Demonstration of feasibility of a complete 160 Gbit/s OTDM system including all-optical 3R

Antonella Bogoni b,*, Paolo Ghelfi b, Mirco Scaffardi a, Claudio Porzi a, Filippo Ponzini a, Luca Potì b

a CEIRC-Scuola Superiore Sant’Anna, Via Moruzzi 1, 56124 Pisa, Italy
b Photonic Networks National Laboratory CNIT, Via Moruzzi 1, 45 56124 Pisa, Italy

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Abstract

A complete 160 Gbit/s single-channel OTDM system experiment is presented. The OTDM system includes all-optical transmitter, 3R (Retiming, Reshaping, and Reamplification), and receiver. Performance measurements of the single subsystems are also reported. Finally, Q-factor measures verify the effectiveness of the whole system.

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1. Introduction

Optical time division multiplexing (OTDM) is very attractive for next generation transmission systems and networks. All-optical technologies allow to overcome signaling rate limits imposed by electronics. A lot of research has been carried out in order to study OTDM subsystems as pulsed source, all-optical clock recovery, 2R (Re-shaping and Re-amplification) and 3R (2R + Re-timing) all-optical regenerator and demultiplexer. However, few works fully report OTDM system experiments at very high bit rates [1–3]. In particular very critical subsystems, as the ultra-fast all-optical regenerator, are often neglected in the OTDM transmission demonstrators.

In this paper we present, a complete OTDM system experiment at 160 Gbit/s in order to verify the feasibility of all needed subsystems and the possibility to exploit them to realize an ultra-fast transmission system. OTDM data generation, transmission, all-optical clock recovery, regeneration and demultiplexing are demonstrated.

Data sheets are reported for the OTDM transmitter and the all-optical clock recovery. Eye diagrams are measured at the transmitter, after propagation through 10 km of dispersion shifted fiber (DSF), and at the receiver after demultiplexing with simultaneous regeneration. A received Q-factor improvement from 3.0, for the distorted signal, to 6.2, for the regenerated signal, is demonstrated.

2. Experimental setup

In Fig. 1, the experimental setup is reported. Data and clock signals are generated by two fiber mode locked lasers (FMLLLs) at 10 GHz. The 5 ps-wide pulses are then compressed to 1.5 ps by a higher order soliton compressor (HOSoC); a pedestal suppressor then eliminates the typical tails due to the compression method, exploiting the unbalanced self phase modulation (SPM) in a nonlinear optical loop mirror (NOLM-based pedestal suppressor, NPS). The signal is modulated through a 10 GHz Mach Zehnder...
(MZ) modulator using a 2 and afterward optically multiplexed using a polarization maintaining (PM) 10–160 optical multiplexer (OMUX) constituted by four split-and-combine stages. The signal at the input of the OMUX is linearly polarized along one of the axis of the PM fiber so that all pulses of the 160 Gbit/s OTDM frame present the same state of polarization. At the output of the OMUX the signal is optically amplified using a not PM optical erbium doped fiber amplifier (EDFA). The 160 Gbit/s OTDM signal is then launched into a 10 km-long DSF with the zero-dispersion wavelength at 1555 nm and the slope of 0.08 ps/nm/km. In our case the main aim was the demonstration of all OTDM subsystems, for this reason we did not optimize the transmission link. In particular the chromatic dispersion was not compensated, and the nonlinear effect are not minimized. Consequently the maximum transmission distance was about 10 km. After the propagation, a portion of the incoming signal is tapped for the clock recovery, whereas the rest is sent to the regenerator and demultiplexer. All-optical clock recovery is obtained by means of an optical phase locked loop (OPLL) composed by an optical voltage control oscillator (OVCO) [4] and an ultra-fast semiconductor optical amplifier-based optical phase comparator (SOA-OPC). The OVCO is represented by the regenerative active fiber mode locking source that produces the clock pulses. Into the laser cavity we insert a piezo-electric optical delay line to modulate the cavity length and consequently to change the pulse repetition rate. This device permits to change the length of the cavity as a function of the tension applied to the piezo tube. By this way the regenerative source can be considered as an OVCO [3] because it is possible to control the pulses repetition rate, by changing the voltage control of the optical delay line. Phase detection is performed exploiting high detuning four wave mixing in the SOA [5]. In this case Intra-band phenomena guarantee very high speed operation. If signal and clock pulse trains are coupled into the semiconductor device, the mean power generated by FWM is proportional to their phase difference and then can be used to generated the low frequency electrical signal that control the OVCO.

Finally the distorted OTDM signal is fed into the regenerator together with the synchronized clock.

