Optical noise reduction in inter-band Raman mediated wavelength conversion

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An all-optical wavelength converter based on nonlinear crosstalk mediated by the saturation of the Raman effect in an optical fibre is described. Wavelength conversion with very significant noise reduction capabilities is demonstrated for 10 Gbit/s data. The converter operates over ~100 nm, from the L- to the S- band, with an optical operational bandwidth of 30 nm.

The Raman effect in optical fibres has attracted much attention as a nonlinear optical effect which degrades performance in WDM systems [1], but, conversely enables amplification with large, flat gain and incomparable noise characteristics [2] providing key tools for operation in previously dark regions of the fibre spectrum [3]. The Raman effect also enables various all-optical functions such as wavelength conversion [4] which, to fulfill the demand of flexible all-optical networks and systems, should have reshaping characteristics [5].

In this Letter we describe an all-optical Raman-mediated wavelength converter with reshaping capabilities. It is based on Raman-induced depletion of a CW probe which is spectrally separated by the Stokes shift frequency from a longer wavelength, noise carrying modulated signal. For negligible walk-off between the two wavelengths, the CW probe undergoes Raman-mediated crosstalk and reproduces the complementary of the original signal. The noise of an input '1' bit (which is mapped into an output '0' bit) undergoes a significant noise reduction. The noise modification of an input '0' bit is not as large since a '0' bit has a smaller effect on the probe signal. The present device converts a signal at 1581 nm to a band between 1470 and 1500 nm with a large noise reduction and a dramatic improvement in bit error rate (BER) performance.

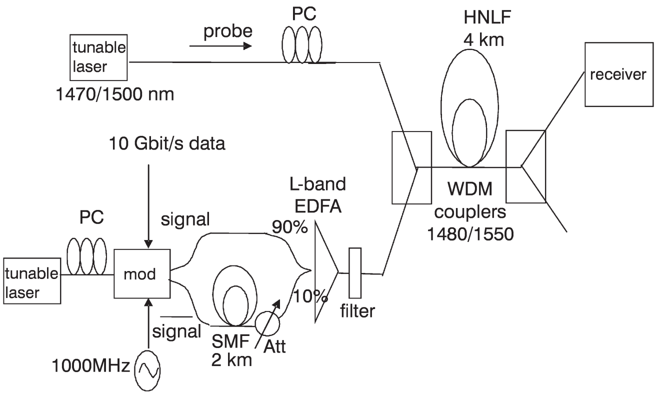

Fig. 1 *Schematic diagram of wavelength conversion system*

Fig. 1 shows the experimental setup. The input comprises two tunable laser sources, one acting as the probe in the S-band with a tuning range of 1470–1500 nm, the second serving as the signal in the L-band (1581 nm). The long wavelength signal is modulated at 10 Gbit/s using an integrated amplitude/phase modulator. Phase modulation at 1 GHz is needed to eliminate stimulated Brillouin scattering. The modulator has two complementary outputs which are used in an asymmetric (90–10%) interferometric configuration to add (artificial) crosstalk noise to the signal. A tunable attenuator placed after the delayed modulator output allows variation of the crosstalk level. The noisy signal is coupled to a high power L-band erbium-doped fibre amplifier (EDFA) followed by a bandpass optical filter. The signal with a launching average power of +19.5 dBm and the probe feed a 4 km-long highly nonlinear fibre (HNLF) through a 1480 nm/1550 nm WDM coupler. The HNLF has an effective area of A_{eff} ~12 μm^2 and a nonlinear coefficient of γ ~10.6 W^{-1}/km. Its zero dispersion wavelength is $\lambda_0 = 1536.3$ nm, its dispersion slope at λ_0 is 0.018 ps/nm^2-km and the losses are $\alpha_s = 0.75$ dB/km, and $\alpha_{pr} = 0.85$ dB/km. A second WDM coupler separates the two wavelengths at the fibre output and the probe is coupled to a receiver.

In the first experiment, the depletion transfer function of the converter was measured in the CW regime. The signal and the probe were separated by the Stokes shift and the depletion of the probe was measured against long wavelength power coupled to the HNLF. The measured transfer function is compared to its analytical expression, derived from the CW power equations for the Raman effect [6] in a strongly depleted regime ($P_s \gg P_{pr}$):

$$D(P_s(0)) = \frac{P_{pr}(L)}{(P_{pr}(0)\exp(-\alpha_{pr}L))} = \exp(-C_R P_s(0) L^s_{eff}) \qquad (1)$$

P_s and P_{pr} are, respectively, the signal and probe powers, L^s_{eff} the effective length at the signal wavelength and C_R is the Raman gain efficiency coefficient. As shown in Fig. 2, the transfer function decreases exponentially with the input signal power. Furthermore, fitting the measured data with the analytical expression (1) enables extraction of the value of C_R which turns out to be $\simeq 3.7\ W^{-1}$/km.

