km and ~8000km, at pre-FEC BER threshold of 3.8×10^{-2} , for EDFA and EDFA + Raman amplifiers, respectively (see Fig. 4).

IV. CONCLUSIONS

We demonstrated record ultra long-haul transmission of 96×100 Gb/s CP-QPSK DWDM traffic over G.655 NZ-DSF (LEAF) in a recirculating loop experiment. Our results confirm ~6500km transmission, at pre-FEC BER threshold of 3.8×10^{-2} , for systems employing EDFA + Backward Raman hybrid amplification, and ~4500km transmission for EDFA only links. This translated to ~1100% increase in capacity-distance product for NZ-DSF, compared to previously reported literature [17].

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