The exploited regeneration scheme permits to achieve in-line regeneration or regenerative demultiplexing functionalities using a 160 or 10 GHz clock respectively. This solution [6] is based on a split of the regeneration process in different steps, in order to use easy and well-known subsystems. In particular the regenerator includes three stages: two pedestal suppressors and a wavelength converter. The first stage exploits a pedestal suppressor and a wavelength converter. The first stage transfers the information from the distorted data signal to the recovered clock, with a logic inversion. By this way, the noise still present on the marks is moved on the spaces, while the quality of the clock pulses, suitable for the transmission of an OTDM signal at high bit rate, permits to achieve both the function of reshaping and retiming. The residual amplitude noise can then be eliminated by the third stage, which is composed by another pedestal suppressor. The reamplification functionality is carried out using a booster amplifier at the input of the last stage able to produce a high power signal at the output of the regenerator. Note that if only the second stage is considered, a not regenerative demultiplexer can be obtained.

Each stage of the proposed regenerator scheme is based on a NOLM structure, whose dynamics are characterized by the ultra-fast response time of the Kerr effect in the fiber loop. In particular the first and the last stages exploit SPM (self-phase modulation), and the second one XPM (cross phase modulation). In a first approximation only one of the two counter-propagating halves of the input signal experiences nonlinear phase shift due to its own power

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**Fig. 1.** 160 Gbit/s OTDM transmission system experimental setup.
(SPM), or to the co-propagating light power (XPM). Nevertheless, the counter-propagating light experiences SPM/XPM due to nonlinear interaction between counter-propagating signals, depending on the mean power of the light responsible for the effect [7]. If the duty-cycle d of the signal inducing SPM or XPM is low (low-bit rate ultra-short pulsed signal), this effect can be neglected, since the mean power is much smaller than the peak power. But when the duty-cycle gets higher these effects rapidly increase and they can strongly affect the NOLM performance. This is the case of NOLMs used for the 160 Gbit/s regeneration. We have demonstrated [8] that a non-polarization maintaining implementation of the NOLMs, including a polarization controller into the loop, allows to compensate for this counter-propagating undesirable effects permitting a performance optimization of the NOLMs also in ultra-fast applications.

### 3. 160 Gbit/s system performance

Each constituent block of the OTDM transmission system, transmitter, all-optical clock recovery, regenerator and demultiplexer, was first characterized alone. Transmitter data sheet is specified in Table 1. The maximum repetition rate is fixed by the pulsewidth and by the number of multiplexer stages. The pulsewidth was measured using an optical sampling oscilloscope (OSO) with a bandwidth of 700 GHz and time resolution lower than 600 fs supplied by ANDO. The insertion into the cavity of an optical delay line allows to synchronize the pulsed source with an external clock 10 GHz in the range ±5 MHz through a PLL line allows to synchronize the pulsed source with an external 10 GHz clock ±5 MHz through a PLL.

A full width at half maximum (FWHM) of 1.2 ps guarantees a crosstalk due to adjacent tributary channels lower than 20 dB at 160 Gbit/s. The wavelength of the signal generated by the FMLL is tunable. This feature only requires a proper adjustment of the input power at the following HOSoC and NPS, in order to keep their efficiency constant. Timing jitter measure, realized though OSO, was limited by the instrument precision and a guard-time between adjacent pulses higher then 30% of the bit time guarantees the complete absence of cross-talk. The measured Q-factor is of 6.3. The signal was than measured after 10 km of DSF with a zero dispersion wavelength $\lambda_0 = 1547$ nm and a fiber dispersion slope $S = 0.08$ ps/nm$^2$/km. The propagation strongly affects the signal, as shown in the middle picture of Fig. 2, leading to a substantial pulse broadening and a well-evident cross-talk between adjacent channels. The Q-factor of the transmitted signal is equal to 3.0.

The regeneration process completely suppresses the cross-talk, as well as the noise on marks and on spaces, producing a well-open eye diagram. The regenerated pulsewidth at 20 dB is lower than 80% of the bit time. The measured Q-factor improvement is from 3.0 to 6.2. Then the regeneration process completely compensates for all distortions effects. In our case the use of a clock at tributary bit rate, allowed us to regenerate only one tributary channel. Nevertheless, shifting the clock with respect to the OTDM frame it is possible to select the channel to be regenerated. Therefore, we tried to separately carry out the regeneration for all channels and we verified the independence of the regeneration effectiveness on the channel to be process. In fact we measured variations in the Q-factor improvement

