IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 7, Number 4, August 2015

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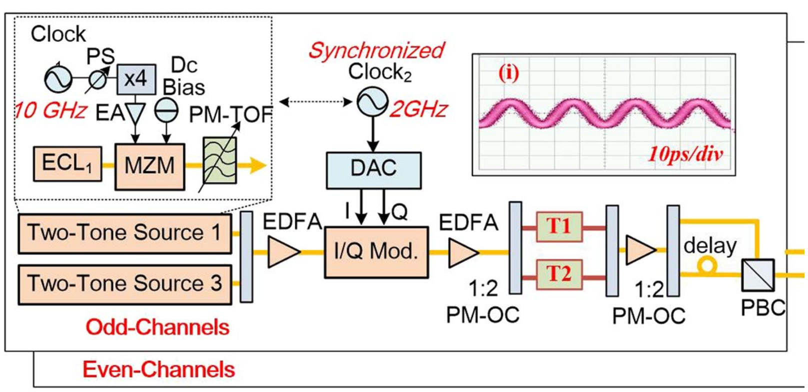

DOI: 10.1109/JPHOT.2015.2464101

WDM Transmission of Single-Carrier 400G Based on Orthogonal OTDM 80-GBd PDM-8QAM

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DOI: 10.1109/JPHOT.2015.2464101

Manuscript received July 7, 2015; revised July 25, 2015; accepted July 29, 2015. Date of publication August 3, 2015; date of current version August 18, 2015. This work was supported in part by the National Natural Science Foundation of China under Grant 61325002 and in part by the National High-Technology Research and Development Program (NHTRDP) (863 Program) of China under Grant 2013AA013401 and Grant 2013AA013603. Corresponding author: J. Zhang (e-mail: hustzjw@gmail.com).

Abstract: We experimentally investigate the wavelength-division multiplexing (WDM) transmission of single-carrier 400G based on an orthogonal optical time-division multiplexed (orth-OTDM) 80-GBd polarization-division multiplexed (PDM) 8 quadrature-amplitude modulation (QAM) signal. The 80-GBd 8QAM signal is generated using the OTDM method based on two tributaries of time-domain orthogonal pulses with 40-GBd 8QAM signals. Full-band coherent detection is utilized with digital signal processing based on a single broadband receiver for the 80-GBd signals. The WDM transmission performance of single-carrier 400G signals within different channel grids and carrier spacing is also investigated. Finally, four 400G channels, each carrying an 80-GBd PDM-8QAM signal within 100-, 80-, and 75-GHz grids, are successfully transmitted over 1600-, 800-, and 400-km standard single-mode fibers with Erbium-doped fiber amplifier (EDFA)-only amplification below a pre-Forward error correction (FEC) bit-error rate (BER) of 2.4×10^{-2} (20% soft-decision FEC), respectively. The achieved spectral efficiency for the 400G channel can be 4, 5, and 5.33 bit/s/Hz, respectively.

Index Terms: PM-8QAM, 400G, optical time-division multiplexed (OTDM), optical coherent communication.

1. Introduction

The fast growth of Internet bandwidth demand for higher data rate year by year has attracted increased research and development interest in the next-generation transport standard 400G wavelength-division multiplexing (WDM) transmissions systems [1]–[13]. In recent reports, the 400-Gb/s channel coherent transmission system can be realized by the two [1]–[5], four [6]–[8], or even eight to ten [9] optical sub-carriers with lower baud rate per sub-channel and separate coherent receivers. These schemes are of immediate commercial interest since they reduce the bandwidth requirements of opto-electronics devices. Considering the transponder complexity and cost, 400G transmission on a single optical carrier remains an attractive solution, which pushes the boundaries of opto-electronic components and modules [10]–[12]. In these reports, the high baud rate signals are all generated by electronically time-division multiplexing (ETDM) method, modulated and coherent detected with broadband transponders. As reported in [11] and [12], single-wavelength all-ETDM 107-GBaud and 110-GBaud quadrature phase-shift keying (QPSK) signal are successfully generated and transmitted as the highest ETDM baud rates. The ETDM signals at these high symbol rates show considerable implementation penalties due to electro-optical bandwidth limitations of the multiplexer and optical modulator, as well as the poor quality of the electrical drivers. Another method, i.e., all-optical orthogonal frequency division multiplexing (AO-OFDM), is also proposed based on optical sub-carriers for high-speed signal generation [14].

