A Simple and Robust High-Speed Wavelength Converter using Fiber Cross-Phase Modulation and Filtering

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1. Introduction

All-optical wavelength conversion can play an important role in future ultra high-speed networks due to the significant increase in flexibility and potential reduction in need for optical buffers [1]. Ultra high-speed wavelength conversion of return-to-zero (RZ) data has previously been demonstrated using four-wave mixing (FWM) in fiber [2] and SOAs [3] and by use of cross-phase modulation (XPM) in the nonlinear optical loop mirror (NOLM) [4]. Using FWM it is not possible to convert an unknown wavelength to a predetermined wavelength and the NOLM requires short pulses compared to the bit period and also suffers from stability problems. The wavelength conversion of short pulses has previously been proposed using XPM and soliton formation in a fiber [5] or using fiber XPM and polarization discrimination [6]. Here 40 Gbit/s wavelength conversion across 8 nm is demonstrated and the method will most likely be scalable to operation at several hundreds of Gbit/s over a broader wavelength range. The basic idea is to utilize XPM in a dispersion shifted fiber followed by an optical notch filter. If the incoming data is combined with a continuous wave (CW) signal and sent through an optical fiber, the data imposes a phase modulation onto the CW light using XPM. This phase modulation generates optical sidebands on the CW signal, which can be converted to amplitude modulation by suppressing the original CW carrier using an optical notch filter. The filter used here was a loop mirror filter (LMF) which consists of short piece of birefringent fiber in a Sagnac interferometer. The advantage of such a filter is that it is adjustable and has repetitive notches which allows conversion to different discrete wavelengths without adjusting the filter.

2. Experiments

Figure 1 shows the experimental set-up of the wavelength converter. The data pulses were generated with an actively mode-locked 10 GHz fiber ring laser giving 10 ps pulses with a time-bandwidth product (TBP) of 0.46 at 1536 nm. 10 Gbit/s PRBS data (2^{31}-1) was subsequently encoded and a 40 Gbit/s data stream was obtained by passively multiplexing 4·10 Gbit/s data streams together. The 40 Gbit/s data was combined with CW light from a tunable external cavity laser and amplified before injected into a 10 km

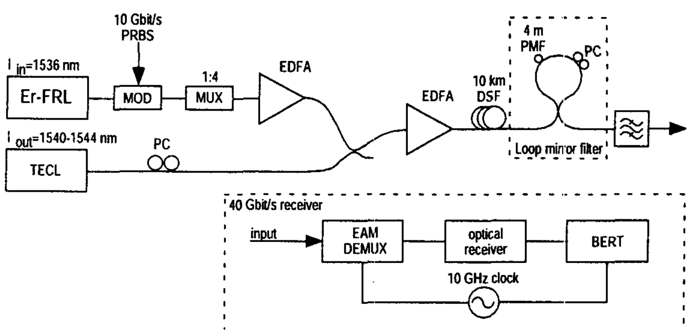

Figure 1. Experimental set-up of the XPM wavelength converter. Er-FRL: Fiber ring laser; MOD: $LiNbO_3$ modulator; EDFA: Erbium-doped fiber amplifier; PC: polarization controller; PMF polarization maintaining fiber; EAM: electro-absorption modulator; BERT: bit-error rate test set.

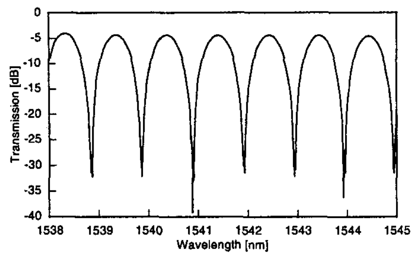

Figure 2. Transmission through the loop mirror filter.

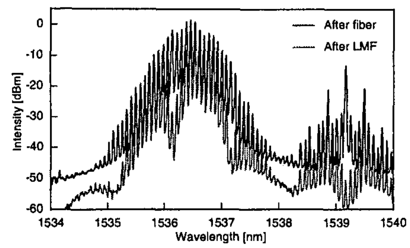

Figure 3. Output optical spectrum of original data and wavelength converted signal before and after the filter.

dispersion shifted fiber (DSF) with a zero dispersion wavelength of 1540 nm. After the DSF a LMF, consisting of a loop mirror with 4 m of polarization maintaining fiber and a polarization controller to allow adjustment of the filter wavelength, was used to suppress the original CW light carrier. The transmission function of the filter is shown in figure 2. The separation between the notches is 1 nm (given by the length of the birefringent fiber) and the suppression of the CW light was >27 dB when adjusting a notch to the wavelength of the CW light. This type of filter generates dispersion between the transmission lobes, in this case 7 ps between each lobe. Therefore a second filter was used to select one of the two generated sidebands as well as suppressing the original data. The use of e.g. a fiber Bragg grating as the notch filter would eliminate this dispersion and thus allows use of both sidebands. However the use of only one sideband retains fairly well the pulse width and TBP from the input pulse. The 40 Gbit/s receiver consisted of an electro-absorption modulator (EAM) with 15 ps switch window to demultiplex 40 Gbit/s to 10 Gbit/s.

