Time domain add-drop multiplexing for
RZ-DPSK OTDM signals

E.J.M. Verdurmen, A.M.J. Koonen and H. de Waardt
COBRA Research Institute, Eindhoven University of Technology
P.O. Box 513, 5600 MB Eindhoven, The Netherlands
e.j.m.verdurmen@tue.nl

Abstract: We show all-optical time domain add-drop multiplexing for a phase modulated OTDM signal for the first time, to our knowledge. The add-drop multiplexer is constructed of a Kerr shutter consisting of a 375 m long highly nonlinear fiber (HNLF), γ=20 W−1km−1. Successful time domain add-drop multiplexing is shown for 80 Gb/s RZ-DPSK OTDM signals with a 10 Gb/s base rate.

© 2006 Optical Society of America

OCIS codes: (060.4370) Nonlinear optics; (060.5060) Phase modulation

References and links

1. Introduction

With the rapid increase in data transfer over the network, the development of all-optical signal processing to improve the speed and avoid the O-E-O conversions will play an important role. By switching all-optical this burden can be overcome. In recent years the interest in phase modulated signals, like differential phase shift keying (DPSK), for long haul transmission has increased significantly. The DPSK format has been shown to improve the receiver sensitivity by 3 dB and has an increased tolerance to fiber nonlinearities compared to on off keying (OOK) [1]. Recent interest in all-optical signal processing of DPSK signals using highly nonlinear fiber (HNLF) showed the feasibility of phase sensitive amplification in a fiber parametric amplifier to regenerate the phase [2]. Furthermore HNLF has shown to be a suitable medium for all-optical time domain add-drop multiplexing [3, 4, 5, 6]. For a fully functional add-drop multiplexer, the targeted channel must be dropped in such a way that the bit slot of the dropped channel is clean enough to insert a new channel at the base rate. One simple switching method to achieve
high speed all-optical add-drop multiplexing is based on the Kerr shutter [7]. This concept is described in more detail in [8]. Despite the increased interest in DPSK signals, time domain add-drop multiplexing for DPSK has not been investigated so far. We have therefore looked at the feasibility to create an add-drop node (ADN) for RZ-DPSK OTDM signals based on the Kerr shutter in HNLF, which has the potential to operate at Tbit/s due to the ultra fast fiber nonlinearities.

2. Operating principle and experimental setup

The schematic of the transmitter is presented in Fig. 1. The transmitter of the 80 Gb/s RZ-DPSK OTDM signal requires a pulse train that is stable in phase from pulse to pulse. Because our mode locked laser (MLL) that is operated at $\lambda_c = 1545$ nm does not fulfill this requirement, a wavelength conversion scheme based on HNLF in a nonlinear optical loop mirror (NOLM) is employed. The NOLM consists of a 125 m long HNLF with nonlinear index $\gamma = 20$ W$^{-1}$km$^{-1}$ and a zero dispersion wavelength $\lambda_0 = 1590$ nm. The control pulse is a 2.3 ps full width half maximum (FWHM) pulse at the repetition rate of 10 GHz and the wavelength $\lambda_c = 1545$ nm. The time domain pictures throughout this paper are made with the Agilent terascope (bandwidth 500 GHz). The continuous wave (CW) signal is operated at $\lambda_s = 1557$ nm. Walk-off between control and data can be neglected because of the small dispersion slope $S=0.029$ ps/km/nm$^2$ and the short length of the HNLF. A polarization controller (PC) in the NOLM is used to optimize the switching characteristics of the NOLM, which was consisting of non polarization maintaining fibers. At the output of the NOLM an optical bandpass filter (OBPF) is used to select the converted signal at 1557 nm. The converted 10 GHz pulse is send to a LiNbO$_3$ phase modulator driven at a 2$^7$-1 pseudo random bit sequence (PRBS). This signal is then amplified, filtered and multiplexed with passive delay line multiplexers up to 80 Gb/s OTDM single polarization. The multiplexer was a commercial device based on Mach-Zehnder interferometers, constructed from polarization maintaining fibers. The bit separation delays were 6.4, 3.2 and