On the other hand, optical TDM with high order modulation formats is considered as another promising technique for high baud rate optical signal generation, which has attracted a lot of research interests for high spectral efficiency and high capacity optical communication system in recent reports [15]–[19], especially combined with full-band coherent detection. In [17], single polarization signals of 107GBaud binary phase-shift keying (BPSK), QPSK, and 16 quadrature-amplitude modulation (QAM) are generated by using OTDM and coherent detection. Although hardware complexity is increased in the transmitter side, their results show better performances compared with ETDM with lower penalties due to the reduced hardware speed requirements. In [19], all optical Nyquist 125-GBaud QPSK signals are successfully generated and full-band coherently detected by one detector. The orthogonal time-division multiplexed (Orth-TDM) is used in the transmitter side based on Sinc-shaped Nyquist pulses, which enable a minimum bandwidth occupation. Enabled by the development of high speed in analog-to-digital converters (ADCs), a single-receiver full-band coherent detection is used with digital signal processing (DSP) in the above OTDM system, which keeps the overall system reasonably simple without using the separate receivers for each of the TDM-tributaries with pulsed local oscillator (LO). Transmission on a single optical carrier using single transponder emerged as an attractive solution. Namely, minimizing the number of channel subcarriers reduces the number of deployed optical components, which typically determinate the transponder cost. There have been a lot of efforts made on this area these years, from device to system. However, the speed and bandwidth of DAC at the transmitter for signal generation are much less than the ADC at the receiver for signal detection these years. Lots of effort has been done in the transmitter side to increase the speed, such as super-channel or multi-carrier [9], ETDM [11], [12], all-optical orthogonal frequency division multiplexing (AO-OFDM) [14] and OTDM [15]–[19] or technology, while keeping the single receiver with broadband components.

Therefore, above orth-TDM scheme for high baud rate signal generation provides an alternative promising solution for the 400G system. In this paper, we experimentally investigate the WDM transmission of single-carrier 400G based on Orth-TDM 80-GBaud PDM 8QAM signal. In previous works [5], [13], 46 and 40-GBaud 8QAM is reported using the digital-to-analog convertor (DAC); however, higher baud rate 8QAM is still difficult to generate due to the bandwidth limitation. The 80-GBaud 8QAM signal is generated using the OTDM method based on two tributaries of time-domain orthogonal pulses with 40-GBaud 8QAM signals. Full-band coherent detection is utilized with digital signal processing based on a single broadband receiver for the 80-GBaud signals. The WDM transmission performances of single-carrier 400G signals within different channel-grid and carrier spacing are also investigated. The feasibility of the Orth-TDM 8QAM based 400G solution is demonstrated and investigated.

2. Experimental Setup and the Principle of Signal Generation

Fig. 1 shows the experimental setup of the four channels single-carrier Orth-TDM 480-Gb/s PDM-8QAM signal generation, transmission, and coherent detection in a WDM system. Four tunable external cavity lasers (ECLs), i.e., ECL1 to ECL4, are used as the source light in our system with the linewidth less than 100 kHz and the output power of 14.5 dBm. For each 400G channel, the 80-GBaud PDM-8QAM signal is generated by the Orth-TDM of two tributaries of 40GBaud signals. The principle of the Orth-TDM or all-optical Nyquist signal generation can be found in [18] and [19], where Nyquist pulses are generated first by the frequency-locked and linear-phase combs. The generation consists of three stages, comb generation, pulse modulation, and tributaries orthogonal time-domain multiplexing.

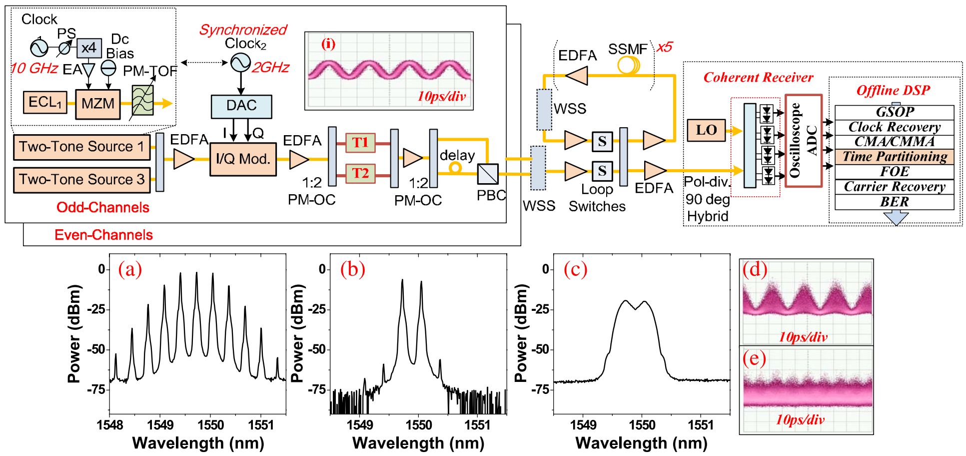

Fig. 1. Experimental setup for the 400G WDM transmission of orthogonal time-division multiplexed 80-GBaud PDM-8QAM. (a) and (b) are the optical spectra before and after band-pass filter, (c) is the modulated two-tone comb, and (d) and (e) are the eye-diagrams of the modulated pulse before and after Orth-TDM. (i) is the Cosine-shaped pulse waveform of the two-tone comb.

