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Optical switching and detection of 640 Gbits/s optical time-division multiplexed data packets transmitted over 50 km of fiber

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We demonstrate 1 × 4 optical-packet switching with error-free transmission of 640 Gbits/s single-wavelength optical time-division multiplexed data packets including clock distribution and short pulse generation for optical time demultiplexing based on a cavityless pulse source.

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Traffic in optical networks has been forecasted to grow exponentially by a factor of 1000 every 10 years [1]. It is therefore envisioned that the optical links that interconnect the nodes of the network will carry data at bit rates well above 100 Gbits/s. Moreover, these data streams might be encoded in a variety of data formats, and depending on the application, these data streams might be circuit- or packet-based. Thus, it is essential to investigate node architectures that are agnostic for data format and bit rate. It is also important that the network nodes have the capability to scale to a large number of ports while introducing little latency. It has been recognized that $1 \times N$ optical-packet switches (OPSs) form a key building block for a scalable node [2], showing data format agnostic behavior and scalability to a large number of ports at the expense of low latency [3].

Here we report for the first time, to best of our knowledge, on the operation of a 1×4 OPS with optical time-division multiplexed (OTDM) data packets at a bit rate of 640 Gbits/s, including optical-packet transmission and optical-packet switching and detection. The packet addresses are encoded by in-band labels, which, in the node, are processed in parallel by utilizing a cascade of optical filters in combination with a simple electronic combinatory network. This approach allows asynchronous operation at very low power and little latency.

The schematic diagram of the OPS concept is shown in Fig. 1. The system consists of four main blocks: the transmitter, a 50 km dispersion-compensated transmission link, the OPS, and the receiver. In the transmitter, optical pulses are generated by an erbium-glass oscillating pulse-generating laser (ERGO-PGL) at 1542 nm with pulse duration of 1.5 ps and 10 GHz repetition rate. Subsequently, the pulses are compressed down to 600 fs by self-phase modulation in 400 m of dispersion-flattened highly nonlinear fiber (DF-HNLF dispersion $D = -0.45$ ps/nm/km and dispersion slope $S = 0.006$ ps/nm^2/km at 1550 nm, nonlinear coefficient $\gamma = 10.5\ \mathrm{W}^{-1}\ \mathrm{km}^{-1}$) and filtered at 1545 nm with a 3 dB bandwidth of 9 nm.

Later on, the pulses are encoded by on–off keying (OOK) with a 10 Gbits/s $2^7 - 1$ PRBS user pattern to form the payload of the optical packets. The packets have a duration of 153.6 ns, consisting of 89.6 ns of data payload separated by a 64 ns guard band. The encoded pulses are sent through a fiber interleaver, which is designed to preserve the pseudorandomness of the used pattern length, and they are time multiplexed to constitute the 640 Gbits/s OTDM data packets. In order to distribute the clock signal in the system [4], a clock pilot was generated by modulating a CW laser with a master clock at 10 GHz and inserted in-band with the 640 Gbits/s OTDM spectrum. This self-synchronization method eliminates the need for an ultrafast phase comparator and a phase-locked loop (PLL), and provides highly stable performance and low timing jitter. The central wavelength of the pilot is centered at 1552.52 nm, which is chosen to avoid crosstalk with the spectral lines at 640 GHz and 1.2 THz of the data signal. To improve the optical signal-to-noise ratio (OSNR) of the clock pilot, a programmable wave shaper filter with 3 dB bandwidth of 0.4 nm and 30 dB suppression of the rejection band centered at the pilot wavelength, is used to carve a portion of the spectrum where the pilot is inserted. The distribution of the clock in the receiver part, is realized by separating the clock pilot from the signal via an optical circulator and a Fiber–Bragg grating (FBG) with central frequency identical to the pilot wavelength.

In order to address the destination of the packets, we employed the in-band labeling technique [3]. The packet address is encoded with labels at wavelengths within the bandwidth of the payload and have duration equal to the payload length. The duration of the payload length was chosen based on the minimum and optimal time-length of the labels encoded by the arbitrary wave generator (AWG) used in this experiment. Each label has a binary value: '0' means no signal, '1' means an optical signal. Thus, 2^N addresses can be encoded by only using N in-band labels. Here we use two in-band labels at 1546.62 nm and 1547.28 nm to encode four addresses. Figures 2(a) and 2(b) show the spectra of the transmitted signal at the receiver side before and after the labels and pilot are extracted. The pilot, located between the first