![Fig. 1. Schematic diagram of the 80 Gb/s RZ-DPSK OTDM transmitter. OBPF: Optical Band Pass Filter, PC: Polarization Controller, EDFA: Erbium Doped Fiber Amplifier, PM: Phase Modulator, MUX: Multiplexer, HNLF: Highly Nonlinear Fiber, PBS: Polarization Beam Splitter, $\tau$: tuneable optical delay line.](image)
1.6 ns respectively. The relative optical phases between the tributaries are not controlled, however this is not required to prove the principle of add-drop multiplexing. Our OTDM rate was limited to 80 Gb/s due the wavelength conversion in the NOLM. When the state of polarization (SOP) in the NOLM loses the optimal SOP due to small fluctuations in the temperature, the extinction ratio of the wavelength converted pulse is deteriorated. Consequently interferometric noise appears on the pulses of the 80 Gb/s signal after the multiplexing sections. The actual ADN is constructed of a Kerr shutter. The schematic of the experimental setup is shown in Fig. 2. The control pulse is obtained from the same MLL as the control pulse depicted in Fig. 1 by splitting the signal with a coupler. The control and data signals are combined and inserted into 375 m of HNLF with $\gamma = 20 \ W^{-1}\ km^{-1}$ and zero dispersion wavelength $\lambda_0 = 1590$ nm. The SOP of control and data signals are aligned in such a way that they are linear and that there is a 45° degrees angle between their SOP, which is the optimized angle according to the theory described in [8]. At the output of the 375 m HNLF an OBPF is used to block the control signal. The PC before the polarization beam splitter (PBS) is adjusted in such a way that the signal is send to the through port without the presence of a control signal. When a control signal is present in the HNLF the data signal experiences an extra amount of birefringence. This birefringence induces a rotation of the SOP of the data signal. The rotation results in a transmittance of the data signal to the drop port. The average power of the control signal in the experiments at the input of the HNLF was $P_c = 17$ dBm. The average power of the data signal was $P_s = -1.7$ dBm. At the through port a new “add-channel”, which is a copy of the 10 Gb/s signal obtained from the NOLM, is inserted in the cleared time slot of the data signal. The SOP of the add-channel is aligned to be equal to the SOP of the 7 through channels. The synchro-

Fig. 2. Schematic diagram of the 80 Gb/s add-drop node. MZI: Mach-Zehnder interferometer, EAM: electroabsorption modulator, VA: variable attenuator. The inset show the in- and output spectrum of the HNLF.
nization between control signal, data signal and add-channel has been performed manually in this experiment using tuneable optical delay lines. In a real system an automated polarization controller and a clock recovery scheme would be required; moreover an "add-channel" would also require an independent wavelength matched source. The DPSK receiver consists of an optical pre-amplifier followed by an OBPF to remove amplified spontaneous emission (ASE) noise and an asymmetric one-bit (100 ps) delay Mach-Zehnder interferometer (MZI) composed of spliced standard single mode fiber (SMF) pigtailed components to convert the phase information into an amplitude modulated signal. At the time of the experiment, the infrastructure to work with balanced photo detectors was not available. Working with balanced photo detectors would have improved the sensitivity of the receiver with at least 3 dB. One problem of the polarization dependent home-made MZI in this setup was a slow drift of the SOP inside the MZI, which changed over time due to temperature fluctuations. We measured a 1-dB insertion loss and a 10-dB extinction ratio for the MZI. The performance of the add-channel and the 7 through channels were measured by assessing the bit error rate (BER). The 80 Gb/s OTDM signal is demultiplexed to 10 Gb/s with 2 consecutive EAMs. The first EAM was driven at 10 GHz and the second EAM was driven at 40 GHz to obtain a switching window sufficiently small enough to demultiplex error free. The EAM switching window is shown in Fig. 3(a) and is 9.5 ps. The eye diagrams of the demultiplexed channel after the first and second EAM are shown in Fig. 3(b) and Fig. 3(c) respectively. Residual of other channels is still visible in the eye-diagram, which causes a penalty at the receiver.

![Switching window 2 EAM demultiplexer.](image)

![Eye diagram after the first EAM. Y-scale: 20 ps/div, x-scale: a.u.](image)

![Eye diagram after the second EAM. Y-scale: 20 ps/div, x-scale: a.u.](image)

Fig. 3. Two consecutive EAMs serve as demultiplexer from 80 to 10 Gb/s.

3. Results

The Kerr shutter is characterized by the measurement of the SOP rotation angle of the data signal. For this measurement a 10 Gb/s RZ-DPSK input signal at $\lambda_s = 1557$ nm and a $\tau = 2.3$ ps control pulse at $\lambda_c = 1545$ nm were used. The PC at the output of the HNLF is optimized such that the power measured at port 1 (through port) is maximized and the power at port 2 (drop port) is minimized in the absence of a control signal. The relation between output power of both ports of the PBS and the SOP angle of rotation ($\Delta\phi$) are described by equation 1 and 2 that describe the transmittivity of the PBS output ports.