As analyzed in [18] and [19], a Nyquist Sinc-shaped pulse sequence is a frequency-locked and flat comb with linear phase in frequency domain. Therefore, for an N tone frequency-locked comb with linear phase and equal amplitude, the time domain optical signal is a periodic sinc-shaped Nyquist pulse. Using the periodic Sinc-shaped Nyquist pulses, the Nyquist pulses can be modulated and multiplexed in the time-domain using the orthogonal TDM method with N tributaries without inter-symbol-interference (ISI). In our previous work [19], we have demonstrated the five-tone comb with five tributaries for 125-GBaud QPSK generation, and each tributary carries 25 GBaud. Here, to keep the overall system reasonably simple, we choose a two-tone source with 2 tributaries for 80-GBaud 8QAM generation and each tributary carries 40-GBaud signal. Fig. 1 shows the detail experimental setup for the two-tone source generation, where the frequency-locked optical comb with 40-GHz carrier spacing is generated by a MZM driven by the clock source. The voltage of the drive clock signal and the DC bias should be adjusted simultaneously and matching each other to obtain a flattened and linear phase combs. One polarization-maintaining tunable optical filter (PM-TOF) is used to choose the two-tone comb with center carrier and long-wavelength first order sideband. The optical spectra of the generated optical comb with 40-GHz spacing before PM-TOF are shown in Fig. 1 as insets (a) and (b). Therefore, the waveform of the two-tone comb shown in inset (i) is the repeated Cosine-shaped pulse as a special case of repeated Sinc-shaped Nyquist pulse [18]. We can see, for the 2×40-GHz comb, the Cosine-shaped pulses have one zero-crossing point between each Nyquist pulse and the pulse repeating period is 25 ps.

After pulse generation, we directly modulate the Cosine-shaped pulse and then multiplex the two time-division channels by polarization-maintaining optical coupler (PM-OC) and tunable optical delay-line (PM-TDL, T) for experiment demonstration. For 8QAM modulation, the 40-GBaud in-phase (I) and quadrature (Q) data signals are generated by a programmable digital-to-analog convertor (DAC) with 64GSa/s. To ensure the orthogonality as well as the de-correlation between tributaries, the delay line of each tributary is tunable and long enough with 125 symbols. In our experiment, the tunable delay line consists of a fixed fiber (PM fiber jumpers, about 5 ns delay for per meter) and a manually tunable time delay module ($0 \sim 300$ ps tunable delay). After that, the PDM is realized by using a PM-OC to split the signals, a PM-TDL to provide over 100 symbols duration with pulse precisely aligned and a PBS for recombination. Then, the 80-GBaud Orth-TDM PDM-8QAM signals with 80-GBaud are generated. Fig. 1(c) shows the optical spectrum of 80-GBaud Orth-TDM 8QAM after modulation. The eye diagrams of 40-GBaud 8QAM of one tributary before TDM and the 80-GBaud 8QAM signal after orth-TDM are shown in Fig. 1 as (d) and (e).

Using this setup, the odd and even channels are modulated and orth-TDM independently and combined together by a wavelength-selective-switch (WSS) for WDM transmission. The

