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Kramers–Kronig detection with adaptive rates for 909.5 Tbit/s dense SDM and WDM data channels

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Abstract *We demonstrate Kramers-Kronig detection of a 909.5-Tbit/s DSDM/WDM signal with adaptive rates through a single-mode 37-core fiber. All 3663 channels (37 SDM × 99 WDM), derived from one source, exhibit error-free performance, achieving an aggregated spectral efficiency of 184.42 bit/s/Hz.*

Introduction

Kramers-Kronig (KK) receiver based direct-detection[1] has shown coherent-detection-like performance with advantages of low-cost and reduced receiver complexity, and have thus been proposed for optical interconnects. Recently, polarization-diversity KK receivers with wavelength-division multiplexing (WDM) have also been demonstrated[2]. Dense space-division multiplexing (DSDM) using high-count single-mode multicore fiber (SM-MCF) with uncoupled cores[3] has been demonstrated for large-capacity transmission without MIMO processing, reducing receiver complexity and latency[4], also providing a promising solution for high-throughput interconnects. In addition, single-source optical frequency combs have been proposed for large capacity transmission with low complexity and potential high energy-efficiency[5,6]. Together, these three technologies form an attractive proposal for optical interconnects with reduced complexity, if stitched together by an appropriate data encoding and error correction coding.

In this paper, we bring together Kramers-Kronig detection with multi-core SM-MCF transmission of DSDM/WDM data channels derived from a single laser comb source, and employ low-density parity-check (LDPC) coding with adaptive overheads to cater to the individual OSNR conditions of each channel. We generate a frequency comb spanning the whole C-band, consisting of 99 lines on a 50 GHz grid, and achieve a 909.5 Tbit/s net-rate DSDM/WDM transmission through a 7.9 km 37-core SM-MCF. All 3663 channels (37 SDM × 99 WDM) exhibit error-free performance with adaptive rates. An aggregated spectral efficiency (SE) of 184.42 bit/s/Hz is achieved. To the best of our knowledge, this is a record transmission throughput using direct-detection.

Experiment setup

Fig. 1 (a) shows the experimental setup. For the optical comb generation, an intensity modulator (IM) and phase modulator (PM) in tandem carve out linearly chirped pulses from a continuous-wave fiber laser (FL) at 1550 nm at a 25 GHz repetition rate, which are linearly compressed in 400 m SMF. The pulse train forms a seed optical comb with a 10 dB bandwidth of 3 nm, which is then amplified, filtered, and launched into two parallel nonlinear frequency comb broadening modules. The first one uses a 200 m dispersion-flattened highly nonlinear fiber (DF-HNLF) (γ=10.7 W^{-1}km-1, β_2=−0.326 ps^2/km, β_3=0.006 ps^3/km, at 1550 nm) with a launch power of ~26 dBm. Due to self-phase modulation (SPM), the optical comb (Comb SPM 1) is broadened to a 10 dB bandwidth of 14.8 nm. The second one produces a broader optical comb with a 10 dB bandwidth of 40 nm (Comb SPM 2) with a

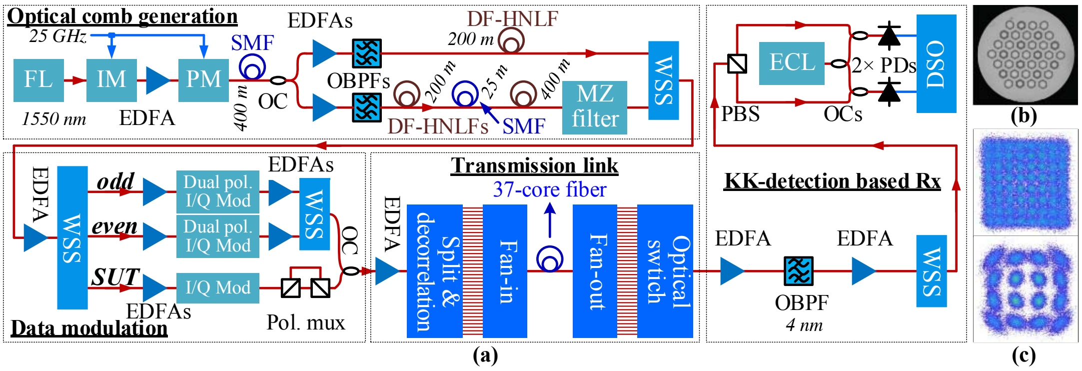

Fig. 1: (a) Experiment setup; (EDFA: erbium-doped fiber amplifier; OBPF: optical band-pass filter; OC: optical coupler; PBS: polarization beam splitter) (b) Cross-section of the 37-core fiber; (c) constellation diagrams for the received 64 QAM (ch. 40, core 7) and 16 QAM (ch. 88, core 7) signals.

launched power of ~25 dBm, using a cascaded nonlinear broadening scheme[7] with 200 m DF-HNLF, 25 m SMF, and another 400 m DF-HNLF (γ=10.7 $W^{-1}km^{-1}$, β_2=−0.446 ps^2/km, β_3=0.0057 ps^3/km, at 1550 nm). A Mach-Zehnder (MZ) interferometer based optical notch filter with a free spectral range of 30 nm is utilized to suppress the low optical signal-to-noise ratio (OSNR) region of the comb around 1550 nm. Through a wavelength-selective switch (WSS), the two broadened combs are combined and equalized with suppression on every other line. A 50-GHz spaced flat comb source across the whole C band with 99 lines is therefore achieved.