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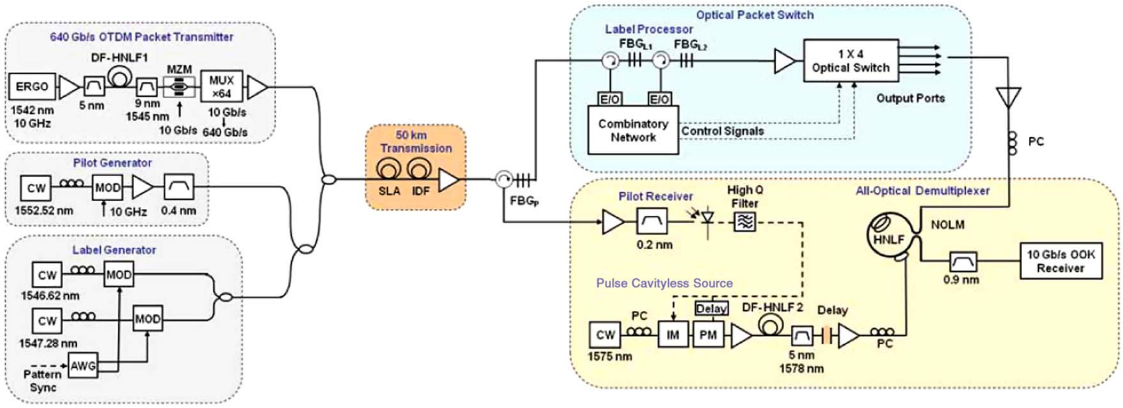

Fig. 1. (Color online) Experimental setup: ERGO, erbium-glass oscillating pulse-generating laser; MOD, modulator; AWG, arbitrary-waveform generator; DF-HNLF, dispersion-flattened highly nonlinear fiber; SLA, super large area fiber; IDF, inverse dispersion fiber; FBG, fiber–Bragg grating; E/O, electro-optical conversion; PC, polarization controller.

(640 GHz) and second (1.2 THz) spectral line of the signal, is considered in-band due to the minimum number of spectral lines required to preserve an undistorted signal pulse. Nevertheless, the pilot can be placed close to the central wavelength if a narrower (0.25 nm) FBG is employed. The 640 Gbits/s OTDM packetized data, together with the pilot and labels are transmitted over a dispersion and dispersion-slope compensated fiber span of 50 km optimized at 1545 nm. The transmission link is composed of 25 km super large area (SLA) fiber ($D = 20$ ps/nm/km, $S = 0.06$ ps/nm^2/km and PMD $=$ 0.04 ps/km$^{1/2}$, where PMD is polarization-mode dispersion) and 25 km inverse dispersion fiber (IDF) ($D = -20$ ps/nm/km, $S = -0.06$ ps/nm^2/km and PMD $=$ 0.02 ps/km$^{1/2}$) with a total loss of 12 dB. After the 50 km transmission link, the 640 Gbits/s data packets are fed into the OPS. As the clock pilot, labels, and payload are transmitted synchronously and are spectrally in band, they are affected by the same impairments, leading to the same phase drifts. Thus, the relative phase between the clock pilot, labels, and data is preserved. The OPS extracts the optical labels by cascading two FBGs (FBG_{L1} and FBG_{L2}), centered at the label wavelengths, and two optical circulators. The FBGs have a Gaussian transfer function with 98% reflectivity and 6 GHz 3 dB bandwidth. The parallel labels are detected and processed by the electrical combinatory network. The combinatory network provides the control signal of the electro-optical switch with latency of <3 ns. Finally, the payload is fed into the 1×4 electro-optical switch based on $LiNbO_3$ technology [3]. According to the encoded addresses, one switch is enabled at a time and the switched optical packet is evaluated in the all-optical demultiplexer (AOD). Figures 2(c)–2(m) show the dynamic operation of the OPS. The extracted labels and the 640 Gbits/s data payload are shown in Figs. 2(c)–2(e), respectively. According to the packet addresses, the control signals generated by the combinatory network to drive the 1×4 switch are shown in Figs. 2(f)–2(i). Figures 2(j)–2(m) show the switched packets from port 1 to port 4 with their respective addresses "11," "10," "00," and "01."

The switched optical packets are then fed into the receiver to measure the performance of the system. The receiver consists of pilot extraction and a cavityless pulse source that produces an optical pulse-train required for 640-to-10 Gbits/s AOD operation. The pilot clock is separated via an optical circulator and FBG_p, with central frequency and bandwidth at 1552.52 nm and 0.4 nm, respectively. The extracted pilot is amplified and filtered with a 3 dB bandwidth of 0.2 nm and converted to the electrical domain by a 12 GHz photoreceiver. The electrical signal is subsequently filtered by a high-Q filter (10 MHz) and used to drive a cavityless pulse source and the bit-error-rate tester (BERT). The cavityless pulse source consists of two RF-driven stages (intensity and phase modulation) and an optimized length of dispersion-compensated fiber to produce pulses as short as 5 ps [5], which are subsequently compressed down to

