All-Optical Signal Processing in Highly Nonlinear Fibres

F. Parmigiani[1], R. Slavík[1], J. Kakande[1], L. Grüner-Nielsen[2], D. Jakobsen[2], S. Herstrøm[2], R. Weerasuriya[3], S. Sygletos[3], A. D. Ellis[3], P. Petropoulos[1], and D. J. Richardson[1]

1. Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK. frp@orc.soton.ac.uk.
2. OFS, Priorparken 680, 2605 Brøndby, Denmark.
3. Tyndall National Institute and Departments of Physics and Electrical Engineering, University College Cork, Cork, Ireland.

***Abstract*—We review our recent work demonstrating two all-optical signal processing devices using high SBS-threshold alumino-silicate highly nonlinear fibers.**

I. Introduction

Ultra-fast all-optical signal processing functions are seen as critical for future high bit rate communications systems to address the growing demand for network flexibility, low cost, low energy consumption and high bandwidth. As a consequence, there is great interest in the development of optical techniques for processing recently emerging advanced modulation formats, such as Differential Phase Shift Keying (DPSK), and duobinary modulation. Advantages of DPSK over conventional On-Off Keying (OOK) include higher receiver sensitivity and tolerance to nonlinear effects. Duobinary signals, which use optical pulses with alternating phases, have several times higher tolerance to residual chromatic dispersion as compare to conventional OOK, making it particularly attractive at high baud rates.

For the generation and all-optical processing of these modulation formats signals, the choice of the optimal nonlinear media is essential. Highly nonlinear fibres (HNLFs) with high nonlinear coefficients and controlled dispersion and dispersion slope are interesting candidates due to their low losses and splicing capability to standard telecom fibres. In many instances the use of narrow-linewidth continuous wave (CW) signals in the nonlinear process dictates the need for nonlinear media with very high Stimulated Brillouin Scattering (SBS) thresholds. To address this issue, in our work, we use an alumino-silicate HNLF that has a significantly higher SBS threshold as compared to conventional Germanium-doped HNLF. A further increase in the SBS threshold can be obtained by applying a strain gradient along the fibre to broaden the Brillouin gain bandwidth and reduce the peak gain. In this way, one can prevent the need to apply active SBS-suppression schemes to avoid limitations on the power levels used thereby simplifying and improving the performance of existing approaches optical signal processor and opening new device opportunities.

In this paper, we will focus on two examples of all-optical signal processing applications that we have recently demonstrated, using high SBS-threshold alumino-silicate HNLFs: (i) all-optical phase regeneratoion based on the phase squeezing capability and the saturated operating regime of a phase-sensitive amplifier (PSA) [1], suitable for DPSK modulated signals; and (ii) the generation of ultra-stable pulse trains with alternating phases at repetition rates of up to 200GHz from a dual-frequency beat-signal [2].

II. All Optical Phase Regenerator

As far as all-optical signal regeneration of DPSK signals is concerned work to date has mainly focused on the elimination of amplitude noise and has ignored the issue of phase jitter [2-6]. Initial proof of concept results on direct phase (and amplitude) regeneration have recently been demonstrated by Croussore et al. [7, 8] using fiber-based PSA schemes in either single- or dual-pump configurations. However, due to their very challenging practical implementations, all the pump and and signal beams were artificially generated from a single laser [7, 8], making the regenerator impractical for use in a real transmission system, where carrier recovery and phase-locking between the newly generated pump(s) needs to be obtained from the incoming DPSK signal itself. We have recently proposed, and experimentally demonstrated the first four wave mixing- (FWM-) based black-box phase regenerator operated in a dual-pump degenerate PSA configuration at repetitions rates of 10Gbit/s and 40Gbit/s [1]. All the required pumps were locally generated within the "black-box" regenerator and

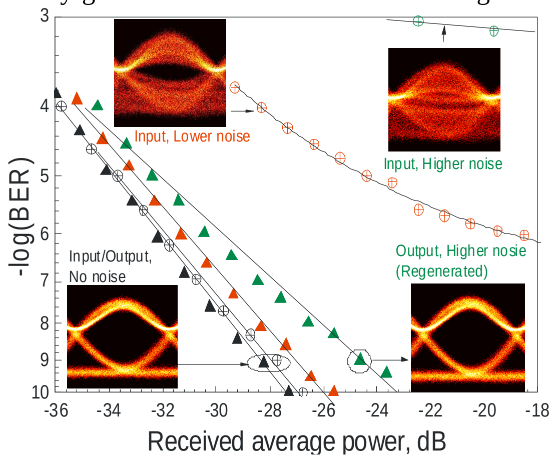

Figure 1: BER curves at the input (circles) and output (triangles) of the 40Gbit/s black box DPSK regenerator based on phase sensitive amplification for different values of added phase noise and corresponding demodulated eye diagrams.

were phase locked to the recovered signal carrier using a combination of FWM in a HNLF followed by injection locking of a discrete-mode semiconductor laser [1] to filter out the high frequency phase (and amplitude) fluctuations present on the original data signal.

The pumps were then combined with the data signal, amplified up to ~34dBm and launched into a new type of alumino-silicate strained HNLF with a linearly strain gradient (length, dispersion, polarization mode dispersion, nonlinear coefficient and attenuation of 177m, -0.13ps/nm/km, $0.11pskm^{-0.5}$, $7.1W^{-1}km^{-1}$ and 15dB/km, respectively) for phase regeneration.

