63-Tb/s (368×183.3-Gb/s) C- and L-band all-Raman transmission over 160-km SSMF using PDM-OFDM-16QAM modulation

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Received October 23, 2013; accepted March 5, 2014; posted online April 4, 2014

By using PDM-OFDM-16QAM modulation, all-Raman amplification, coherent detection, and 7% forward error correction (FEC) threshold, we successfully demonstrate 63-Tb/s (368×183.3-Gb/s) signal over 160-km standard single mode fiber (SSMF) transmission in the C- and L-bands with 25-GHz channel spacing. 368 optical channels with bandwidth spacing of 25 GHz are generated from 16 external cavity laser sources. After 160-km SSMF transmission, all tested bit error rate (BER) are under 3.8×10-3, which can be recovered by 7% FEC threshold. Within each channel, we achieve the spectral efficiency of 6.85 bit/s/Hz in C/L band.

OCIS codes: 060.0060, 250.0250, 070.0070.
doi: 10.3788/COL201412.040601.

In recent years, the ever-increasing data traffic is driving increasing demand for high capacity optical transport system. To meet the demand, the combination of high spectral efficiency (SE) modulation formats with high per-channel bit rates, coherent detection with digital signal processing, and wideband low noise optical amplification techniques have been pursued as potential solutions[1]. Several optical transport systems with 10 to 100 Tb/s capacity have been demonstrated[2−14]. A summary of total capacities above 60 Tb/s reported in recent wavelength-division multiplexed (WDM) transmission experiments in single-core single-mode fibers are shown in Table 1. The first experiment achieving >60-Tb/s beyond was demonstrated in 2010 using single carrier coherent detection of polarization-diversity modulation (PDM)-36QAM in the C- and L-bands at spectral efficiency of 8 bit/s/Hz[5]. Lately, ultra high order modulation formats such as 128-QAM, 512-QAM, and 1024-QAM were reported to increase the spectral efficiency to enlarge the transmission capacity[13−16]. So far, two experimental demonstrations of more than 100-Tb/s single mode fiber transmission have been reported in Refs. [13] and [14].

In this letter, we demonstrate a 63-Tb/s (368×183.3-Gb/s) coherent optical PDM-OFDM-16QAM C- and L-band transmission over 160-km standard single mode fiber link (SSMF) with ITU-T standardized 25-GHz channel spacing with the spectral efficiency of 6.85 bit/s/Hz. Unlike the previous works[10−13], we generate 368 optical channels with bandwidth spacing 25-GHz from 16 tunable cavity lasers (ECLs) by using multi-carrier generators. Each of the 25 GHz spacing channels is partitioned into three 8.25-GHz sub-bands. Two digital-to-analog converters (DACs) running at 24 GSample/s as the transmitters from Micram Corporation are employed to generate a 61.1-Gb/s OFDM signal modulated with OFDM-16QAM at each sub-band.

Figure 1 shows the experimental setup for the 368×183.3-Gb/s transmission system modulated by PDM-OFDM-16QAM. To emulate 25-GHz spacing 368 optical channels in C- and L-band at the transmitter, eight ECLs in C-band and eight ECLs in L-band are firstly divided into four pairs based on the odd/even mode, respectively. Then each pair is fed into a phase modulator (PM), which is used as multi-carrier generator. The PMs are driven with strong RF sine waves (∼1.5 W) at frequency of 25 GHz. Each laser is able to generate up to 23 optical carriers. Figure 1(a) and (b) show the optical spectrum of odd (four lasers) and even (four lasers) pairs after optical phase modulators in C- and L-band, respectively. In this fashion, sixteen lasers provide totally 23×16=368 optical carriers. Two programmable wavelength selective switches (WSSs) are used to combine the PMs' outputs, which simultaneously perform the function of spectral

Table 1. Over 60 Tb/s of WDM Experiments over Single-core Single-mode Fiber

Total Capacity (Tb/s)	Modulation Format per Channel	Band	Channel Spacing (GHz)	Distance (km)	Fiber Type	Amplication Scheme	Year
64[10]	107G-PDM-36QAM	C, L	12.5	320	ULAF (127 μm^2)	EDFA+Raman	2010
69[11]	171.2G-PDM-16QAM	C, L$^+$	25	240	PSCF (110 μm^2)	EDFA+Raman	2010
101.7[13]	294G-PDM-128QAM-OFDM	C, L	25	165	SMF (80 μm^2)	All Raman	2011
102.3[14]	548G-PDM-64QAM-SC-FDM	C, L$^+$	50	240	PSCF(110μm^2)	All Raman	2012

