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# 160 Gb/s Raman-Assisted Notch-Filtered XPM Wavelength Conversion and Transmission

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**Abstract:** In-line wavelength conversion of 160 Gb/s data by Raman-assisted notch-filtered XPM is demonstrated for 130 km total transmission. The improvement in system performance from applying Raman gain during conversion is shown.

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## 1. Introduction

Single channel bit rates in commercial optical communication systems have steadily increased reaching 10 and now 40 Gb/s. The rapid advance of electronic technologies for transmitters and receivers [1] is expected to further increase the channel bit rates. Systems for high speed signal processing for future network nodes need to be developed and all-optical signal processing is a promising candidate for performing several ultra fast networking functionalities. Wavelength conversion of optical signals at high bit rates (160 Gb/s and above) is expected to be a key element in future optical communication systems. A limited number of schemes for high speed wavelength conversion have been demonstrated up to 160 Gb/s including [2-5] using all-optical signal processing. Raman-assisted Cross-Phase Modulation (XPM) is a promising candidate for high-speed wavelength conversion. Raman gain has been suggested to improve the performance of XPM for wavelength conversion at 160 Gb/s [2] and 2R regeneration of the data signal during wavelength conversion has been demonstrated [6].

This paper reports on the first demonstration and characterisation of Raman-assisted notch-filtered XPM for in-line wavelength conversion in a 160 Gb/s transmission setup. The potential for utilising this conversion scheme in a wavelength converting node is demonstrated and the effect of applying Raman gain to assist the wavelength conversion is also shown.

## 2. Experimental procedure

The experimental setup for in-line wavelength conversion is shown in Fig. 1. A 10 GHz pulse train of 2 ps pulses at

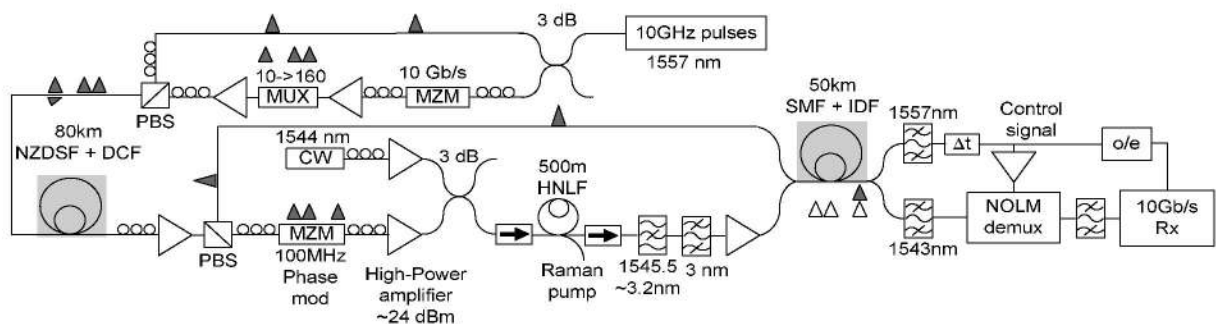


Fig. 1 Set-up for Raman-assisted notch-filtered XPM wavelength conversion

1557 nm is data modulated (PRBS  $2^7-1$ ) in a Mach Zender Modulator (MZM) before multiplexing it to 160 Gb/s in a PRBS maintaining passive fibre delay multiplexer (MUX). The data signal is then combined with the original 10 GHz pulse train at perpendicular polarisation before transmission. The transmitted 10 GHz pulse train is used as control pulses for demultiplexing the 160 Gb/s data signal into its 16 10 Gb/s tributaries at the receiver after transmission and wavelength conversion of the signal. After transmission through 80 km of Non-Zero Dispersion Shifted Fibre (NZDSF) compensated by Dispersion Compensating Fibre (DCF) the data signal and control pulses are separated in a Polarisation Beam Splitter (PBS). The data signal is then wavelength converted to 1543 nm and optionally retransmitted through a 50 km span of Single Mode Fibre (SMF) and Inverse Dispersion Fibre (IDF) along with the control pulses at 1557 nm. For wavelength conversion the signal is phase modulated at 100 MHz to suppress Stimulated Brillouin Scattering (SBS) during conversion [6]. The signal is amplified to  $\sim 24$  dBm and