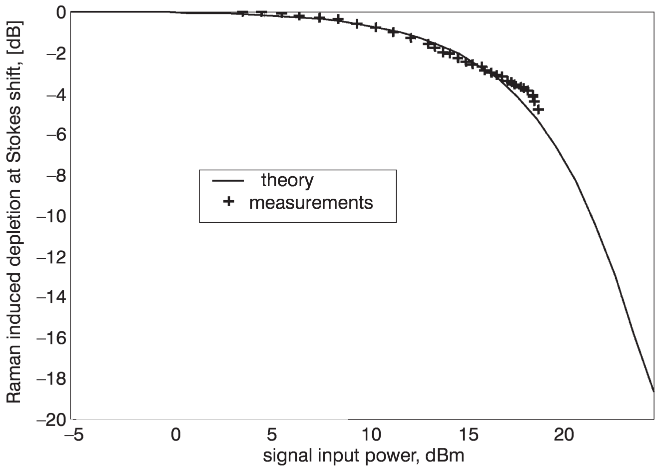

Fig. 2 *Depletion transfer function at Stoke shift frequency*

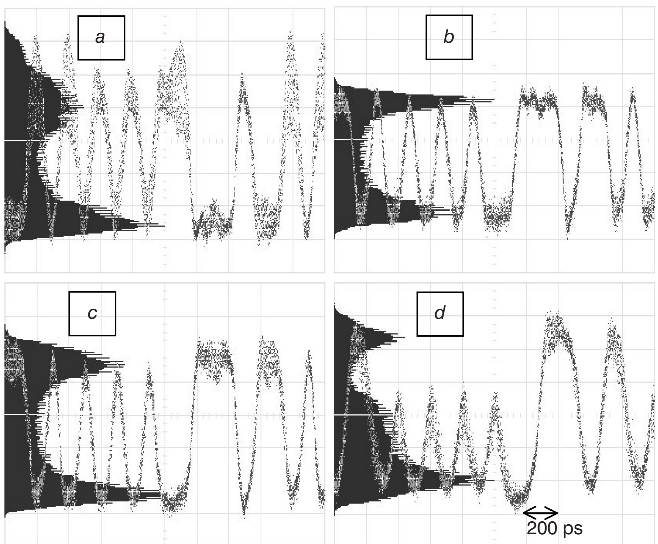

Fig. 3 *Detected bit patterns at original wavelength and three converted wavelengths.*

Histograms added to highlight noise reduction
In all cases, horizontal scale is 200 ps/div
a 1581 nm
b 1500 nm
c 1490 nm
d 1470 nm

Fig. 3*a* shows the 10 Gbit/s trace of the noisy input signal with a crosstalk level of −18 dB, presenting large self beating fluctuations in both '0' and '1' bits. Fig. 3*b*, *c* and *d* show the converted signals at 1500, 1490 and 1470 nm, respectively. These traces represent of course the complementary mapping of the original signal while exhibiting significant noise reduction. The added histograms highlight the dramatic changes in the noise distributions. All traces were recorded with the same average optical power ensuring that they are equally affected by the receiver thermal noise.

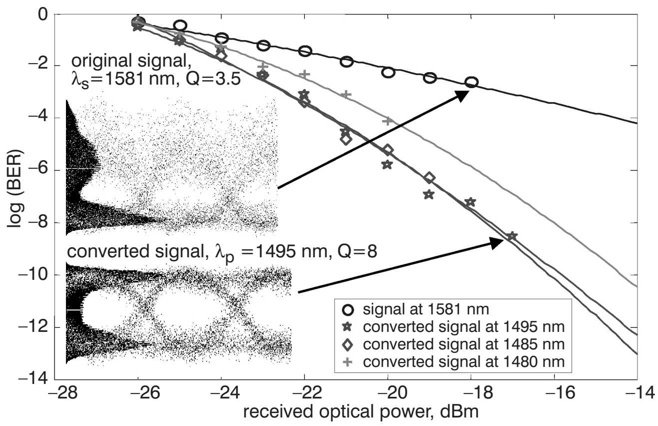

Fig. 4 *BER curves and detected eye diagrams for 10 Gbit/s input signal with large noise and three converted wavelengths*

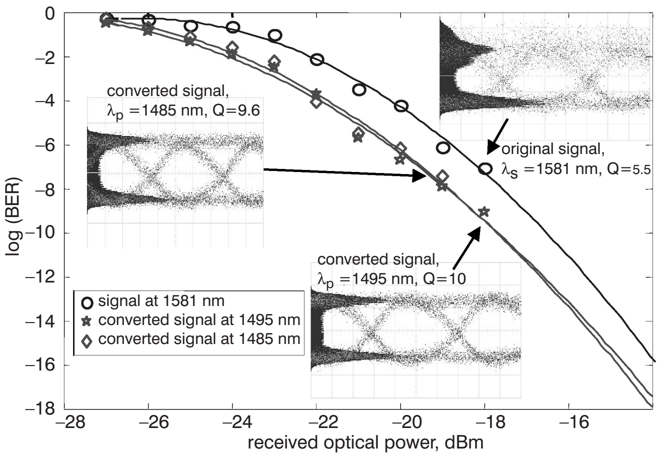

Fig. 5 *BER curves and detected eye diagrams for 10 Gbit/s input signal with moderate noise level and two converted wavelengths*

At 1500 and 1490 nm the probe is close to the Stokes shift frequency and exhibits a small walk-off (<20 ps) yielding an extinction ratio (ER) larger than 12 dB. At 1470 nm, the walk-off increases to ~110 ps while at the same time the Raman efficiency is reduced so that the converted signal presents distortions and the observed ER decreases to 9.5 dB.

The performance of the wavelength converter was examined by BER measurements for a 10 Gbit/s signal and with two levels of crosstalk. Fig. 4 shows the BER curves for the original signal with a large level of crosstalk (−13 dB) and for three converted probes at 1495, 1485 and 1480 nm. Also shown are detected eye diagrams for the original and one of the converted signals. The noisy input signal exhibits a clear BER floor but the converted signals enable error-free operation. The BER curve at 1480 nm is extrapolated beyond −20 dBm because of the limited available probe power. The superior BER performance is consistent with the enhanced Q-factor seen clearly in the detected eye diagrams.

Fig. 5 shows the case of an input signal with a lower crosstalk level (−18 dB). In this case the original signal exhibits low error rates but since $Q = 5.5$, it does not reach a BER of 10^{-9} level. The converted signals have very large Q-factor values, as seen in the detected eye diagrams and reach error-free operation.

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