Figure 3 shows the spectra, as measured with a spectrum analyzer with 0.1 Å resolution, before and after the LMF. The original data is spectrally broadened due to self-phase modulation and the carrier at 1539 nm is suppressed by the LMF, leaving two amplitude modulated sidebands. The longer wavelength sideband originates from the derivative of the leading edge of the input pulse and the sideband towards shorter wavelengths originates from the trailing edge of the pulse. By selecting only one of the sidebands using a band-pass filter, the output pulse width should ideally be shorter than the input pulse. Due to dispersive walk-off between input and output data the output pulses are slightly broader than the input. The output pulse width was measured as a function of wavelength and with a 9 ps input pulse the output pulse width varied between 10 and 12 ps for all output wavelengths between 1538 and 1548 nm. However, the required input peak power for full switching increases with larger conversion span due to the dispersive walk-off. For wavelength conversion between 1536 nm and 1540 nm the TBP was 0.46 at both input and output which indicates the possibility to further transmit the data. The nonlinear transmission characteristic is shown in figure 4 for a 10 km DSF as well as for a 5 km DSF as measured with 10 ps input pulses with 10 GHz repetition frequency for wavelength conversion from 1536 nm to 1540 nm. The transmission follows a $\sin^2$ function due to the transmission function of the LMF and is thus the same function as the NOLM. With a 10 km DSF, 200 mW peak power was required for full switching which is about the same as for the NOLM. Figure 5 shows the received eye-pattern of the original and wavelength converted 40 Gbit/s data as well as bit-error rate measurements for wavelength conversion from 1536 nm to 1540 nm and 1544 nm. The power penalty @BER=10^{-9} was 3 dB compared to the original 10 Gbit/s data and 2.5 dB compared to the input 40 Gbit/s data for all 4 10-Gbit/s channels. This penalty is believed to be partly due to distortion in the LMF and partly due to polarization interference noise between adjacent pulses. The 40

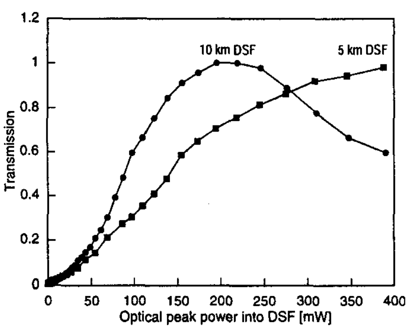

Figure 4. Transmission versus input peak power for the wavelength converter using a 10 km and 5 km DSF.

Gbit/s pulse sequence at the multiplexer output has every other pulse in orthogonal polarization state. Due to polarization dependence in the wavelength converter any polarization instability in the data pulses will give rise to noise in the converted data. The power penalty for 6 nm wavelength conversion at 10 Gbit/s was only 0.6 dB for the same pulse width which indicates that polarization interference might be a major reason. The polarization dependence for such a fiber XPM based device is 5 dB but can be eliminated by either using a diversity scheme [7,8] or by utilizing polarization scrambling [9-10]. Even though a 10 km fiber was used, no stability problems were observed and the system is only mechanically polarization sensitive before combining the data and CW light. Since the LMF was polarization insensitive environmental disturbances to the 10 km fiber did not affect the performance apart from a small timing shift, which can be compensated for by a clock recovery circuit.

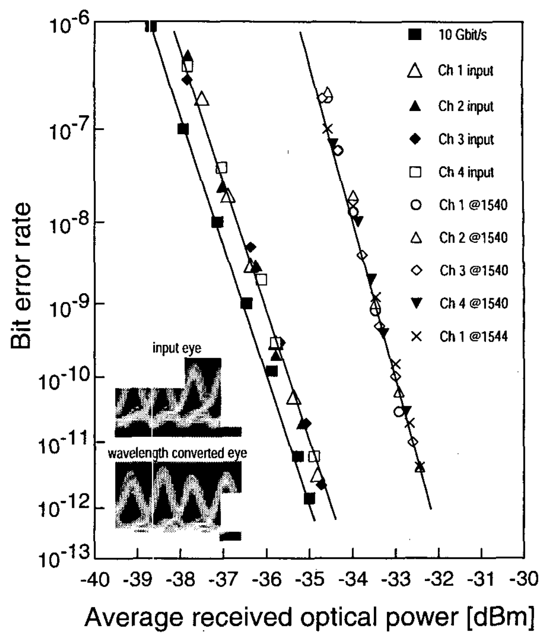

Figure 5. Bit-error rate measurements for wavelength conversion of 40 Gbit/s data from 1536 nm to 1540 nm and 1544 nm.

3. Conclusions

A new, simple and robust wavelength converter is proposed and experimentally demonstrated at 40 Gbit/s. If a polarization maintaining fiber with high nonlinearity [11] is utilized together with a high power EDFA, the scheme has the potential to realize a compact polarization independent broadband wavelength converter.

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4. References

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