Project: FP7-22457 PHASORS

PHase sensitive Amplifier Systems and Optical Regenerator and their applicationS

Project start date: 1st July 2008
Project completion date: 30th June 2011

Publishable Summary from annual review report June 2010

The publishable summary is taken from the second year report for the PHASORS project and outlines the full project objectives and workplan and results from the first two years.

Summary of project objectives

The PHASORS project is targeted at the development and applications of fibre based phase sensitive amplifier (PSA) technology in 40Gbit/s broadband core networks. PSAs have the potential to be a disruptive technology within future optical communications enabling ultra-low noise amplification and a host of important ultrafast optical processing functions for networks employing high spectral efficiency phase encoded signals. To this end the primary objectives are:

- Development of a reliable technology base for the realisation of practical PSAs
- Investigation of both interferometric and non-interferometric fibre based approaches for PSA.
- Demonstration of a non-interferometric based PSA system.
- Demonstration of a PSA with a record noise figure of less than 1dB.
- Demonstration of the benefits of the low noise properties of PSA for transmission applications.
- Demonstration of the use of PSAs within two different application spaces.

Realisation of the above systems level objectives requires advances in the state of the art and optimisation of a number of components and subsystems, in particular:

- Development of high power, high coherence narrow-linewidth and pulsed lasers
- Use of comb generation techniques to provide phase coherent pump and signal
- Optimised fibre design and fabrication (microstructured fibre/conventional doped structures)
- Development of numerical modelling tools for PSAs.

To demonstrate communications applications we are undertaking work on two subsystems;
1- Optical sampling: A novel approach to allow the analysis of arbitrary amplitude- and phase-encoded signals in the complex plane is being investigated. Optical fibre-based all-optical sampling, in which we will use a phase-sensitive detection scheme to recover not only amplitude but also the optical phase, will be used.
2- Regeneration of phase encoded signals: Utilising a suitable PSA developed within the project, we plan to develop non-interferometric based regenerators for both DPSK, and if possible DQPSK formats, and to confirm their performance through a full system characterisation. We will investigate both single channel regeneration and multi-wavelength generation within the project.

Summary of work undertaken since project commencement

The technical workplan of the project is structured into five workpackages, two developing key, high performance components – lasers and fibres, one theoretical analysis, one addressing the PSA and finally a workpackage investigating subsystems. The first two years have been focussed on assessing current technology, specifying requirements and capabilities, developing components to meet the PSA specifications and preliminary work on defining the PSA, regenerator and sampling systems to meet the final objective.

Laser development activities

The Eblana Discrete Mode laser work has addressed the issues involved in developing a laser to meet the demanding specification of the PSA and associated OPLL sub-systems. This has included aspects of laser noise measurement, linewidth narrowing and packaging. Lasers have been delivered to the partners in line with the work programme. In parallel Onefive has focused on the improvement of its single frequency laser platform "SUMO" by developing a new cavity design and packaging technology. The new packaging technology is designed to decouple acoustic and mechanical vibrations from the cavity components, to improve short, as well long term stability.

ORC has developed tools for the characterization of the phase noise of state-of-the-art narrow linewidth lasers. Frequency noise measurement capabilities over an extended range from 10 Hz up to 1 GHz have been implemented. Further, we heterodyne the lasers under test with an 'optical ruler', a highly stable carrier-envelope stabilized optical comb. This enables measurement of the laser linewidth over arbitrary times, laser lineshape and long term carrier frequency stability. These new techniques have been used for a comparative study of state-of-the-art lasers and allow for detailed comparison of the lasers developed within the project with others available commercially.

An optical injection phase lock loop (OIPLL) synchronization subsystem has been developed by Tyndall. Two different schemes that generate phase synchronized pump waves, from an input signal, in a dual pump phase sensitive amplifier have been also developed. One scheme used in the development of the 'black box' PSA demonstrated in WP4 uses FWM in HNLF to generate frequency symmetric NRZ-BPSK. The other approach makes use of an MZM-based comb generator and injection locking to generate the phase synchronized pumps. This scheme is appropriate for phase sensitive amplification of signals which have carrier, and successful performance has been demonstrated for a 10 Gbit/s NRZ ASK. Also, a carrier extraction scheme for phase modulated signals using a DPSK regenerator to perform feed-forward based modulation stripping has been demonstrated.

