117-Gb/s Optical OFDM Super-channel Transmission over 1200-km SSMF Using Direct Detection and EDFA-Only Amplification

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Abstract: With EDFA-only amplification, we successfully demonstrate the transmission of a 4-QAM, 117-Gb/s (100 Gb/s without overhead) DDO-OFDM super-channel over 1200-km SSMF with only 1-dB OSNR penalty. We also discuss the impact of PMD on the transmission link.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation

1. Introduction

In the regime of long-haul transmissions, it appears that the coherent detection has won out in performance in the competition between the coherent and direct-detection receiving techniques [1-3]. With an extra consideration of cost, the direct detection would still stand a chance due to the lower implementation cost and the offered moderate performance. Direct-detection transmissions have been extensively reported over the past years. However, most of them focus mainly on the dispersion managed link which has recently lost its appeals for most system providers due to its complex design process and link architecture. On the other hand, the dispersion-unmanaged link, accompanied with the digital chromatic dispersion (CD) compensator, has been getting more and more interests over the recent years by virtue of the fast advances of high speed electronics. Therefore, it would be quite advantageous if the direct-detection scheme could be employed in a dispersion unmanaged link.

To incorporate the direct-detection scheme in a dispersion-unmanaged link, there have been mainly two proposals: 1) single-carrier transmission with pre-distortion [4], and 2) multi-carrier transmission with post-compensation [5]. The first choice [4], pre-distortion at the transmitter, could work very well against the CD, while it requires the link information beforehand which might limit its application in some dynamics transport network. The second choice [5], commonly referred to as direct-detection optical orthogonal frequency division multiplexing (DDO-OFDM), can dynamically estimate and compensate the accumulated CD at the receiver and need not the link information at the transmitter. Thus, the DDO-OFDM should be seriously re-evaluated as a promising format for the dynamically-transport networking such as the general metropolitan transmissions.

In spite of the above-mentioned advantages, the conventional DDO-OFDM has a limited transmission performance which might constraint its applications only for those short- or medium-reach networks. A later improved version, called the self-coherent OFDM [5], has been proposed with a purpose to extend the capacity and reach, while it, unfortunately, greatly enhances the complexity of the receiver which diminishes the inherent advantages of using direct detection. Therefore, a laudable goal for DDO-OFDM system would be to improve its transmission performance with simple solutions which can keep the low-cost nature of the direct detection.

Recently, we have proposed and demonstrated a single-polarization 16-QAM, 214-Gb/s DDO-OFDM super-channel (DDO-OFDM-S) with a very simple optical multiband receiving (OMBR) method [6], achieving a distance of 720-km standard single mode fiber (SSMF). In this paper, we further explore its transmission performance with 4-QAM and 117 Gb/s (100 Gb/s without overhead) over 1200-km SSMF. We demonstrate an record sensitivity (in the world of 100-Gbps DDO-OFDM systems) of ~21 dB and a transmission penalty of ~1 dB after 1200-km SSMF,

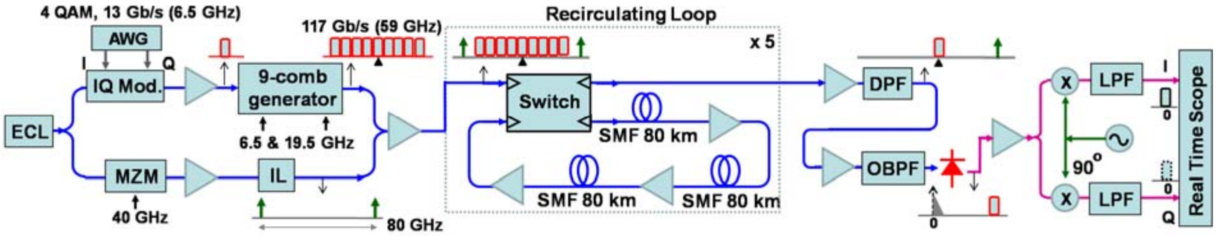

Fig. 1 Experimental setup for the 107 Gb/s direct-detection optical OFDM super-channel over 1200-km SSMF transmission with optical multiband receiving (OMBR). ECL: external cavity laser, AWG: arbitrary waveform generator, IL: inter-leaver, DPF: dual-passband filter.

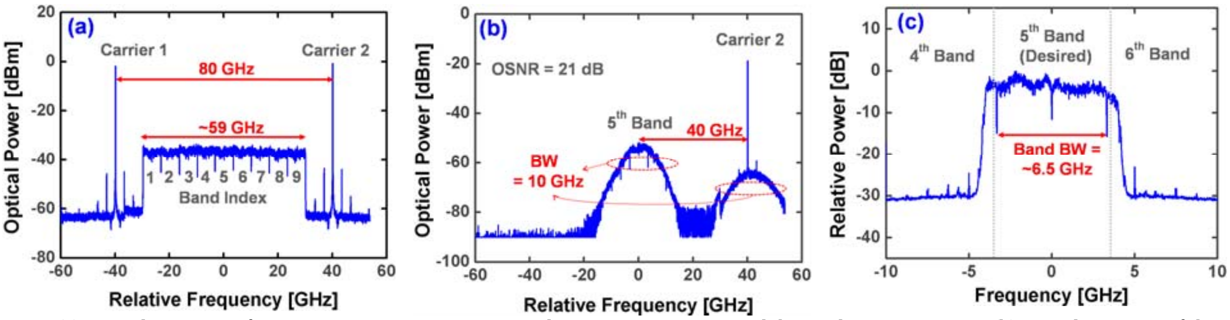

Fig. 2 (a) Optical spectrum of transmitter output. Frequency is relative to 192.757 THz and the resolution is 20 MHz, (b) optical spectrum of the 5th band after DPF filter, and (c) digital spectrum of the 5th band after down-converted to the baseband.