combined with a CW probe at 1544 nm. Wavelength conversion by XPM is performed in 500 m of Highly Non-Linear Fibre (HNLf) with  $\gamma \sim 10 \text{ W}^{-1} \text{ km}^{-1}$ , zero dispersion wavelength  $\lambda_0 \sim 1551 \text{ nm}$  and  $S \sim 0.017 \text{ ps/nm}^2 \text{ km}$ . The converted signal is extracted using a combination of a 3.2 nm notch filter centred at 1545.5 nm and a 3 nm tunable band pass filter at the output of the HNLf. A counter propagating Raman pump (1450 nm and  $\sim 31 \text{ dBm}$ ) in the HNLf supplies Raman gain to assist the XPM. The wavelengths of the CW probe and the data signal are placed nearly symmetrically around  $\lambda_0$  to reduce the group velocity dispersion induced walk-off between the two signals to  $\sim 0.1 \text{ ps}$  in the HNLf.

After wavelength conversion and retransmission the converted data signal is demultiplexed in a Non-linear Optical Loop Mirror (NOLM) using the transmitted control pulses which are also used to generate an electrical clock signal for synchronising the receiver electronics to the transmitted data. In this way a simple setup for characterising a high-speed system and transmission has been realised using a single pulse source and a simple demultiplexer.

### 3. Results of Raman-assisted XPM wavelength conversion and transmission

In the HNLf in the setup described above spectral sidebands were generated on the CW probe due to XPM by co-propagating data marks in the amplified 160 Gb/s data signal. Thus the spectral sidebands contain the intensity modulation of the input signal and can be extracted as a wavelength converted output. Due to a phase mismatch between the two sidebands one of them must be suppressed along with the probe in order to reduce noise in the output signal [7]. Fig. 2 shows the spectrum of the wavelength converted 160 Gb/s signal where the notch filter and band pass filter are used to suppress the CW probe, the higher wavelength sideband and the original data signal. The spectra clearly show a reduction in the noise level of  $\sim 5 \text{ dB}$  when applying Raman gain to the conversion process.

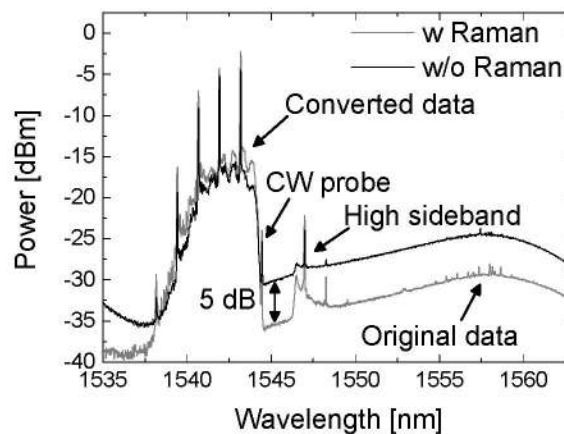


Fig. 2 Spectrum of the wavelength converted signal with and without Raman gain

In-line notch-filtered Raman-assisted XPM wavelength conversion has been achieved in a 160 Gb/s transmission setup. Two different configurations for transmission have been investigated. In one case the 160 Gb/s data was transmitted 80 km and then wavelength converted before being detected in the receiver. In the other case the converted signal was transmitted another 50 km, i.e. for a total transmission of 130 km, before it was received. Fig. 3a shows the BER measurements of the transmitted signals. For the 80 km transmission BER curves are shown for both cases of wavelength conversion with and without Raman gain to assist the XPM process. It is seen that using Raman gain in the conversion improves the BER sensitivity by  $\sim 0.7 \text{ dB}$  in this case. It is also seen that the transmitted and converted 160 Gb/s signal (Fig. 3b upper) has clear eye openings and that the 10 GHz electrical sine clock extracted from the transmitted control pulses contains very little noise. All the 16 10 Gb/s tributary channels are seen to achieve error free performance within a 3.1 dB range of receiver power at BER  $10^{-9}$  (Fig. 3c upper). The first channels overlap partially in time with the transmitted control signal and this is believed to be the cause of the reduced sensitivity compared to the remaining channels due to transfer of power between the two polarisations and limited isolation in the PBS ( $\sim 20 \text{ dB}$ ). Transmitting the converted signal an additional 50 km before demultiplexing and detecting it induces a  $\sim 2 \text{ dB}$  sensitivity penalty (Fig. 3a) and both the 160 Gb/s eye and the extracted electrical 10 GHz clock contain more noise than in the case of no transmission after conversion (Fig. 3b lower). Despite the added noise 15 of the 16 transmitted channels show error free performance within 4.5 dB receiver power range (Fig. 3c lower).

