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Transmission of 7 ps RZ data over 141 km of installed standard fibre using an all-fibre polarisation-independent phase conjugator incorporating noise reduction

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Abstract - **We demonstrate MSSI transmission of 7 ps RZ data over 141 km of installed standard fibre using a novel polarisation-independent all-fibre phase conjugator pumped by orthogonally polarised fibre DFB lasers. A system noise performance is analysed and noise suppressing fibre grating is incorporated to improve conjugator performance considerably. With this new practical conjugator design, a power penalty of < 0.7 dB compared to back-to-back is achieved at 10 Gbit/s with negligible polarisation penalty. This new conjugator is thus highly suitable for deployment in real system upgrade.**

Introduction

Midspan spectral inversion (MSSI) is one of a few promising dispersion compensation techniques to upgrade the installed fibre base. A practical spectral inverter or phase conjugator has to be insensitive to signal polarisation. Amongst various polarisation independent schemes, four-wave mixing (FWM) using dual orthogonal pumping scheme [1] is one of the most promising candidates. Recently we have demonstrated such a polarisation independent scheme in an all-fibre configuration, whereby two single polarisation fibre DFB lasers are cascaded with orthogonal polarisations to serve as FWM pumps [2]. This simple configuration has also been applied to high bit-rate phase conjugation or wavelength conversion in the laboratory [3]. In this paper, we demonstrate an MSSI transmission system operating over 141 km of installed standard non-dispersion-shifted fibre (NDSF) using this novel all-fibre conjugator. A noise suppressing fibre grating is incorporated to give superior performance. We analyse the noise characteristics of such system and quantify its limits.

Experiments and Results

Fig. 1 shows the experimental setup. The pulse source is an actively mode-locked fibre ring laser operating at 10 GHz and producing 7 ps pulses with a spectral width of 0.6 nm. A Mach-Zehnder lithium niobate ($LiNbO_3$) external modulator, driven by a 10 Gbit/s pattern generator (2^{23} - 1 PRBS), is used to generate the RZ data signal. Optionally, a x4 optical multiplexer is inserted to give 40 Gbit/s interleaved OTDM signal. The signal is amplified and launched into a first 70 km span of standard installed fibre (NDSF, D = 17 ps/km·nm at 1550 nm). The phase conjugator is an all-fibre polarisation-independent device employing two in-line fibre DFB lasers as FWM pumps which have orthogonal polarisations and 1.3 nm wavelength separation [2, 3]. A high power EDFA is used to amplify the pumps and the data signal, injected through the cascaded fibre DFBs, to a high power level of 21.6 dBm before they are launched into the nonlinear fibre. A hole burning grating (HBG), with >20 dB of suppression over 0.6 nm bandwidth, is inserted at the output of the high-power EDFA to suppress ASE noise at the conjugate wavelength and hence improve the optical signal-to-noise ratio (SNR) [4]. A 440 m length of highly-nonlinear dispersion-shifted fibre (HNL-DSF) is used as a FWM media giving a flat conversion bandwidth of > 20 nm [5]. By monitoring the output spectrum from the HNL-DSF, the polarisation states of the two single polarisation fibre DFB lasers are orthogonally aligned by minimising the pump-pump mixing products using a polarisation controller (PC) [2, 3]. The conjugated output is filtered and launched into a second 71.6 km span of installed fibre. At the receiver end, the conjugated signal is amplified and filtered before it is optically detected in a photodiode.

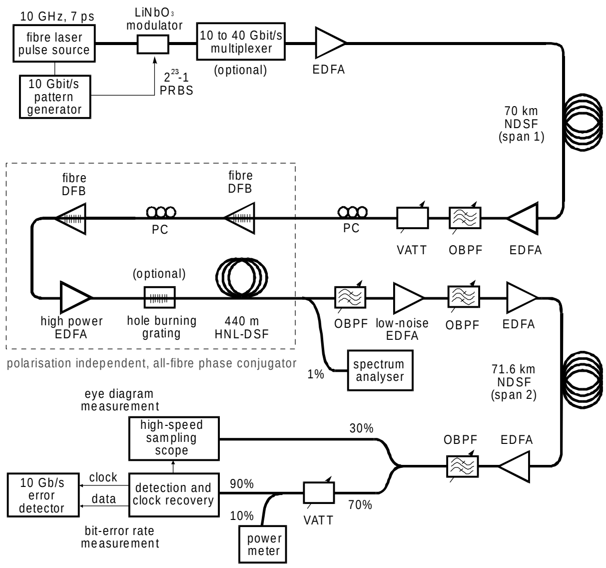

Figure 1. Experimental setup of 141 km MSSI transmission using a polarisation independent, all-fibre phase conjugator.

An autocorrelator is used to study the received pulse width. We achieve a full recovery of the 7 ps pulse width with an additional 1.6 km of offset fibre inserted at the second span. The eye-opening at 40 Gbit/s is wide and clear, indicating the feasibility of the system at ultra-high bitrate operation (Fig. 2).

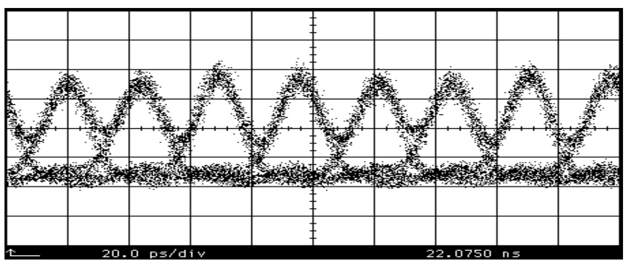

Figure 2 Eye diagram at 40 Gbit/s.