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Transmitter data sheet</th>
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<tbody>
<tr>
<td>Repetition rate</td>
<td>160 GHz ± 5 MHz</td>
</tr>
<tr>
<td>Pulsewidth at 3 dB</td>
<td>1.2 ps</td>
</tr>
<tr>
<td>Crosstalk level</td>
<td>&lt;−20 dB</td>
</tr>
<tr>
<td>Time · Bandwidth</td>
<td>0.318 (=theoretical limit)</td>
</tr>
<tr>
<td>Signal wavelength</td>
<td>1540–1565 nm</td>
</tr>
<tr>
<td>Mean output power</td>
<td>&gt;1 dBm</td>
</tr>
<tr>
<td>Signal-to-noise ratio</td>
<td>&gt;50 dB</td>
</tr>
<tr>
<td>Polarization state</td>
<td>Arbitrary</td>
</tr>
<tr>
<td>Jitter</td>
<td>&lt;200 fs (instrument limit)</td>
</tr>
<tr>
<td>Stability</td>
<td>Several hours</td>
</tr>
<tr>
<td>Synchronization</td>
<td>External 10 GHz clock ±5 MHz</td>
</tr>
</tbody>
</table>

Table 2 shows clock recovery data sheet. The operating data rates were verified at 10, 40, 80, and 160 GHz with a lock-in range limited to 200 kHz. This limit is due to the clock FMLL regenerative configuration that needs very narrow feedback electrical filters. Back-to-back measures give the minimum data mean input power of −10 dBm at 160 Gbit/s. Timing jitter was inferred from the electrical spectrum to be lower than 600 fs. Due to the presence of a SOA as ultra-fast phase detector, the maximum number of consecutive zeros that keeps the SOA saturated, is 1000 at 160 Gbit/s. In our case we used a $2^{31}−1$ pseudo-random sequence with a maximum number of consecutive zeros lower than 31.

Concerning the 2R regenerator and simultaneous demultiplexer, each NOLM was optimized for an incoming data stream at 160 Gbit/s and the extracted local clock at 10 GHz. In this way, 10 Gbit/s tributary channel was extracted and regenerated at the same time. The peak power of the regenerated channel was 21 dBm.

The used receiver is composed by a conventional photodetector optimized for 10 Gbit/s (non return-to-zero) NRZ signals without any optical preamplification.

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Fig. 2 shows the eye diagrams along the system measured with the OSO. In the transmitted eye-diagram the jitter measure is limited by the instrument precision and a guard-time between adjacent pulses higher then 30% of the bit time guarantees the complete absence of cross-talk. The measured Q-factor is of 6.3. The signal was than measured after 10 km of DSF with a zero dispersion wavelength $\lambda_0 = 1547$ nm and a fiber dispersion slope $S = 0.08$ ps/nm$^2$/km. The propagation strongly affects the signal, as shown in the middle picture of Fig. 2, leading to a substantial pulse broadening and a well-evident cross-talk between adjacent channels. The Q-factor of the transmitted signal is equal to 3.0.

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<table>
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<tr>
<th>Table 2</th>
<th>Clock recovery data sheet</th>
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<tbody>
<tr>
<td>Operating data rate</td>
<td>N×10 Gbit/s up to 160 Gbit/s</td>
</tr>
<tr>
<td>Lock-in range</td>
<td>200 kHz</td>
</tr>
<tr>
<td>Data mean input power</td>
<td>&gt;−10 dBm at 160 Gbit/s</td>
</tr>
<tr>
<td>Mean output power</td>
<td>&gt;10 dBm</td>
</tr>
<tr>
<td>Clock output RMS jitter</td>
<td>&lt;600 fs</td>
</tr>
<tr>
<td>Maximum number of consecutive zeros</td>
<td>&gt;1000 at 160 Gbit/s</td>
</tr>
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</table>
lower than 10% and strictly related to the $Q$-factor of the selected channel at the input of the regenerator.

The use of a clock signal at the tributary bit rate does not limit the effectiveness of the scheme for high bit rate transmission systems. As a matter of fact, the first stage works at 160 Gbit/s, and in the second stage, where the 10 Gbit/s clock signal does not induce any nonlinear effect, the phase shift is induced by the 160 Gbit/s signal. Only the third stage works at 10 Gbit/s, but its mean input power has been properly scaled, so that the same peak power could be obtained from an EDFA with 27 dBm saturated output power amplifying a 160 Gbit/s signal. Moreover, the use of more efficient fibers, as the highly non-linear fiber or the photonic crystal fiber, would allow the processing of even higher bit rates, reducing the limitations due to chromatic dispersion and power requirement.

4. Conclusions

A complete 160 Gbit/s OTDM system, including transmitter, 3R and receiver, has been experimentally demonstrated. Transmitter and clock recovery data sheets have been reported. Eye diagrams of the transmitted and received aggregate data streams were measured together with the extracted 10 Gbit/s tributary channel. $Q$-factor measurements are also carried out. A $Q$-factor improvement from 3.0 to 6.2 was measured due to the regeneration process.

Acknowledgment

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References