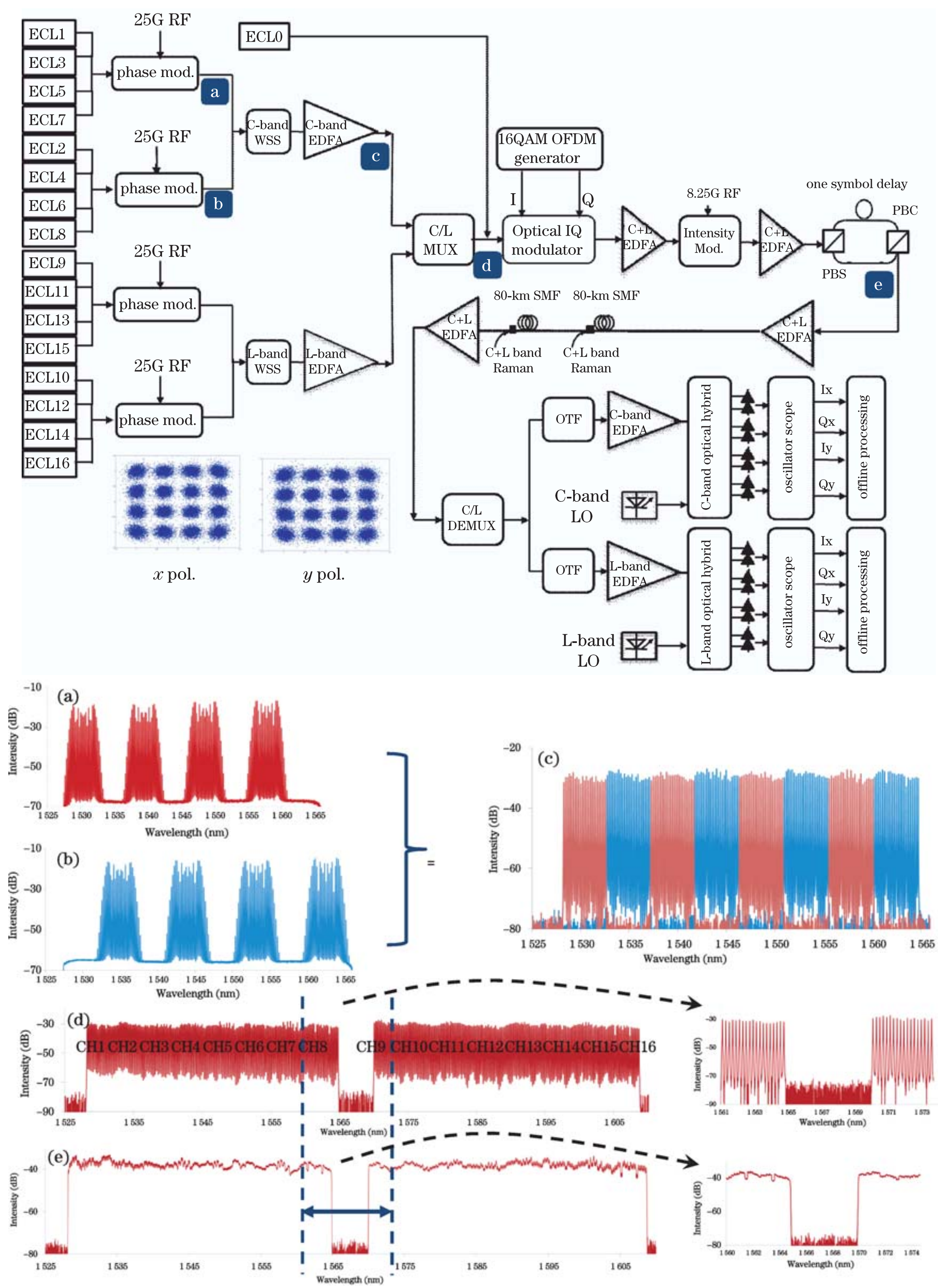

Fig. 1. Experimental setup for 368×183.3-Gb/s PDM-OFDM-16QAM transmission: (a) odd pair 4 laser sources in C-band after optical phase modulator; (b) even pair 4 laser sources in C-band after optical phase modulator; (c) reshaped by WSS; (d) 368 carriers generated by optical phase modulator; (e) 368×183.3-Gb/s PDM-OFDM-16QAM signal. Right inserted figures show the carriers and modulated signal in 8th and 9th channels.