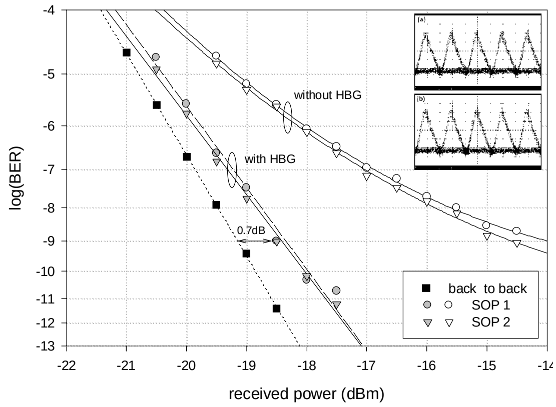

Figure 3 The BER characteristics of the MSSI transmission at extreme cases of signal SOPs with and without HBG. Insets show the received 10 Gbit/s eye diagrams of the case with HBG.

The 10 Gbit/s bit-error-rate (BER) performance of the 141 km MSSI transmission is shown in Fig. 3, with the signal polarisation state set to the two extreme cases, co-polarised with each pump. The system has negligible polarisation dependency with and without the noise suppressing HBG. Insets of Fig. 3 (a) and (b) shows the received eye diagrams for the two cases and indicate less than 10% amplitude change.

As shown in Fig. 3, without the HBG, the conjugate suffers increased ASE noise giving ~ 5 dB power penalty at a BER of 10^{-9} and evidence of an error floor. When the HBG is employed, the BER performance is greatly improved to only 0.7 dB power penalty at 10^{-9} BER and error-free operation is easily achieved.

Noise Analysis

Although we have clearly demonstrated that, the insertion of a HBG greatly improve conjugator noise performance, and have analysed the noise characteristic of a single pump conjugator [4], FWM process employing two orthogonal pumps has different noise characteristics.

Consider an input signal S which participates in a FWM process with two orthogonal pumps P_x and P_y, as shown in Fig. 4. Three conjugates at different wavelengths C_{xx}, C_{yy} and C_{xy} will be generated, of which the first two are polarisation dependent components and the third is polarisation independent. They can be viewed as being converted through the mixing of two pump photons and a signal photon to generate a conjugate photon. Depending on the origin of the pump photons, the conversion efficiencies (η) are denoted by the two participating pump photons, i.e. η_{xx} involves two pump photons from P_x, η_{yy} involves two pump photons from P_y and η_{xy} involves pump photons from both P_x and P_y. The polarisation independent conjugate is C_{xy}. Assuming a large rejection spectral hole is burned at the conjugate wavelength to suppress ASE noise before conjugation, the noise contribution at that wavelength can be written as (Fig. 4):

$$Nc = \eta_{xy}(Ns \cdot \hat{x} + Ns \cdot \hat{y}) + \eta_{xx} Ns \cdot \hat{x} + \eta_{yy} Ns \cdot \hat{y}$$

whereas $\hat{x}$ and $\hat{y}$ are unit vector co-polarised with P_x and P_y respectively. Additionally, with equal pump powers, the conversion efficiencies are similar in magnitude: $\eta=\eta_{xy}=\eta_{xx}=\eta_{yy}$, and the conjugate noise expression can therefore be further reduced to $Nc=2\eta Ns$. The ASE noise in

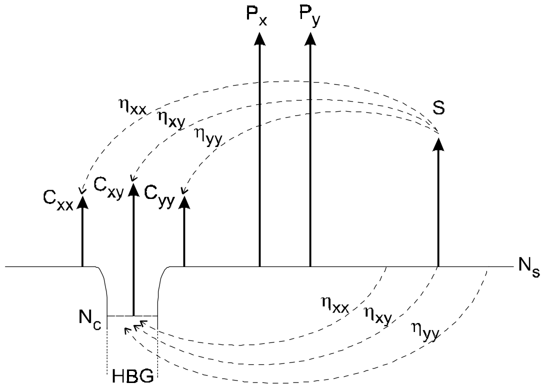

Figure 4 Signal and noise conversion characteristics of a FWM process employing orthogonally polarised pumps.

this case is found to be 3 dB higher than that of the single pump case $Nc=\eta Ns$. In order to suppress the additional noise penalty in a dual-pump setup, the ASE noise at both side of the signal can be filtered, either by a narrow bandpass filter centred at the signal wavelength or by using notch filters (e.g. HBG) to suppress ASE noise at those wavelengths.

Conclusions

In conclusion, we have demonstrated MSSI dispersion compensated transmission of 7 ps RZ data pulses over 141 km of standard installed NDSF link using a novel polarisation-insensitive all-fibre phase conjugator. With the incorporation of an ASE noise suppressing fibre grating (HBG) in the conjugator, we have achieved a power penalty of only 0.7 dB at 10 Gbit/s with negligible polarisation sensitivity. We have also studied the noise limitations on such a phase conjugator and possible optimisations are proposed. The measured eye diagrams at 40 Gbit/s show promising performance. In summary, a practical phase conjugator has finally been realised in a real system test. This novel conjugator is highly suitable for future deployment to upgrade installed standard fibre links.

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