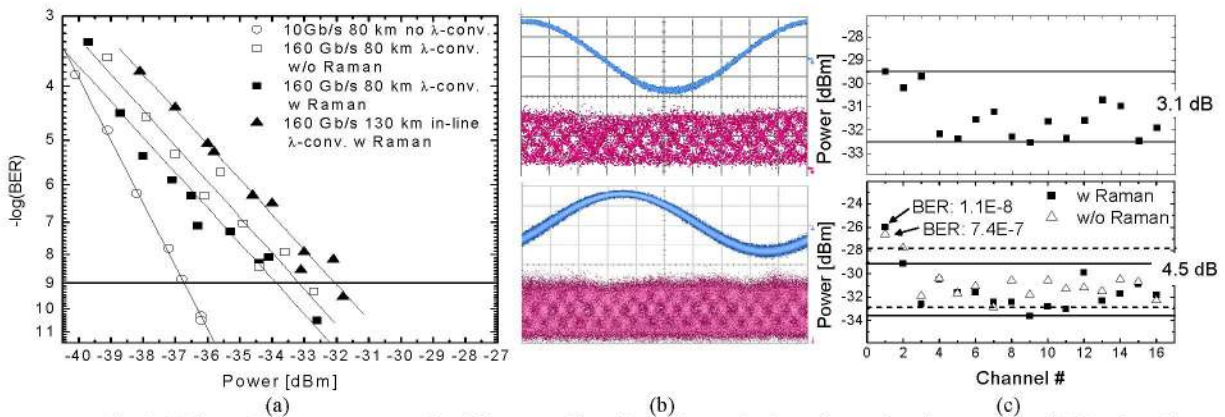


Fig. 3 (a) Shows BER measurements for different configurations of transmission and wavelength conversion. (b) Wavelength converted 160 Gb/s eye diagram and transmitted 10GHz control signal for 80 km transmission (upper) and 130 km transmission (lower). (c) Channel receiver sensitivities for 80 km transmission (upper) and 130 km transmission (lower)

The channel overlapping with the transmitted control pulse could no longer achieve error free operation. From the sensitivity measurements it is seen that applying Raman gain to assist the XPM conversion improves the receiver sensitivity of 11 of the 16 channels ( $\sim 70\%$ ).

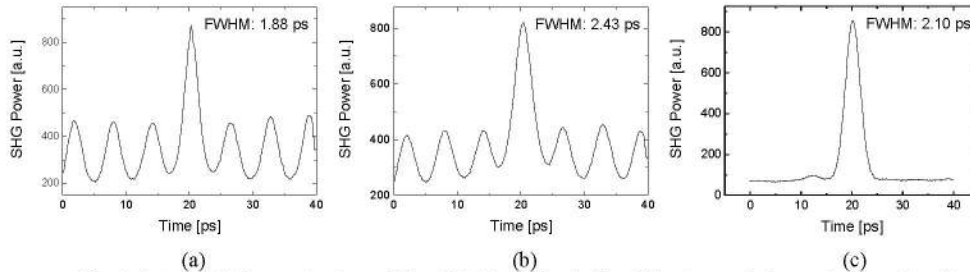


Fig. 4 Autocorrelations and pulse widths of: (a) data signal after 80 km transmission and conversion (b) data signal transmitted additional 50 km after conversion (c) 10 GHz control pulses transmitted 130 km

Autocorrelation of the wavelength converted data signal after 80 km transmission (Fig. 4a) shows no pulse broadening in the transmitted and converted signal compared to the 2 ps input pulses and only a very small pulse overlap can be seen. Transmitting another 50 km after conversion (Fig. 4b) introduces some pulse broadening  $\sim 0.5$  ps and this in turn causes increased pulse overlap as seen from the autocorrelation. This pulse broadening is expected to be due to slight chirping of the pulses by the applied filtering scheme in the wavelength converter. The transmitted control signal (Fig. 4c) shows virtually no pulse broadening after 130 km transmission and is suitable for demultiplexing in the receiver.

#### 4. Conclusion

This paper has demonstrated Raman-assisted notch-filtered XPM for in-line wavelength conversion in a 160 Gb/s transmission system spanning a total distance of 130 km. Error free operation was achieved for all channels except the one overlapping with the transmitted control signal required for this simplified characterisation setup. A noise reduction from applying Raman gain to the conversion and its improvement on system performance is characterised.

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