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Comparison of demultiplexing techniques using XPM and FWM in HNLF

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Highly nonlinear fiber (HNLF) has shown to be a promising component for all optical signal processing at 160, 320 and 640 Gb/s data rates. We compare three demultiplexing techniques using a HNLF as the nonlinear medium. The first technique is based on cross phase modulation (XPM) in a nonlinear optical loop mirror. The second technique is based on XPM induced spectral broadening and filtering and the third technique is based on four wave mixing (FWM). We demonstrate the demultiplexing from a 160 Gb/s OTDM signal to a 10 Gb/s tributary in all three cases. We compare the three techniques on the basis of performance, complexity of implementation and the robustness.

Introduction

High speed optical time division multiplexed (OTDM) networks above 100 Gb/s require all-optical signal processing, e.g. demultiplexing, add-drop multiplexing, wavelength conversion etc., because the speed of signal processing reaches the current limit in electronics. A promising solution is the use of highly nonlinear fiber (HNLF) as all-optical signal processor. Fiber signal processors have the potential to operate at Tb/s speeds, due to their almost instantaneous response time. One disadvantage of using fiber as nonlinear element is that is requires long length and high power. However, recent developments in highly nonlinear fiber (HNLF), like e.g. the Bismuth Oxide-based fiber [1] with a nonlinear coefficient of ~ 1100 W^{-1}km^{-1}, can reduce the required fiber length to just one meter and relax the input power requirements. Several techniques have been proven successful in demultiplexing at high speed OTDM rates. In [2] a nonlinear optical loop mirror (NOLM) is used to demultiplex from 640 to 10 Gb/s. And demultiplexing based on four wave mixing (FWM) has been shown to be successful at a 500 Gb/s data rate [3]. In [4] a method based on cross phase modulation (XPM) induced spectral broadening is used to demultiplex from 160 to 10 Gb/s. We will compare these three methods, to offer an overview of these three attractive fiber based techniques. The parameters used for comparison are: performance, complexity of implementation and the devices physical dimensions, switching pulse power, spectral properties of the switching mechanism and the robustness.

Operation Principles

The three methods are schematically visualized in figure 1. The first method uses XPM spectral broadening by a control pulse in a HNLF. The incoming data signal is combined with a high energy control pulse at a different wavelength. The control pulse induces a phase modulation on the incoming data signal. This phase modulation is observed as a spectral broadening of the data signal. The XPM induced broadened part of the spectrum is filtered to convert the phase modulation to amplitude modulation. The second method for demultiplexing, based on degenerate FWM in a HNLF, uses an intense input

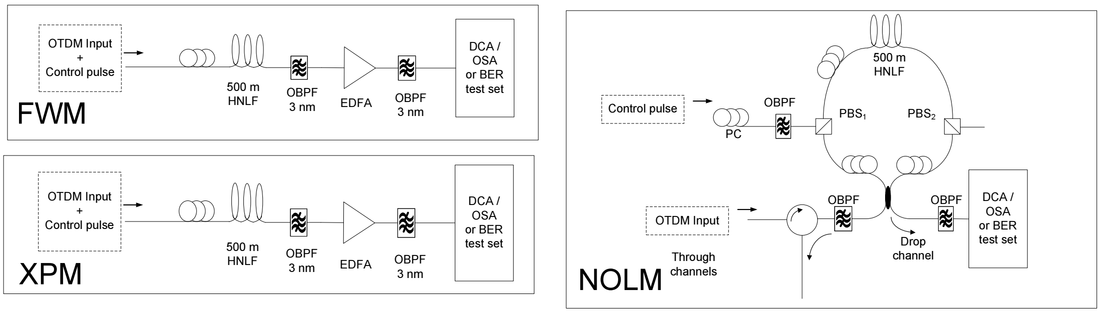


Figure 1: Three different methods for demultiplexing from 160 Gb/s OTDM to a 10 Gb/s base rate.

OTDM signal and a weaker control pulse. The FWM process will transfer energy from the strong input signal to the demultiplexing frequency: $f_{demux} = 2 \cdot f_{OTDM} - f_{control}$. The third method, which is a well-known technique in all-optical switching, is the nonlinear optical loop mirror (NOLM). A fiber based NOLM exploits the nonlinear phase shift induced in a fiber placed in a loop mirror for optical switching. In the NOLM the input signal is split into two parts: one clock-wise and one counter-clockwise signal. An external control pulse is introduced into the loop in one of the directions, as shown in figure 1. The input signal that co-propagates with the control channel experiences a phase shift induced by XPM from a high energy control pulse. The clockwise and counterclockwise signal meet again at the 50-50 coupler after traveling through the loop. The phase shifted channel of the input signal will be sent to the ”switched data” output port, while the unchanged channels will be reflected back to the input port. To prevent crosstalk between control and data, different wavelengths are used for both signals.