Fibre development

The main focus for the solid silica Highly Non Linear Fibre (HNLF) has been on suppression of Stimulated Brillouin Scattering (SBS). Two paths have been followed. The first has been to replace the germanium doping in core of the HNLF with aluminium (Fig. 1). This gave a 4.8 dB increase in SBS threshold for the same amount of non-linearity. The second path has been to spool the HNLF with a linear strain gradient. Using this on the Al-doped HNLF an additional 4 dB improvement has been demonstrated resulting in an SBS threshold of 1.6 W. This fibre has been one of the enablers for the Phase sensitive 'black box' regenerator.

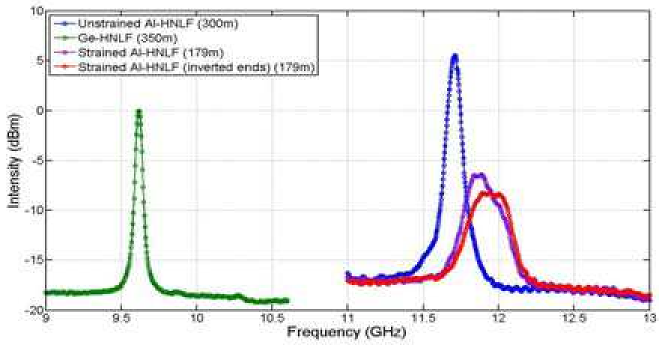

Fig. 1 Measured SBS spectra of unstrained and strained Al-doped HNLF in comparison with Ge-doped HNLF

Three different forms of highly nonlinear, dispersion-controlled, soft-glass microstructured optical fibers (SGMOFs) have been designed and fabricated offering different combinations of dispersive and nonlinear characteristics: an air:SF57 glass, a small-core SGMOF via stacking of extruded elements; direct extrusion of an all-solid Bragg-type SGMOF (with a record <0.8 dB/m loss); and an all-solid, W-structure, SGMOF offering improved dispersion flatness stacked using extruded rods and tubes. The all-solid, W-structure fibres have being chosen as the most promising form of highly nonlinear, dispersion-controlled soft glass optical fibres, offering improved dispersion flatness stacked using extruded rods and tubes. The fibre has been fabricated and characterized in terms of its nonlinear, dispersion and Brillouin properties and has subsequently been used in various four-wave mixing based experiments utilizing telecommunications signals.

Work on stress rod supported polarization maintaining solid silica fibres using a new manufacturing technique has continued. Large preforms resulting in fibre length > 90 km have been demonstrated.

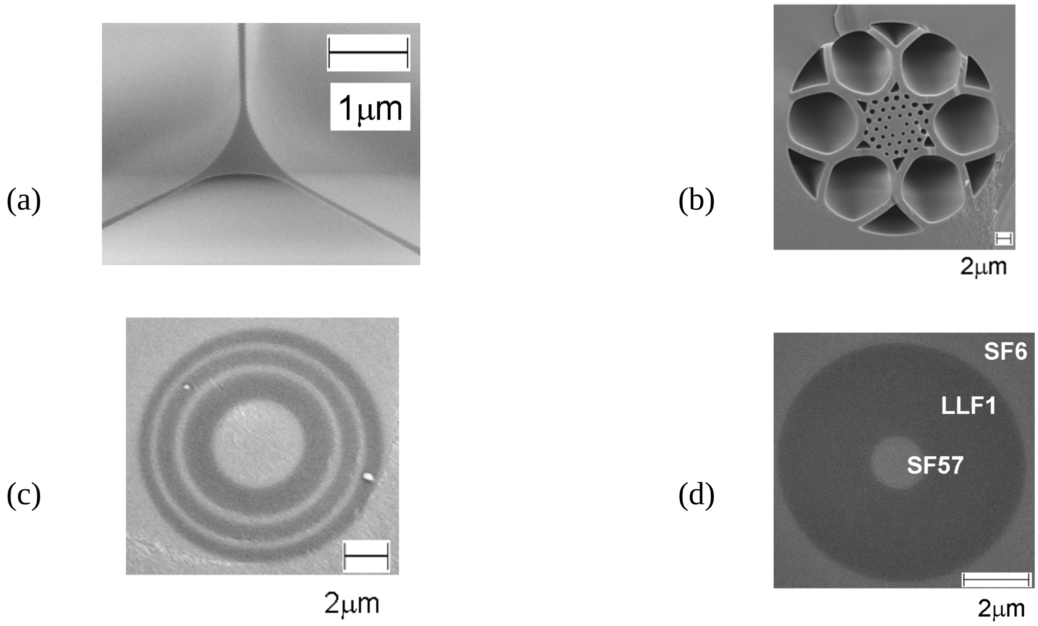

Fig. 2 (a) Air Suspended Core ultrahigh γ fibre in SF57 glass, (b) dispersion-shifted SF57 MOF, (c) solid 1-D dispersion-shifted MOF and (d) dispersion-flattened W-fibre