which illustrates its potential use for the long-haul applications. In addition, the 1st order polarization mode dispersion (PMD) tolerance of the DDO-OFDM-S is given and its impact on the transmission link is also discussed.

2. Experimental Setup for 117 Gb/s DDO-OFDM Super-channel

In Fig. 1 we depict the experimental setup for the 117-Gb/s DDO-OFDM-S system. A 100-kHz linewidth external cavity laser (ECL) operated at ~192.76 THz is used as the transmitter light source followed by a 1x2 optical splitter which equally couples the laser output into the upper sideband path and lower carrier path. In the sideband path, the light is firstly modulated with the electrical OFDM signal via an in-phase/quadrature-phase (I/Q) modulator. The OFDM signal is generated offline with Matlab and composed of frames with each containing 2 training symbols and 150 data symbols. For each OFDM symbol, binary data is randomly generated and modulated onto 166 subcarriers with 4-QAM (QPSK) format, which is zero-padded to a fast Fourier transform (FFT) size of 256. No pilot is utilized in this demonstration. After Inverse FFT (IFFT), a length of 16-point cyclic prefix (CP) is added to each OFDM symbol, leading to 272 points per symbol. The OFDM waveform is then loaded into an arbitrary waveform generator (AWG) which has its "real" and "imaginary" outputs driving the IQ modulator with a 10 GS/s sampling rate. Hence, the raw data rate of the output signal is ~13 Gb/s occupying a bandwidth of ~6.5 GHz. The output of the I/Q modulator is sent to a 9-comb generator for emulating a 9-band super-channel [6]. The channel spacing is set at ~6.5 GHz and the total data rate and bandwidth of this super-channel is 117 Gb/s and 59 GHz, respectively. After removing the training, CP and 7% FEC overhead, this super-channel carries a net data rate of 100 Gb/s. An optical coupler is followed to combine this super-channel and the signal from the lower path. As to the lower carrier path, the light is firstly modulated with a 40-GHz electrical sine-wave signal with one Mach-Zehnder modulator (MZM) biased at the null, and then the output passes through a 50:100-GHz inter-leaver (IL) to suppress the original optical carrier. The two newly-generated carriers, spaced with a frequency of 80 GHz, are combined with the 59-GHz super-channel. This dual-carrier-assisted super-channel is then sent to an re-circulating fibre loop, which consists of three EDFA and three spools of 80-km SSMF. After 1200-km transmission, the signal is fed to the optical multi-band receiver. At the receiver, the signal is firstly pre-amplified with an EDFA and then passes through a tunable dual passband filter (DPF), which has two 10-GHz passbands targeting at one optical carrier and the desired signal band, respectively. Due to the loss of DPF, an EDFA and an 80-GHz optical band-pass filter (OBPF) are applied to raise the signal power before the signal enters the photodiode. The converted electrical signal is down-converted to its baseband with an electrical I/Q demodulator, which consists of two broadband double-balanced mixers. The I/Q baseband signals are injected through one pair of low pass filters (LPFs) with a 3-dB bandwidth of 3.7 GHz and are recorded by a real time scope operated at 20 GS/s. Synchronization, cyclic prefix removal, channel estimation and equalization (including I/Q imbalance compensation [7] with the intra-symbol frequency domain average approach [8]) are conducted offline with Matlab program. The bit error rate (BER) is evaluated with error counting method and for each BER analysis 2 million sampling points are considered.

In Fig. 2 we show the optical spectra (resolution = 20 MHz) of the transmitter output and of the DPF output (targeting at 5th band), and the digital spectrum of the 5th band after the real time scope. In experiments, the super-channel bands from 1-4 are demodulated with carrier 1 and the bands from 5-9 are with carrier 2. The carrier and band index numbers are defined in the inset of Fig. 2(a).

3. Results and Discussions

For demonstrating this 107-Gb/s super-channel transmission, the utilized carrier-to-sideband-power-ratio (CSPR) is ~3 dB, which is found to be optimum for achieving the minimum required OSNR. In experiments, the measured OSNR are ~38 and ~28 dB, respectively, before and after 1200-km SSMF transmission. Throughout this paper the OSNR is measured with 1.6-nm (200-GHz) resolution covering the whole signal's bandwidth and later scaled to the presented value with 0.1-nm noise bandwidth.