reshaping. The re-shaped optical spectrum of the generated carriers in C-band is shown in Fig. 1(c) and after C/L MUX, the total 368 optical carriers are combined (Fig. 1(d)). The right inserted figure shows the generated multi-carriers in the 8th and the 9th channels. Note that, for the measurement at each interest sub-wavelength, the corresponding optical carrier is suppressed and replaced with an individual ECL. The transmitted signal is

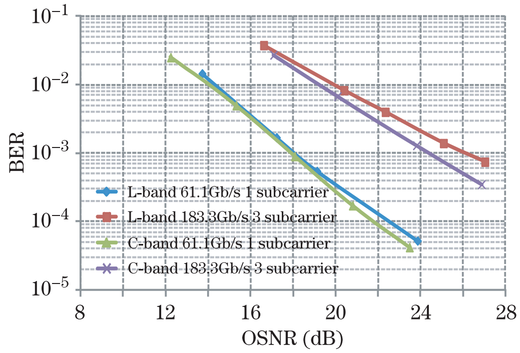

Fig. 2. BER performance againsts OSNR in a back-to-back configuration.

generated off-line by MATLAB program with a data sequence of $2^{31}-1$ pseudo-random binary sequence (PRBS) and mapped onto 16-QAM constellation. Two FPGAs and DACs from Micram Corporation producing RF signal at 24 GS/s are used to generate 8.25-GHz OFDM-16QAM baseband signal. Then, all optical carriers are simultaneously modulated by an optical I/Q modulator. It is worthy to point out that, all the modulated subbands are correlated. Un-correlated configuration for neighboring bands may further improve the transmission performance[17]. Another optical intensity modulator (IM) driven by a 8.25-GHz sine wave is used to further duplicate the OFDM signal to three copies. Thus, the bandwidth of the transmitted signal within each optical channel is 8.25×3=24.75 GHz, which is slightly less than the channel spacing of 25 GHz.

For each sub-band, the payload mapped with 16-QAM is constructed with 168 subcarriers. The FFT length is 512. The middle 4 subcarriers are unfilled. Meanwhile, other 4 subcarriers are used to estimate the phase noise. 1/32 of the symbol period is used for cyclic prefix to avoid the channel dispersion. The optical OFDM signal is then fed into a polarization splitter, with one branch delayed by one OFDM symbol period to emulate the polarization-multiplexing[18]. The modulated optical spectrum is shown in Fig. 1(e). The net rate is then calculated as 24×168/(512+16) ×4×2=61.6 Gb/s per sub-band. Thus, the data rate for each channel is 3×61.1 Gb/s=183.3 Gb/s. The spectral efficiency within each channel is 6.85 bit/s/Hz after 7% forward error correction (FEC) threshod. The transmission link consists of two spans of 80-km standard SMF-28 fiber. Its loss coefficient is 0.21 dB/km. The attenuation of each 80-km span is about 16.8 dB. In order to compensate the span loss and improve the OSNR, we utilize all-Raman amplification scheme and the C+L bands signal is amplified simultaneously. The backward-pumped distributed Raman amplifiers (DRA) with pump wavelengths from 1529 to 1605 nm yield the on-off gain of 17 dB. At the receiver side, the signal is divided into C-band and L-band by a C/L de-multiplexer and detected by typical coherent receivers respectively. In each coherent receiver, the 8.25-GHz OFDM sub-band of interest is selected by an optical tunable filter (OTF). Another ECL is utilized as the optical local oscillator (LO). The four RF signals for the two IQ components are then fed into a Tektronix oscillator scope and acquired at 50 GS/s, followed by off-line processing. The recovered 16-QAM constellations in both polarizations are also shown in the left inserted figures in Fig. 1.