Theoretical analysis

Analysis has focused on the understanding of the theory governing the gain and noise properties of phase sensitive fibre parametric amplifiers (PSAs) with the aim of delivering the specifications for the individual components of the parametric amplifier based on initial PSA device specifications. Analytical and numerical models were developed to specify the amount of pump power required and the nonlinear and dispersion characteristics of the fibre. The work focused on the optimized design of the building blocks of the phase sensitive amplifier (PSA) so as to meet the requirements of low noise figure (NF)<1dB, high gain (>20dB) broadband amplification (~30nm). Two configurations of 'black-box' phase sensitive amplifiers for two applications; optical amplification and phase regeneration were studied. Both configurations showed exceptional performance for both applications exhibiting noise figure values less than 1.5dB and phase noise squeezing.

Phase sensitive amplifier

Experimental work has been undertaken on schemes to demonstrate phase-sensitive amplification and also demonstrate a noise figure below 1 dB for such an amplifier. A two-stage approach was used in which a first stage non-phase sensitive parametric amplifier serves as a seed for the second, phase-sensitive stage. The second stage is interferometric in which the pump propagates in a different path from that of the signal and idler waves before being recombined in the fibre used for phase sensitive amplification. This allows e.g. simultaneous modulation of the signal and idler waves (independent of the pump) for analysis of temporal performance. Using this approach it was possible to verify several very distinct and unique features of phase-sensitive amplifiers as well as a noise figure of less about 1 dB under certain conditions. With unequal signal/idler power ratio, a NF << 0 dB was observed for the weaker wave. Also, clear dynamic phase squeezing was observed. A novel scheme of using PSAs as in-line DWDM compatible amplifiers in transmission links was proposed, in which the link noise performance is improved by 6 dB compared with the use of lumped EDFA amplifiers. Bit-error-rate measurements were also performed showing clear sensitivity improvements.