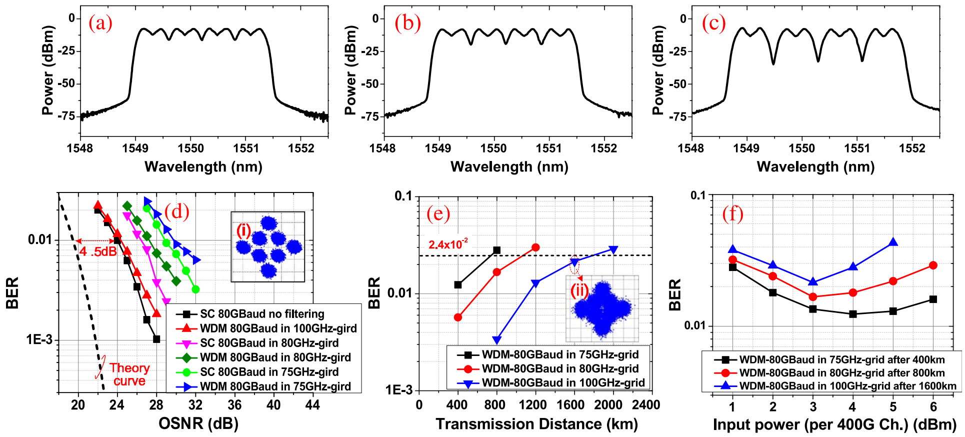

Fig. 2. (a)–(c) Optical spectra of WDM signals in 75, 80, and 100-GHz-grid, where (d) the back-to-back BER results as a function of OSNR. Inset (i) is the error-free constellation of 80-GBaud PDM-8QAM signal. (e) BER of Ch. 2 versus the fiber transmission distance. Inset (ii) is the constellation of recovered signal in 100-GHz-grid WDM after 1600-km transmission. (f) BER performance of Ch. 2 versus the input power per 400G channel.

channel spacing and bandwidth of the WSS are fully programmable and the performances of single-carrier 400G signals within different channel-grid and carrier spacing is studied. The four-channel WDM Orth-TDM 80GBaud PDM-8QAM signals are then launched into a re-circulating fiber loop, which consists of five spans of 80-km stand-single mode fiber (SSMF) with attenuation of 0.2 dB/km and chromatic dispersion (CD) of 17 ps/km/nm, loop switches (SWs), optical coupler (OC), and Erbium-doped fiber amplifier (EDFA)-only amplification without optical dispersion compensation. Therefore, the fiber length within each re-circulating loop is 400 km. One wavelength selective switch (WSS) is placed in the loop, which is programmed to work as an optical band-pass filter to suppress the ASE noise.

At the receiver side, a free-running ECL with linewidth less than 100 kHz is utilized as LO. Instead of using pulsed LO for each TDM-tributary, a single-receiver full-band coherent detection is used with digital signal processing (DSP). An optical 90° hybrid is used for phase-diversity coherent detection. The bandwidth of the balanced detector is 50 GHz. The sampling and digitization (A/D) is realized by the high speed real-time digital oscilloscopes with 160-GSa/s sample rate and 65-GHz electrical bandwidth. After the ADC, the off-line digital signal processing is then applied for four channel 160 GSa/s sampled data sequence, as shown in Fig. 1. The data is first resampled to 2 samples per symbol, and then processed by the modified 8QAM digital signal processing including digital CD compensation. Since the phase between the symbols in each tributary is unknown, we need to do the time partitioning after the classic line equalizer CMA/CMMA, and before the frequency and phase recovery [19] as shown in Fig. 1. If phase stabilized OTDM mux is used like [17], then there is no need for the separating. In our work, the 80GBaud 8QAM signals are generated by the orth-OTDM of two tributaries of 40-GBaud 8QAM signals. Therefore, the 400G data transmission can be realized by the 80GBaud PDM-8QAM signal with 6 bit/s per symbol after excluding the 20% soft-decision FEC overhead.

Fig. 2(a)–(c) are the optical spectra of WDM signals in 75, 80 and 100-GHz-grid. Fig. 2(d) shows the back to back (BTB) BER performance versus the OSNR (with a 0.1-nm reference bandwidth) for single carrier (SC) and WDM Orth-OTDM 80-GBaud PDM-8QAM signals under different frequency grids. The required OSNR of SC Orth-OTDM 80-GBaud PDM-8QAM without any filtering at BER of 1×10^{-2} is about 24-dB, and negligible penalty is observed for the WDM case in 100 GHz-grid at the same BER level. However, more than 2.5-dB OSNR penalty at the same BER level is observed for SC and WDM channels within 80-GHz grid. The required OSNR for that super-Nyquist WDM channel under 75 GHz filtering (75 GHz-grid WSS) at the BER of 1×10^{-2} is about 29.8 dB/0.1 nm, which has 2.5-dB penalty compared with that in the

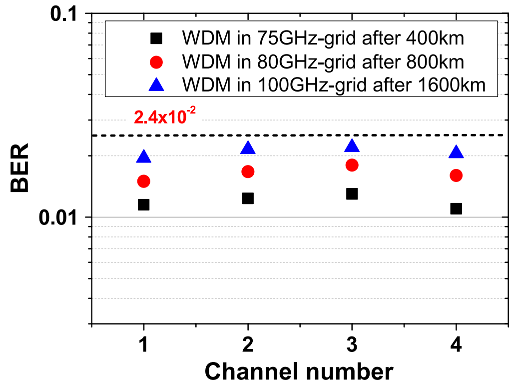

Fig. 3. Measured BER of all four OTDM 80-GBaud PDM-8QAM channels after fiber transmission.