The quality of the signal before and after the regenerator was assessed when either no noise or different levels of deterministic phase-only noise were induced, see Fig.1. These results highlight the regenerative capabilities of the PSA, which acts on the absolute bit phase, and show that it is able to restore a completely closed differentially detected eye, allowing error-free performance for all the noise levels with power penalties below 3.5dB as compared to the back-to-back case. Preliminary studies, not reported here, suggest the suitability of this PSA scheme for the elimination of amplitude noise as well as the simultaneous regeneration of both amplitude and phase noise.

III. Short pulse train Generator

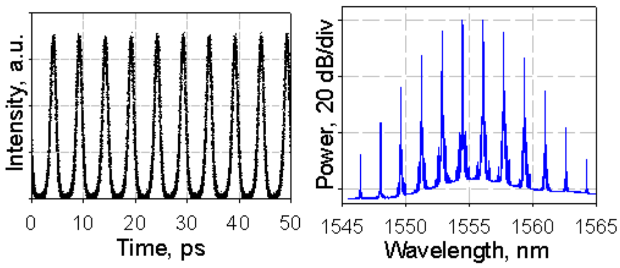

Figure 2: Measured temporal and spectral traces at 200 GHz spacing.

The basic principle of this scheme lies in the non-linear compression of a beat signal generated by mixing two CW signals, which are offset in frequency by the desired pulse train repetition rate. The temporal intensity profile of such a beat signal corresponds to pulses (a sine wave) with alternate phases with full width at half maximum (FWHM) corresponding to half of the signal period. These relatively long pulses can then be, temporally compressed using FWM processes in anomalously dispersive HNLF, or in normally dispersive HNLF, followed by an anomalously dispersive media [9]. To obtain a stable pulse train, the two CW signals have to be phase locked. In our approach, this was achieved by injection-locking of two semiconductor lasers (with a frequency separation corresponding to the desired repetition rate) to an optical comb [2]. The two, now properly phase-locked CW signals, were then amplified up to about 32 dBm and launched into a 300-m-long alumino-silicate HNLF (dispersion of -0.8 ps/nm·km) in order to generate new frequency components via FWM, followed by a few tens of metres of single mode fibre (SMF) to temporally compress the pulses. Fig.2 shows the signal in the time and spectral domains at 200GHz frequency spacing as measured using an optical sampling oscilloscope (temporal resolution of 800 fs) and an optical spectrum analyzer, respectively, at the output of the system. The corresponding final temporal FWHM could be reduced down to ~1ps, giving a compression factor of ~2.5. Assuming a Gaussian pulse shape, the corresponding time-bandwidth product was ~ 0.5.

It is worth adding that the repetition rate of the generated pulse train could be easily varied by changing the frequency spacing between the two injection-locked lasers,

IV. Conclusions

We have reported two examples of all-optical signal processing techniques based on the use of high SBS-threshold alumino-silicate HNLF.

V. Acknowledgments

The authors would like to thank Eblana Photonics Inc., Dublin, Ireland, for providing the coaxial discrete mode laser used in the experiment. This research has received funding from the European Communities Seventh Framework Programme FP/2007-2013 under grant agreement 224547 (PHASORS) and by Science Foundation Ireland under grant number 06/IN/I969.

References

[1] F.Parmigiani, R. Slavík, J. Kakande, C. Lundström, M. Sjödin, P. Andrekson, R. Weerasuriya, S. Sygletos, A. D. Ellis, et.al., “All-Optical Phase Regeneration of 40 Gbit/s DPSK Signals in a BlackBox Phase Sensitive Amplifier”, ”, in Proc Optical Fiber Communication Conference (OFC/NFOEC 2010), San Diego (USA) Paper PDPC3, (2010).

[2] F. Parmigiani, R.Slavik, A.Camerlingo, L.Gruner-Nielsen, D.Jakobsen, S.Herstrom, R.Phelan, J.O'Gorman, S.Dasgupta, J.Kakande, S.Sygletos, A.D.Ellis, P.Petropoulos, D.J.Richardson, “Generation of high repetition rate (>100 GHz) ultrastable pulse trains from a coherent optical beat-signal through non-linear compression using a high SBS-threshold fiber”, Nonlinear Photonics 2010 Karlsruhe Germany 21-24 Jun 2010 NThA5.

[3] K. Cvecek, K. Sponsel, C. Stephan, G. Onishchukov, R. Ludwig, C. Schubert, B. Schmauss, and G. Leuchs, "Phase-preserving amplitude regeneration for a WDM RZ-DPSK signal using a nonlinear amplifying loop mirror," Opt. Express 16, 1923-1928 (2008).

[4] K. Croussore, and G. Li, “Amplitude regeneration of RZ-DPSK signals based on four-wave mixing in fibre,” Electron. Lett. **43**(3), 177–178 (2007).

[5] Masayuki Matsumoto and Kenichi Sanuki, "Performance improvement of DPSK signal transmission by a phase-preserving amplitude limiter," Opt. Express 15, 8094-8103 (2007).

[6] M. Matsumoto and H. Sakaguchi, "DPSK signal regeneration using a fiber-based amplitude regenerator," Optics Express Vol. 16, pp. 11169-11175 (2008).

[7] K. Croussore, et.al., “Demonstration of phase-regeneration of DPSK signals based on phase-sensitive amplification,” Optics Express, Vol. 13, pp.3945-3950 (2005).

[8] K. Croussore and G. Li, “Amplitude regeneration of RZ-DPSK signals based on four-wave mixing in fibre,” Electronics Letters Vol. 43, pp.177-178 (2007).

[9] S. Pitois, J. Fatome, and G. Millot, “Generation of a 160-GHz transform-limited pedestal-free pulse train through multiwave mixing compression of a dual-frequency beat signal”, Optics Letters 27, 1729 (2002).