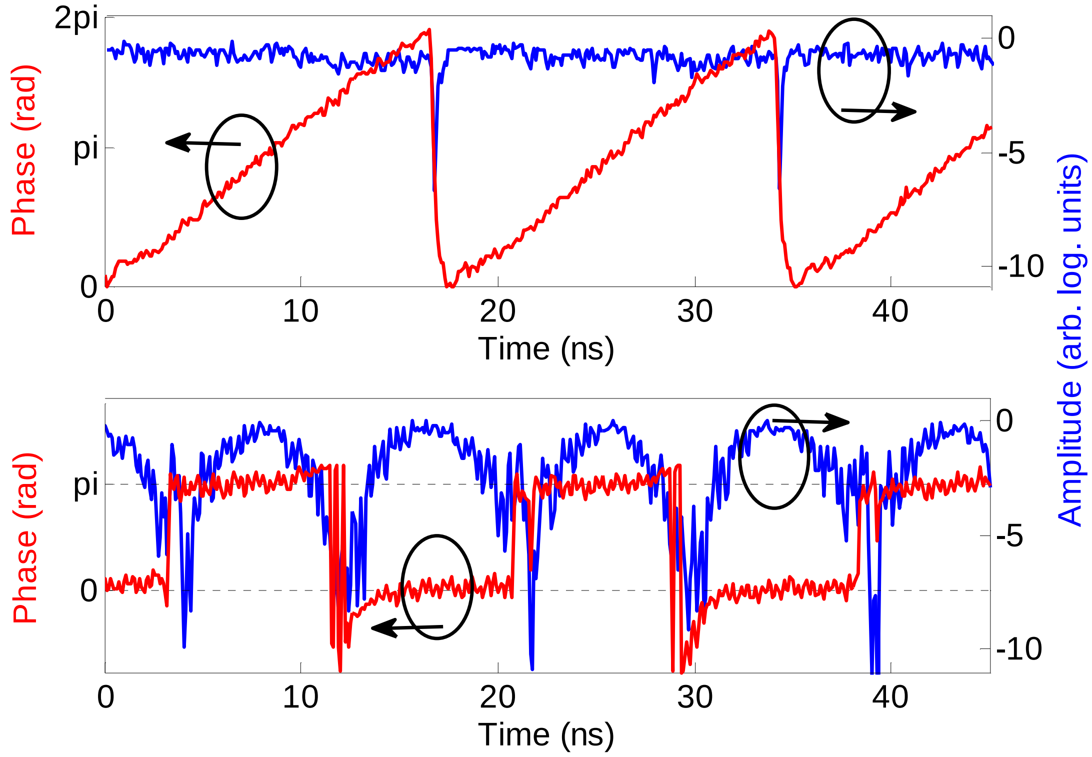

Fig. 3 PSA input (top) and output (bottom) amplitude and phase when the input phase is swept linearly. The output phase is squeezed into two discrete stated while the amplitude becomes sinusoidally modulated.

40 Gbit/s subsystems

Optical sampling: Work toward a practical system capable of capturing sophisticated optical waveforms in which both optical intensity and phase is used to encode information has been undertaken. We have investigated three different sampling system designs and reached the conclusion to use a coherent mixing approach. This approach yields strong performance while still being cost effective. A coherent mixing sampling system have now been designed and implemented as a bench top solution which is portable for sharing among the partners. The phase sensitive sampling system has been used to characterize sophisticated optical data signals such as 40 GBd DP-QPSK, 8-PSK and 16-QAM. At this time in the project the bench top sampling system is ready for initial sharing among the partners to assist them in characterizing their results, for example in the regeneration work.

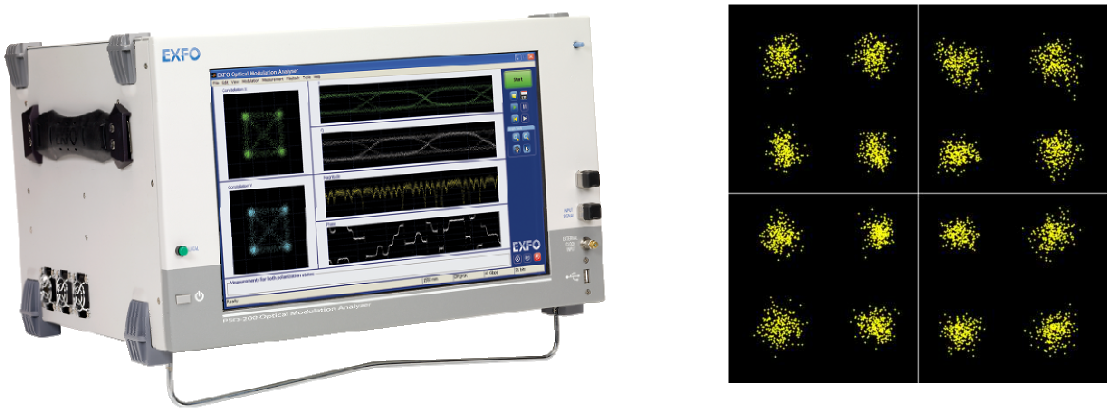

Fig. 4 Measured constellation diagram (right) of a 28 GBd 16-QAM optical signal using the bench top phase sensitive sampling system prototype (left).

Regeneration: A test bed which is suitable for quantifying the performance of phase regenerators has been set up. Following this, a DPSK regenerator based on PSA has been successfully developed and tested. Phase-only, amplitude-only and simultaneous phase and amplitude regenerative properties have been demonstrated at repetition rates up to 40Gbit/s, showing no limitation to a further increase in the signal repetition rate.