80 GHz-grid. Large OSNR penalties are observed when reducing the bandwidth and carrier spacing of the WDM channels, and we believe it is due to the increased inter-channel-interference (ICI) and ISI. Inset (i) is the error-free constellation of generated OTDM 80-GBaud PDM-8QAM signal. The theoretical BER performance of an 80-GBaud PDM-8QAM signal is also added in Fig. 2(d) as the black dash line. Compared with the theoretical BER curve, there are about 4.5-dB OSNR penalty for 80-GBaud PDM-8QAM signal at the BER of 1×10^{-2}. We believe that a better way is to apply pre-equalization at the transmitter side and using integrated OTDM devices, which will be investigated in future work. It is worth noting that the 400G signals based on QPSK in our previous work [12] show better performances. We believe there are two major reasons. First, the previous work in [12] is based on QPSK at 110GBaud; however, the work in this paper is based on 8QAM at 80GBaud. Theoretically, the BER performance of 110GBaud QPSK is better than that of 80Gbaud 8QAM, and there is more than a 2.5-dB OSNR gain at the same BER level of 1×10^{-2}. Second, since the orthogonal OTDM in our paper are realized by manually tunable optical delay line, the accuracy and resolution of the time delay is limited. These time errors reduce the pulse orthogonality in time domain and cause ISI. We believe better performance can be achieved by integrated signal generation and modulation setup.

Fig. 2(e) shows the BER results of channel 2 versus the transmission distance in different WDM grids of 100, 80 and 75-GHz. Considering the BER limitation of 20% soft-decision FEC overhead at 2.4×10^{-2} [9], the maximum transmission distance of 400 G channel in 100 GHz-grid WDM is 1600 km. Due to the larger ISI and ICI, the maximum transmission distances of 400G WDM channels in 80 GHz and 75 GHz grid are less than that of channels in the 100 GHz grid. About 800 and 400-km loop fiber transmission distance below BER of 2.4×10^{-2} can be obtained for the 80 and 75 GHz grid WDM channels, respectively. The constellation of the received signal channel 2 processed by off-line DSP is also inserted as (ii) in Fig. 2.

The BER performance of channel 2 within different frequency grids after corresponding transmission distance versus the launch power per 400G channel is shown in Fig. 2(f). The input power is controlled by the attenuator at the input of each span of fiber. The optimal input power per 400G channel is about 3-dBm for the 100 and 80-GHz grid cases after 1600 and 800-km transmission, while it is about 4-dBm for the 75 GHz grid case after 400-km transmission. The BER increasing at power larger than optimal value is believed to be due to the fiber nonlinear impairments. However, the BER performance also degrades fast at power less than optimal value per channel due to the OSNR decrease.

For all four 400G channels, the measured BER of 100, 80, and 75-GHz grid WDM signals after 1600, 800, and 400-km transmission is presented in Fig. 3. The BER for all channels are below 2.4×10^{-2}, the SD-FEC limitation. Therefore, the achieved spectral efficiency (SE) for the 400G channel with 1600, 800, and 400-km transmission can be 4, 5, and 5.33 bit/s/Hz, respectively. It is worth noting that the orthogonal rule is broken when we suppress the channel bandwidth to increase the SE. These experimental results of the Orth-OTDM 80-GBaud PDM-8QAM have shown technical potential for next generation 400G system under different transmission distance and SE. It is worth noting that the framing and protocol overhead are not considered here. Therefore, the actual SE of net data could be lower if all this overhead is removed.

3. Conclusion

We experimentally investigate the WDM transmission of single-carrier 400G based on Orth-OTDM 80-GBaud PDM 8QAM signal. The 80G-Baud 8QAM signal is generated using the OTDM method based on two tributaries of time-domain orthogonal pulses with 40-GBaud 8QAM signals. Full-band coherent detection is utilized with digital signal processing based on a single broadband receiver for the 80GBaud signals. Finally, four 400G channels, each carrying an 80-Gb/s PDM-8QAM signal within 100, 80, and 75-GHz grid, are successfully transmitted over 1600, 800, and 400-km SSMF with EDFA-only amplification below the 2.4×10^{-2} (20% soft-decision FEC). The achieved SE for the 400 G channel can be 4, 5, and 5.33 bit/s/Hz, respectively. These experimental results of the Orth-OTDM 80GBaud PDM-8QAM have shown technical potential for next-generation 400G transmission.

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