Another WSS splits the comb into odd, even, and signal-under-test (SUT) channels, which are modulated at 32 GBd by an arbitrary waveform generator with a sampling rate of 64 GSa/s. The signal is digitally pulse shaped by a root-raised cosine filter with 401 taps and roll-off factor of 0.01. A single-polarization I/Q modulator together with a polarization multiplexer is used to generate the SUT channel, which is swept across the whole comb for performance evaluation. With another WSS and an optical coupler, the modulated channels are combined to a 99-channel WDM signal.

The WDM channels are then amplified, split, de-correlated, and launched into a 7.9 km 37-core fiber through a free-space based fan-in device. The launched power for each core is approximately 8 dBm and varies within 1 dB. The heterogeneous single-mode 37-core fiber has a crosstalk < −50 dB at 1550 nm [3]. At the output of the 37-core fiber, the SDM channels are demultiplexed and selected using a free-space based fan-out device and an optical switch.

The selected spatial channel with an average optical power of 2 dBm is amplified and filtered to extract the SUT channel. This is then launched into a polarization-diversity KK receiver comprising an external cavity laser (ECL) as local oscillator and two 70-GHz photodiodes (PD). The optical power of the SUT channel at the receiver frontend is around 4 dBm. The output power of the ECL is 12 dBm, resulting in a carrier-to-signal power ratio of 8 dB. A digital storage oscilloscope (DSO) with 65 GHz bandwidth and 160 GSa/s sampling rate captures the signal for offline digital signal processing (DSP), with 2 million samples.

Results and discussions

Fig. 2 (a) shows the optical spectra of the seed comb, and the two combs from the nonlinear broadening modules. Fig. 2 (b) gives the optical spectrum of the equalized 50 GHz spaced optical comb. The flat optical comb consists of comb lines from nonlinear broadening module 1 in the range of 1542.22 nm (channel, ch. 63) to 1557.848 nm (ch. 24) and from nonlinear broadening module 2 in the range of 1527.68 nm (ch. 99) to 1541.824 nm (ch. 64) and 1558.256 nm (ch. 23) to 1567.212 nm (ch. 1). Fig. 2 (c) gives the spectrum of the WDM channels.

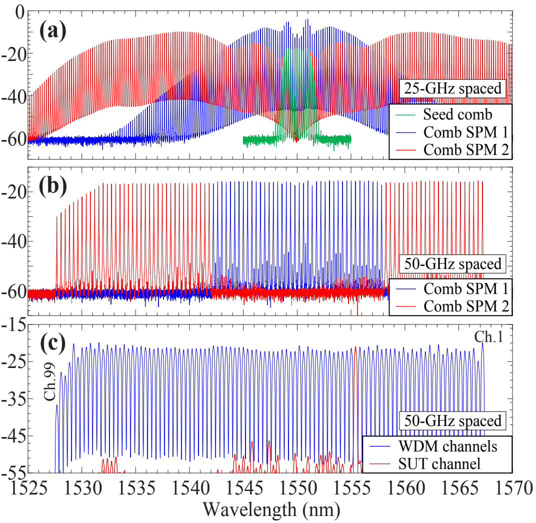

Fig. 2: Spectra of the (a) 25-GHz broadband comb source, (b) 50-GHz equalized comb source, and (c) WDM channels.

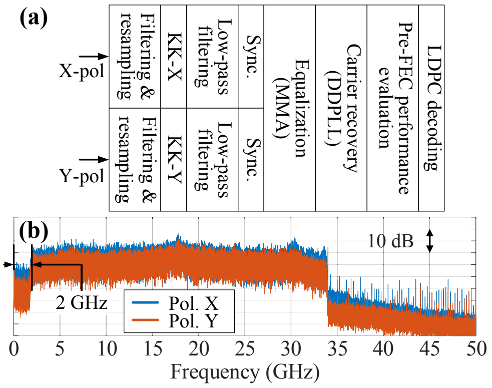

Fig. 3: DSP flow and electrical spectrum (channel 88, core 7).