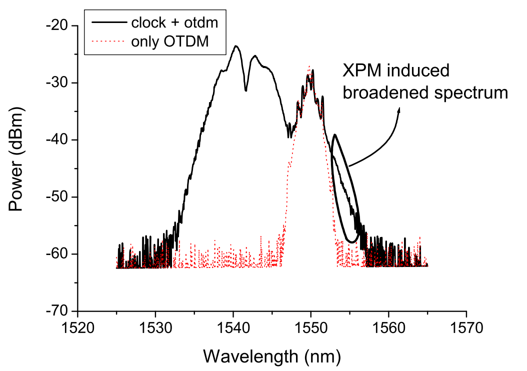
Experimental Results

The clock signal and the OTDM signal are obtained from the same Mode Locked Laser (MLL) source. The input pulse at 10 GHz is converted to a different wavelength to create the control signal. The wavelength conversion is based on super continuum generation (SC) in a 2.25 km Dispersion Shifted Fiber (DSF), with nonlinear index γ=2.6 $W^{-1}km^{-1}$ and zero dispersion wavelength $\lambda_0 = 1550$ nm. The 160 Gb/s OTDM signal is generated by modulating at a 10 Gb/s base rate (PRBS 2^7-1) and passively multiplexing this channel up to 160 Gb/s. The parameters of the HNLF that is used as nonlinear medium are: nonlinear coefficient: γ= 15 W^{-1} km^{-1}, length: L=500 m, zero dispersion wavelength: λ_0 =1545 nm, fiber attenuation: α=0.57 dB/km and dispersion slope: S=0.03 ps/km/nm^2. The values of the input powers and wavelengths of the OTDM and control signal are shown in table 1. For the XPM spectral broadening method, the spectral broadening of the OTDM signal by the control

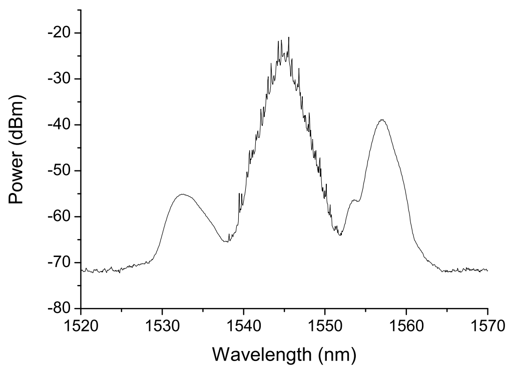
Experimental parameters			
parameter	XPM	FWM	NOLM
P_{OTDM} [dBm]	9.5	13	8.5
$P_{control}$ [dBm]	9	1.5	15
λ_{OTDM} [nm]	1550	1545	1550
$\lambda_{control}$ [nm]	1540	1557	1545
$P_{received}$ [dBm]	-14	-20	-8
P_{in}(per base rate channel) [dBm]	-2.5	1	-3.5
efficiency η [dBm]	-11.5	-22.5	-4.5

Table 1: Parameters used in the experiments.

pulse can be seen in figure 2(a). The conversion from phase modulation to amplitude modulation takes place by spectral slicing at $\lambda = 1554$ nm, with a $\Delta\lambda = 0.78$ nm bandwidth filter. This results in a demultiplexed pulse at 10 Gb/s with a full width half maximum (FWHM) of 6.7 ps, shown in the inset of figure 3(a). A small filter bandwidth is required to minimize the transmission of the not selected data channels, whose spectrum is not broadened. To compare with literature, in [4] they showed 160 to 10 demultiplexing with a 0.3 nm band pass filter. For the FWM method we chose the OTDM signal as the pumping signal, because of practical reasons. This results in a FWM product at $f_{demux} = 1532.7$ nm, as is shown in figure 2(b). For the demultiplexing experiment using a NOLM the parameters are shown in table 1.



(a) Spectrum after the HNLF with (solid) and without an external control signal (dashed); res: 0.2 nm.