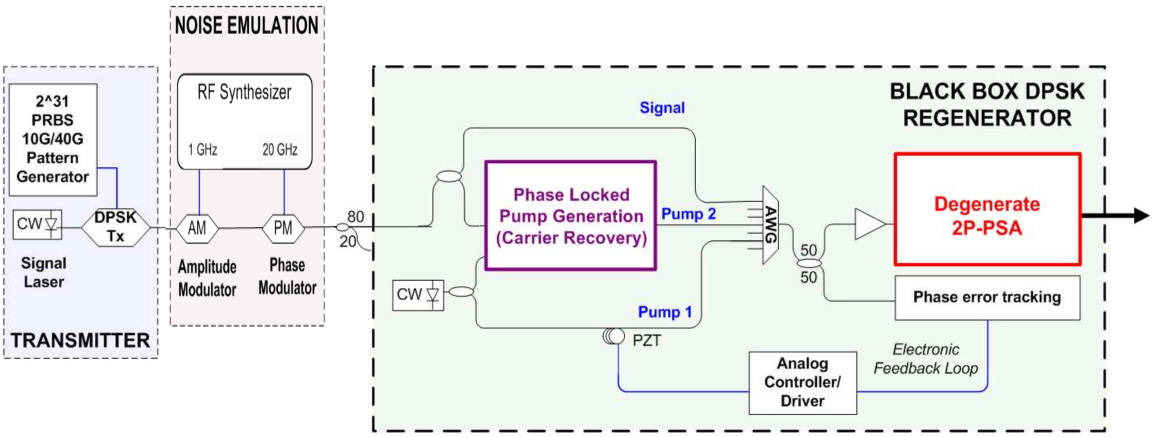

Fig. 5: FWM 2P-PSA DPSK Regeneration Scheme

Lasers

- Stable reproducible 85 kHz emission linewidth demonstrated.
- Reduction by several orders of magnitude of the free running laser linewidth from 200kHz to 5kHz demonstrated for measurement times in the 1 ms range.

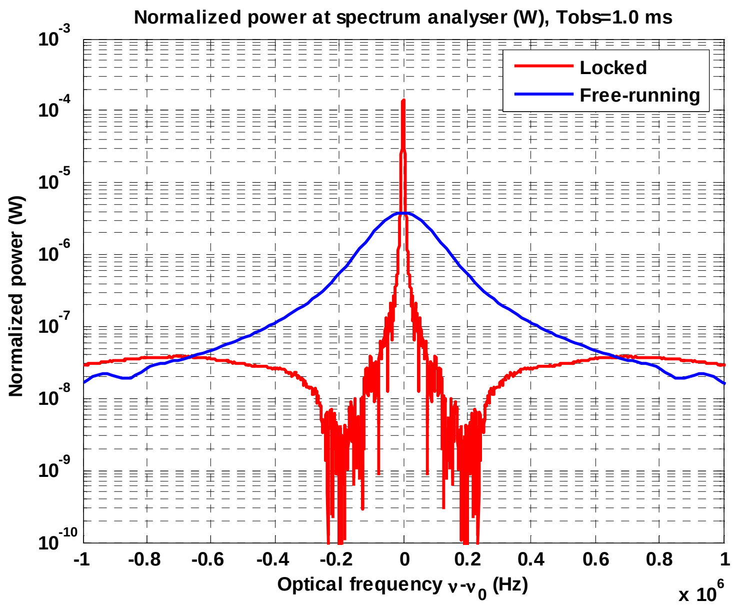

Fig.6 DM Laser linewidth of free running (blue) and locked (red) over a 1ms timeframe $\Delta\nu$ of 5 kHz demonstrated.

- High performance well matched laser diode sources designed fabricated and packaged and delivered to relevant partners for phase locked experiments.
- The laser characterization set-up to perform phase noise spectral measurements up to a frequency of 1GHz.
- A carrier recovery and phase locking scheme has been developed based on FWM in a HNLF fibre and injection locking. The proposed scheme has been used to demonstrate the first successful implementation of a “black-box” phase sensitive amplifier
- A phase locking scheme based on a MZM comb generator and a 2 stage injection locking process has been developed. Successful phase sensitive amplification has been shown.
- A homodyne coherent receiver for a 10.664Gbit/s (D)PSK signal by using an injection-locked low cost commercially available DFB laser as a local oscillator source. This was enabled by using a novel carrier extraction scheme based on a DPSK regenerator to strip off the modulation of a (D)PSK signal in a feed-forward operation. The carrier extraction system enables OIPLL systems to work with carrier-less (D)PSK signals without the need for any pilot tones, and it is attractive for PSA applications with carrier-less (D)PSK signals where an extracted carrier could be used to generate the required pump/idler signals

Fibre

- Tools for modelling of SBS are in place. Good agreement between modelled and measured performance has been demonstrated.
- HNLF with an aluminium doped core has been designed and fabricated. Considerable improvement in SBS threshold has been obtained. The fibre has shown superior performance in various applications
- Equipment for spooling HNLF with a linear strain gradient is in place. Considerable improvement in SBS threshold has been demonstrated.
- Large preforms with good homogeneity has been demonstrated using new manufacturing method for stress rod supported PM-fibres.