Fig. 3 (a) illustrates the DSP flow of the KK-receiver. The detected X- and Y-polarization signals are filtered and resampled to 16 Sa/sym for KK-based optical field re-construction. The field-reconstructed signals are low-pass filtered, and synchronized. Pilot-aided radius-directed adaptive equalization with 220 taps is then used to perform polarization demultiplexing and to compensate the dispersion and inter-symbol interference due to imperfect frequency response of the transmitter and receiver. The pilot overhead is 4%. A decision-directed phase-locked loop (DDPLL) is then used for frequency offset correction and carrier phase recovery. The transmission performance is evaluated in terms of mutual information (MI). The signal is LDPC decoded to evaluate the bit-error rate (BER). Fig. 3 (b) shows the electrical spectrum of the photo-detected signal (ch. 88, core 7). Note that a 2 GHz gap between the local oscillator (LO) and the start frequency of the signal is inserted for eliminating out-of-band noise from the LO. Fig. 1 (c) gives the 64-QAM (ch. 40, core 7) and 16-QAM (ch. 88, core 7) constellations out of the DSP. Nonlinear phase noise is clearly observed

Table 1: The choice of modulation format, LDPC coding overhead, the resulted net rate, and the SE of each channel

Channel index	Modulation speed (Gbaud)	Modulation Format	LDPC overhead	Pilot overhead	Outer HD-FEC overhead	Net rate (Gbit/s/ch/core)	SE (bit/s/Hz)
24–63	32	64 QAM	33%	4%	0.8%	274.73	5.495
5–23, 64–83		64 QAM	50%			244.2	4.884
1–4, 84–99		16 QAM	20%			203.5	4.070

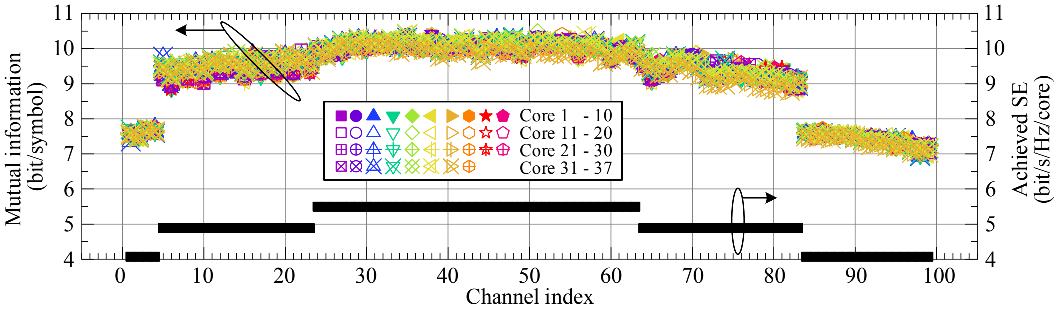

Fig. 4: Calculated mutual information and achieved net rate of each WDM channel.

for the 16-QAM signal, which originates from SPM based spectral broadening[8].

As shown in Table 1, the choice of modulation format and LDPC coding overhead for the WDM channels (for the SUT channel) depends on OSNR of the comb lines. In total, 345600 and 259200 symbols per channel for 64 QAM and 16 QAM signals are evaluated for LDPC decoding (16 and 8 code blocks) and BER assessment, respectively. After LDPC decoding, all channels show BER < 10^{-5}. An outer hard-decision FEC (HD-FEC) of 0.8% overhead is assumed to remove any BER < 10^{-5} error floor of the LDPC code[9], which can correct the remaining errors and bring the BER below 10^{-15}. With this HD-FEC, all channels measured in the experiment are claimed to exhibit reliably error-free performance. A net rate of 274.73, 244.2, and 203.5 Gbit/s/ch are achieved, respectively. Combining all 37 SDM channels with 99 WDM channels, this result in a total net rate of 909.5 Tbit/s, and an SE of 184.42 bit/s/Hz (4.98 bit/s/Hz/core). Fig. 4 gives the Monte-Carlo calculated MI and achieved SE for each channel.

We attribute the performance degradation for edge channels to the phase noise associated with SPM spectral broadening[8], and available OSNR of the comb lines. There are a number of ways to achieve a better overall performance and a larger capacity. The seed comb is limited by the electro-optical modulation followed by optical amplifiers, which result in OSNR degradation. A parametric-mixer based scheme for the seed comb can be implemented to get higher OSNR[10]. It can also be filtered line-by-line by a narrow-band comb-shaped filter. Gain-flattened EDFAs can be used to mitigate the excess loss during comb equalization. The WSS used to combine and split the comb lines has limited frequency resolution and suppression ratio, which result in extra attenuation and crosstalk. This can be solved by replacing the WSS with commercial arrayed waveguide gratings (AWGs). In addition, overall capacity can be increased with a better match of symbol rate and comb spacing.

Conclusions

A record-high data throughput for direct-detection of 909.5 Tbit/s has been demonstrated with a single-mode 37-core fiber and KK receiver. A 50 GHz spaced optical comb based on a single optical source is implemented for 37 SDM channels with 99 WDM channels. Using LDPC codes with different overheads, all channels exhibit error-free performance after 7.9-km transmission, with an SE of 184.42 bit/s/Hz.

Acknowledgements

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