$$T_{PBS1} = \frac{1}{4} |1 - \exp(i\Delta\phi)|^2 = \sin^2 \left( \frac{\Delta\phi}{2} \right)$$

$$T_{PBS2} = \cos^2 \left( \frac{\Delta\phi}{2} \right)$$

By sweeping the power of the control signal, the amount of rotation of the data signal can be deduced from the power measured at the output ports of the PBS, shown in Fig. 4(a). In Fig.
4(b) it is seen that 17 dBm is required for a rotation of 0.8\pi. Because we didn’t achieve a full \pi rotation of the SOP, separate optimization of the add and drop port is required to minimize the receiver sensitivity penalty. The switching windows, measured with CW, are shown in Fig. 4(c). The window of the drop port is 2.1 ps and the window of the through port is 5.3 ps. These switching windows predict also good operation at higher bit rates, i.e. 160 Gb/s. Contrast ratios are larger than 15 dB. The spectra of the signal at the input of the 375 m HNLF and at the output are visualized in the inset of Fig. 2. The spectrum of the control pulse is broadened considerably. A further increase in the control power would lead to overlapping of the spectrum of control and data signal, resulting in crosstalk and degradation of the data signal. The eye diagrams of the 80 Gb/s OTDM RZ-DPSK time domain ADN are presented in Fig. 5. In Fig. 5(a) we see the through channels and one cleared time slot. In Fig. 5(b) we see that a new channel is added in the cleared time slot and in Fig. 5(c) the eye diagram of the dropped channel can be observed. All eye diagrams show clear and open eyes, which indicates excellent operation. After the time domain add-drop multiplexing the quality of the dropped, added and through channels is assessed by measurement of the BER. The BER of the dropped channels compared to the 10 Gb/s RZ-DPSK back-to-back (B2B) signal is shown in Fig. 6(a). The BER is measured versus the received power indicated as point $P_{\text{rec}}$ in Fig. 2. All channels show error free operation and no error-floor is observed, which indicates excellent performance of the ADN. The sensitivity penalty of the dropped channels at BER $10^{-9}$ is 2.6 dB for the best channel and 3.2 dB for the worst channel. The penalty of the dropped channels can be attributed to the interferometric noise that appears on the 80 Gb/s signal after multiplexing plus the penalty inherent to the Kerr
Fig. 6. BER measurement of the 80 Gb/s RZ-DPSK OTDM add-drop node.

switch. Inherently, the 10 Gb/s add channel suffers far less from interferometric noise (see also Fig. 5(b)). It’s main penalty contribution should be assigned to the dual stage EAM demultiplexer. The 80 Gb/s RZ-DPSK OTDM signal after the ADN is demultiplexed by 2 consecutive EAMs. The performance of the added and through channels are visualized in Fig. 6(b). A 2.1 dB penalty is observed for the add-channel compared to the B2B channel. For the through channels the sensitivity penalty is 3.3 dB for the best channel and 4.6 dB for the worst channel. The better performance of the add-channel can be understood by the fact that we insert the add channel after the multiplexer and Kerr switch. A large contribution to the penalty of the through channels is due the limited extinction ratio of the transmitter which causes the interferometric noise in the pulses of the 80 Gb/s signal after the multiplexing sections. The variation of the receiver sensitivity in the BER of the through channels is an adding up of the polarization instability penalties caused by the polarization dependence of the MZI, NOLM and EAM’s. The imperfect OTDM receiver, consisting of two EAMs, of which the switchingwindow is depicted in Fig. 3 adds an extra penalty compared to the dropped channels. An optimized input signal and an optimized receiver would significantly reduce the penalty. A summary of the penalty contributions for drop, add and through channels relative to the B2B BER curve is shown in table 1.

4. Conclusion

We have shown all-optical time domain add-drop multiplexing for a 80 Gb/s RZ-DPSK OTDM signal based on a Kerr shutter consisting of 375 m HNLF. The phase information in the signal is preserved in the complete add-drop node and the demultiplexer of the OTDM receiver, including a highly nonlinear fiber, a polarization beam splitter and 2 EAMs. In this experiment we were limited to 80 Gb/s because of the limited extinction ratio at the transmitter side, but in
Table 1. Summary of the penalty contributions relative to the back-to-back BER curve.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Value</th>
<th>Penalty contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>drop</td>
<td>2.6-3.2</td>
<td>Interferometric noise after the multiplexer + Kerr switch</td>
</tr>
<tr>
<td>add</td>
<td>2</td>
<td>dual EAM demultiplexer + Kerr switch</td>
</tr>
<tr>
<td>through</td>
<td>3.3-4.6</td>
<td>Interferometric noise after the multiplexer + Kerr switch</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ dual EAM demultiplexer</td>
</tr>
</tbody>
</table>

principle the ultra fast fiber nonlinearities ensures the possibility to upgrade the system to 160 Gb/s and higher.

**Acknowledgment**

This research was supported by the Ministry of Economic Affairs of the Netherlands through the Towards Freeband Communication Impulse of the technology programme.