- Using two phase-locked tones with a frequency separation of either 100, 160 or 200GHz and the generation of new frequency components through FWM in the Al-doped HNLF, high quality short pulses at the said repetition rates were generated.
- An all-solid W-type lead silicate single mode fibre with a nonlinearity of $820W^{-1}km^{-1}$ and propagation loss of 2.1dB/m at 1550nm has been fabricated.
- The dispersion of the W-type fibre was measured in the full range between 1300 and 1700nm using a broadband low-coherence interferometer based on a supercontinuum source. The fibre has been shown to exhibit normal dispersion with an absolute value lower than 5ps/nm/km across the whole wavelength range between 1430 and 1600nm.
- No Brillouin scattering could be observed in a 3-m sample of the W-type fibre even for as high pump powers as 29dBm, indicating that this fibre can be used in applications where a high-power cw pump is required.
- First attempts towards splicing solid lead-silicate fibres to silica patchcords have been successful. A splicing loss of 2.2dB has been achieved between a high-NA silica fibre and a lead-silicate 1D-MOF.
- Broadband FWM has been observed in the fabricated dispersion shifted lead-silicate fibres. A uniform FWM conversion efficiency of 0dB has been measured on the W-type fibre over a 40nm wavelength band around 1550nm.
- Simultaneous wavelength conversion of three 40Gbit/s DPSK channels with minimal power penalty has been achieved in a 2.2m length of the W-type fibre.
- Spectral broadening of a beat signal originating from two phase locked lines with a separation of either 160 or 200GHz in 3 m of the W-type fibre has been observed, leading to the generation of clean ps pulses. The generated ultrafast waveforms have been measured directly on an optical sampling oscilloscope.
- Necessary fibres have been delivered to the partners in a timely manner

Theoretical analysis

All the partners collaborated so as to find solutions regarding the detrimental effects that cancel out the potential advantages of phase sensitive amplification. The most significant problems the consortium decided to focus on are;

- Input losses which degrade the signal to noise ratio (SNR)
- Stimulated Brillouin Scattering (SBS) which limits the parametric gain in optical fibers.
- Precise frequency and phase locking among the interacting waves which is a prerequisite for low noise phase sensitive amplification.

The first and the third problem were solved utilizing optical mixing methods, such as comb generation and four-wave mixing (FWM), in order to preserve frequency and phase locking and injection locking which has the unique property of reproducing the phase content of the incoming signal and simultaneously improve its SNR. The second issue was addressed with the manufacturing of a new class of highly nonlinear optical fibers (HNLFs) having aluminium silicate doped core which exhibit a 6dB higher SBS threshold compared to their conventional counterparts. Moreover, additional techniques such as straining can provide an overall SBS threshold increase close to 10dB compared to conventional silica based HNLFs.

PSA

- Successful phase-locking of cw-waves generated in a first stage copier, with independent fast modulation of the signal and idler simultaneously.
- First direct measurement of PSA phase squeezing vs. input phase, and first measurement of phase squeezing in a non-degenerate-idler PSA.
- First measurement of PSA phase squeezing vs. PSA gain.
- First measurement of PSA phase squeezing of broadband white noise.
- A record 1.1 dB NF was measured in a frequency non-degenerate PSA at >26 dB gain, which is the lowest ever measured NF in optical fibre amplifiers with reasonably large gain. Broadband NF spectrum was measured to show noise well below the quantum limit over 8 nm.
- Both signal and idler NFs with un-equalized input powers were measured, and much lower than -3 dB NF can be obtained for the weaker input.
- A copier + PSA amplification scheme was proposed with the best ever SNR performance. A 6-dB NF advantage over the conventional EDFA amplified transmission link has been theoretically and experimentally proven.
- WDM amplification of the copier + PSA scheme has been demonstrated at arbitrary channel spacing.
- Substantial BER sensitivity improvement compared with a conventional EDFA amplified system has been demonstrated in a 10 Gb/s PSA link.

40 Gbit/s subsystems

- Coherent mixing approach selected as the preferred implementation for the phase sensitive sampling sub-system
- Key parameters of the sampling strobe source affecting the measurement quality were identified.
- Added timing jitter in the sampling sub-system is well below 500 fs.
- Measurements of 40 GBd advanced modulation format optical data signals including QPSK, 8-PSK and 16-QAM.
- Both phase and amplitude regeneration of 10 and 40Gbit/s NRZ-DPSK signals has been observed in a system based on a fibre PSA using only locally generated pump signals.
- Regenerative multicasting of 40Gbit/s NRZ-DPSK signals to generate at least 5 copies of the original signal has been observed in a fibre PSA.