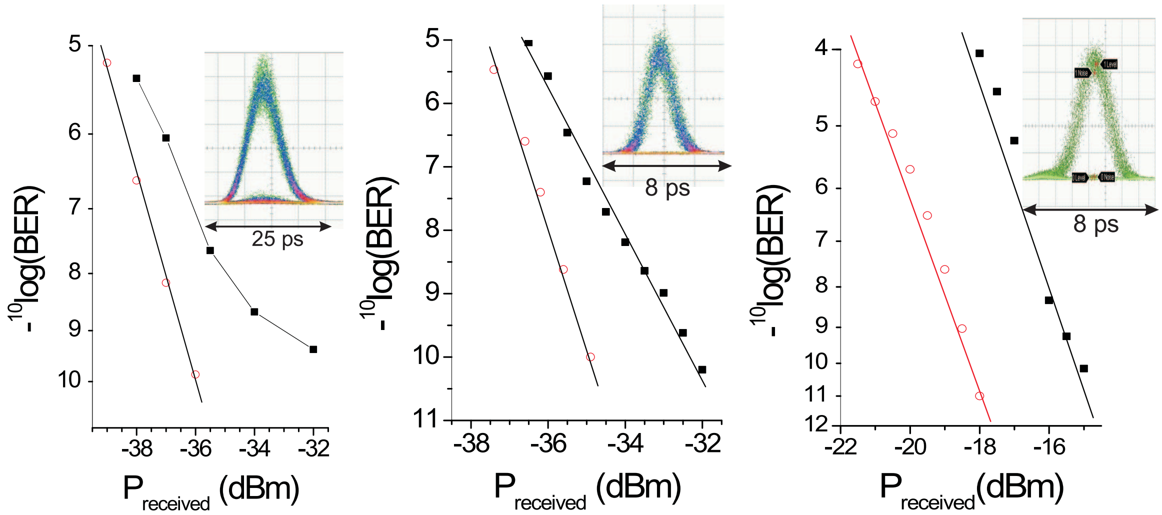


(b) FWM spectrum; res: 0.06 nm.

Figure 2: Spectra of the XPM spectral broadening method (a) and the FWM based method (b).

Comparison and Discussion

We compare the performance of the three demultiplexing methods based on the BER measurements of the demultiplexed channels, which are shown in figure 3. We observed error-free performance for the methods based on FWM and on the NOLM. The sensitivity penalties at BER=10^{-9} for FWM and for the NOLM are respectively 2 and 2.5 dB. On the other hand, an error-floor behavior is observed for the XPM spectral broadening method with a sensitivity penalty of ~ 3 dB. The larger penalty for this method is due to crosstalk resulting from the spectral broadening of the control pulse and spectral overlapping of the filter with the original data signal, which can be seen in figure 2(a). No error floor is expected when further optimization steps for the input signals, the filter shape and the filter bandwidth are performed. Regarding the complexity of implementation and the devices physical dimensions, the number of required components is the largest for the NOLM demultiplexing method, which makes it a complex system. FWM and XPM spectral broadening require the same number of components, and are therefore less complex. On the other hand, the NOLM is more advantageous when more demanding requirements are to be met, e.g. add-drop multiplexing. It is possible to employ the NOLM for the simultaneous creation of a drop and a through channel. Comparing FWM and XPM spectral broadening, we see that the XPM method strongly depends on the spectrum of the input signal and the accuracy of the filter, while for FWM, these requirements are less



(a) XPM BER, T_{fwhm}=6.7 ps. (b) FWM BER, T_{fwhm}=2 ps. (c) NOLM BER, T_{fwhm}=2 ps.

Figure 3: BER performance of the three methods, o: B2B and ■: XPM, FWM,NOLM.

strict. The conversion efficiency is defined as the ratio between the power of the input signal per base rate channel divided by the power of the demultiplexed signal. The value of the conversion efficiency for the three methods are listed in table 1. The efficiency is the best for the NOLM and the worst for the FWM. However, for the FWM method the input signal is used as pumping signal due to practical reasons of the wavelength allocation. Adjusting the control to be the pumping signal, similar efficiencies would be obtained for the XPM as well as the FWM method. The polarization dependence of these methods requires that an accurate control of the polarization has taken place, before launching of the signals into the fiber. The wavelength flexibility is the highest for the FWM, because we are free to choose the wavelength of the control pulse, which determines the wavelength of the demultiplexed pulse. Moreover, FWM has the advantage of being format independent, because FWM preserves both amplitude and phase information. This is advantageous because of recent interest in advanced modulation formats, e.g. RZ-DPSK. In conclusion, all three methods perform sufficient for all-optical demultiplexing. For more complex systems that require add-drop multiplexing the NOLM seems the most advantageous. However, the extraction of only one channel at the base rate can be better performed by the FWM process, because of the simple implementation scheme and the most relaxed requirements on pulse width, wavelength and filter shape.

Acknowledgements

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