We firstly conduct a back-to-back bit error rate (BER) versus optical signal-to-noise rate (OSNR) performance measurement for one subcarrier and 3-subcarrier PDM-OFDM-16QAM signals at 1562.538 nm in C-band and 1572.737 nm in L-band, which is shown in Fig. 2. The required OSNR for BER of 1×10^{-3} is 17.8 dB for both 61.1-Gb/s one subcarrier PDM-OFDM-16QAM signal at 1562.538 nm and at 1572.737 nm. The required OSNR for 183.3-Gb/s 3-subcarrier case at 1562.538 nm is 24 dB, and 26 dB at 1572.737 nm at the BER level of 1×10^{-3}. The OSNR penalty due to implementation error is 1.5 dB at 1562.538 nm, while 3.5 dB at 1572.737 nm. The performance of L-band signal is a little weaker than C-band signal, mainly due to the distinctions of the optical amplifier gains and noises of the C- and L-band amplifiers. Figure 3 shows the measured BER as a function of the launch power after 160-km SSMF transmission at 1562.538 nm when the 368×183.3-Gb/s WDM signal is passed through 2×80-km SSMF. An optimum launch power of −16.3 dBm per channel is observed[13], in which nonlinearity weakens its performance. The transmission reach can be extended by combining conventional OFDM with DFT-spread technique or using fiber nonlinearity compensation technique[19−21].

Finally, we carry out the BER measurement for all 368 bands after 160-km SSMF transmission. The result is shown in Fig. 4. All the tested BERs are under 7% FEC threshold (3.8×10^{-3}). The inset shows the optical spectrum of the entire C-band and L-band signals after 160-km transmission.

In conclusion, we successfully demonstrated a 63-Tb/s (368×183.3-Gb/s) PDM-OFDM-16QAM transmission over 2×80-km SSMF at 25-GHz channel spacing with all Raman amplification. Instead of using all independent CW lasers to be channel optical sources, we generated the 368 optical carriers from 16 tunable laser sources using multi-carrier generator, and spectral efficiency within each channel of 6.85 bit/s/Hz was achieved in the C+L bands. Larger total capacity transmission experiments in single-core single-mode fibers can be achieved through inducing new higher modulation format, such as OFDM-256QAM[22,23].

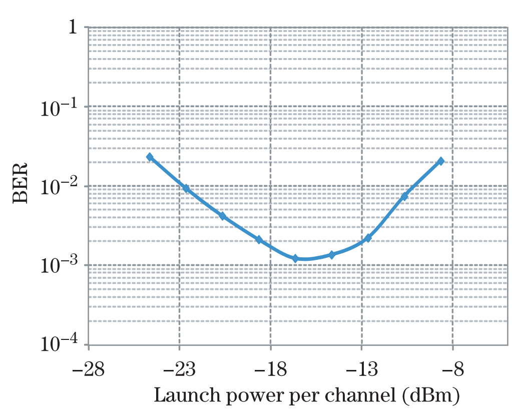

Fig. 3. BER versus launch power after 160-km transmission.

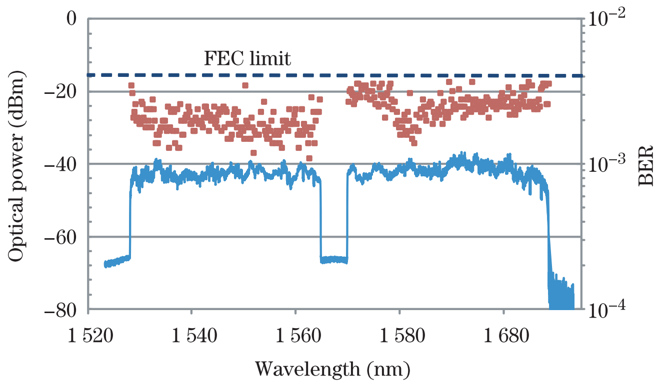

Fig. 4. BER performance for the 368 WDM channels after 160-km transmission.

This work was supported by the National “973” Program of China (No. 2010CB328300) and the National “863” Program of China (No. 2012AA011302).

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