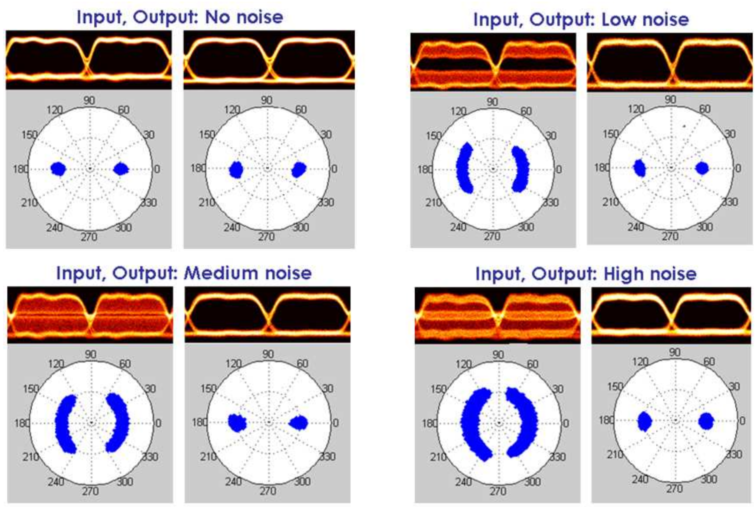

Fig. 7(a): Demodulated eye diagrams after balanced detection and differential constellation diagrams (showing bit-to-bit phase changes) at the input/output of the PSA black box.

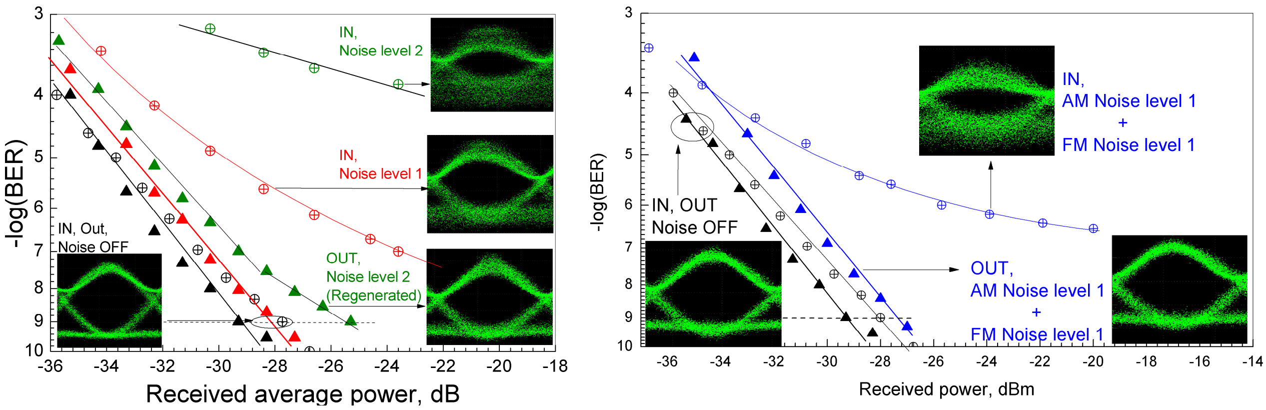

Fig. 7(b): 40 Gbit/s NRZ-DPSK BER when only amplitude noise and simultaneous phase and amplitude noise were added.

Expected final results and potential impact

PSA based regenerators will provide significant increase in repeater spacing with increased network capacity. Tuneable dispersion and PMD elements will not be required and cross-talk and filter concatenation penalties will be reduced for all-optical OADM and OXC technologies. Easier design will be facilitated through relaxation of component tolerances, less route dependence, interoperability between equipment manufacturers and potentially greater tolerance to changes in the network load. All these aspects improve costs within the final network. The consumer will benefit from enhanced communication/information access capacity at reduced cost.

The coherent mixing sampling system has potential of being a breakthrough in characterization of high-speed coherently modulated optical data signals. The commercial potential is large.

Further project information

Dr Ian Giles ipg@orc.soton.ac.uk, www.eu-phasors.eu