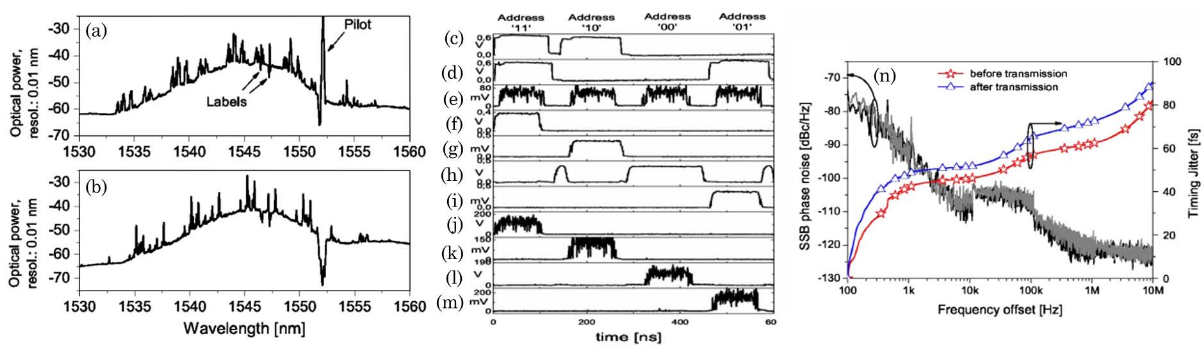

Fig. 2. (Color online) Spectra of the 640 Gbits/s OTDM signal after transmission at the receiver side: (a) before labels and pilot extraction, (b) after labels and pilot extraction, (c)–(m) dynamic operation of the optical packet switch, and (n) phase noise of the distributed clock.

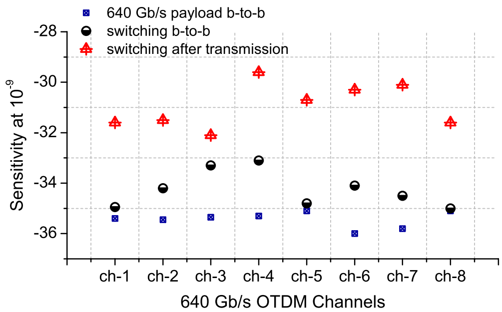

Fig. 3. (Color online) BER curves of the payload and switched packets at each output port before and after transmission.

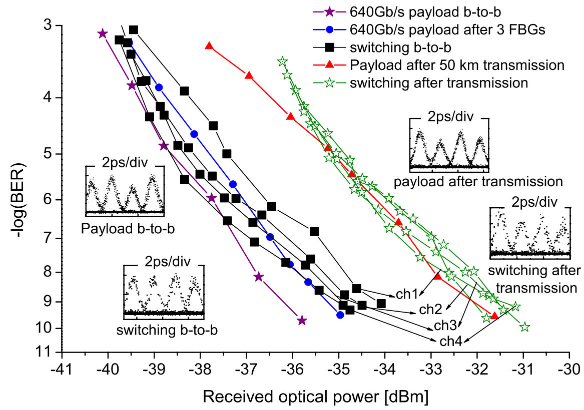

Fig. 4. (Color online) Sensitivity at 10^{-9} of eight consecutive channels.

1 ps duration and a 10 GHz repetition rate at 1578 nm. This scheme allows for generating an optical clock pulse on the fly once the RF pilot clock is applied, thus avoiding costly optical clock pulse generation based on mode-locked lasers in combination with optical/electrical PLL circuitry. The phase noise of the clock is shown in Fig. 2(n). The integration of the noise spectrum in the range between 100 Hz and 10 MHz reveals a timing jitter of 80 fs with an increase of 10 fs after 50 km transmission. The generated optical short pulses serve as control pulses in an AOD based on a nonlinear optical loop mirror.

The quality of the time-demultiplexed signal is analyzed by the BERT, which is triggered by the extracted clock. Bit-error-rate (BER) curves recorded for the switched packets at each output port are shown in Fig. 3. As a reference, we plot the BER curve of the back-to-back (b-to-b) payload (filled stars). Error-free operation with 1 to 1.5 dB of penalty was measured at output ports 1–4 (filled squares). The measured penalty is attributed to the carving effect of the FBGs and the accumulated amplified spontaneous emission (ASE) noise of the amplifier used in the optical switch. Furthermore, after 50 km fiber transmission, we measured error-free operation with a 3 dB penalty compared to the b-to-b case for both the payload (triangles) and the switched outputs (stars). The reported penalty is introduced by accumulated ASE noise, uncompensated PMD, and by an increase in the timing jitter of the distributed clock. The diagrams shown in Fig. 3 are clear and open, although not equalized due to temperature-control issues in one of our optical multiplexers, creating amplitude imbalance in neighboring channels. As a representative example of the integrity of the total number of channels of the 640 Gbits/s payload, we measured the receiver sensitivity at a BER of 10^{-9} of 8 over 64 consecutive channels at one of the output ports of the optical switch. As shown in Fig. 4, the BER at $<10^{-9}$ could be measured for the channels before (circles) and after (triangles) transmission.

This Letter is the first report, to the best of our knowledge, on the operation of optical-packet switching and detection of 640 Gbits/s single-wavelength OTDM data packets based on the in-band label concept, including ultrafast self-synchronization after 50 km fiber transmission. The self-synchronization method eliminates the need for an ultrafast phase comparator and a PLL, and provides highly stable performance and low timing jitter to drive a cavityless pulse source for an all-optical 640 to 10 Gbits/s demultiplexer. Error-free operation after transmission is achieved with a penalty of only 3 dB.

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