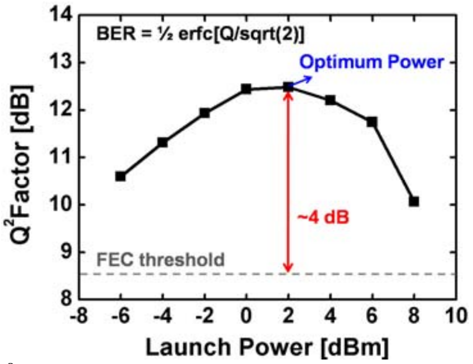

Fig. 3 Q^2 factor versus the launch power. The optimum power is found to be 2 dBm with the carrier to sideband power ratio (CSPR) = 3 dB.

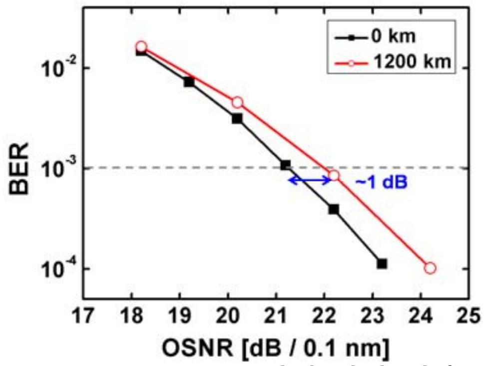

Fig. 4 OSNR sensitivity in back to back and after 1200-km SSMF transmission. The OSNR penalty is ~ 1 dB.

In Fig. 3 we show the Q^2 factor, evaluated with the measured BER, with respect to the launch power after 1200-km SSMF transmission. The optimum launch power, trading the accumulated ASE with the fiber nonlinearities, is found to be ~2 dBm, which is smaller than our previous results [6] due to the lower CSPR here. With this optimum launch power, the BER versus the OSNR is depicted in Fig. 4. The baseline in back-to-back is also shown here as an reference. From this figure there are two points worthy of our attention. First, in back to back we find the OSNR sensitivity at a BER of 1e-3 is ~21.1 dB, which outperforms the previous 120-Gbps self-coherent OFDM system (~24.2 dB) by ~3 dB [5]. This improvement might come from the following facts: 1) all 4-QAM formats here vs. the 4 and 16 hybrid QAM formats in [5], 2) the use of interleaving mode between two AWGs in [5] would lead to a worse signal quality, 3) herein the use of OMBR which detects the super-channel with single band per time and thus could greatly reduce the broadband (super-channel x ASE) beating noise (The similar noise reduction technique can be found in [9]). Second, the OSNR penalty after 1200-km SSMF transmission is found to be ~1 dB, resulted mostly from the fiber nonlinearities, demonstrating its high potential for ~1000-km SSMF transmission.

It is worth noting that, since the super-channel is transmitted with only one polarization, some minor power variation due to the PMD effect might happen, particularly for those central bands (band 4 ~ 6). To take the PMD penalty into account, multiple measurements would be required for each band to consider its average effect. However, in the offline experiment this would consume too much time for all the 9 bands and therefore we only pick the lower BER value whenever the power variation happens. Thus, the penalty shown in Fig. 4 is mostly resulted from the fiber nonlinearities. In fact, based on our experimental observations and theoretical approximations, the PMD would only contribute ~ 0.5 dB OSNR penalty to the system (PMD coefficient of lab fiber = 0.07 ps/sqrt(km)).

Even though the PMD effect might be negligible in the 1200-km experiment, it is still of importance to study the PMD tolerance of the single-polarization DD-OFDM-S as an reference for a longer distance. In Fig. 5 we depict the Q^2 factor versus the instantaneous differential group delay (DGD) with a 1st-order PMD emulator in the absence of transmission fiber. The results show that the Q^2 penalty reaches ~3 dB when the instantaneous DGD = ~ 10.5 ps (mean DGD = 2.6 ps given an outage probability of 7.4e-9). With the consideration of 0.07-ps/sqrt(km) PMD coefficient of the lab fibers, 1200-km link would yield a mean DGD value of ~ 2.5 ps, which from Fig. 5 would need a 3-dB Q^2 margin to promise an outage probability of 7.4e-9. Since the demonstrated system provides an ~4-dB Q^2 margin (Fig. 3), the proposed DDO-OFDM-S system could, in principle, transmit over 1200-km SSMF with a PMD outage probability of lower than 7.4e-9.

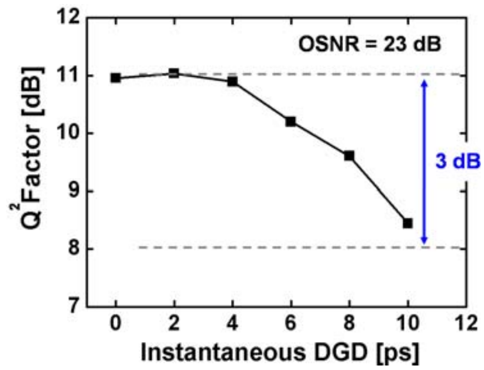

Fig. 5 Q^2 factor versus the 1st order PMD in terms of the instantaneous differential group delay (DGD).

This work was partly supported by National Institute of Information and Communications Technology (NICT) of Japan.

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