Novel synchronous DPSK optical regenerator based on a feed-forward based carrier extraction scheme

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Abstract: We experimentally demonstrate a novel synchronous 10.66Gbit/s DPSK OEO regenerator which uses a feed-forward carrier extraction scheme with an injection-locked laser to synchronize the regenerated signal wavelength to the incoming signal wavelength. After injection-locking, a low-cost DFB laser used at the regenerator exhibited the same linewidth characteristics as the narrow line-width transmitter laser. The phase regeneration properties of the regenerator were evaluated by emulating random Gaussian phase noise applied to the DPSK signal before the regenerator using a phase modulator driven by an arbitrary waveform generator. The overall performance was evaluated in terms of electrical eye-diagrams, BER measurements, and constellation diagrams.

OCIS codes: (060.4510) Optical communications; (060.2360) Fiber optics links and subsystems; (060.5060) Phase modulation.

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1. Introduction

The increasing demand for high capacity transmission networks is linked to the vast spread of bandwidth hungry internet applications [1]. In response to such demand, research worldwide has been heavily geared towards increasing the capacity of current optical fiber transmission systems. Recently, researchers have demonstrated transmission capacity on a single fiber of 69 Tb/s [2]. With such high data rates which are expected to grow even further in the future, impairments from amplification, optical filtering, dispersion and nonlinearities will limit the reach to shorter distances. In order to increase the transmission distance and improve the operation margin, regeneration and efficient modulation formats should be employed [3,4]. Regeneration can be realized either in the electronic domain through optical-electrical-optical (OEO) conversion, or purely in the optical domain using non-linear devices such as semiconductor optical amplifiers (SOA) or highly non-linear fibers (HNLF) [4–8]. Different advantages and drawbacks are claimed for each approach. For example, it is argued that all-optical regenerators are more power efficient in comparison to OEO regenerators. This might be true only for solutions that make use of SOAs. HNLF based schemes still require high optical power volumes and thus the use of high power EDFAs. In addition, OEO regenerators offer the advantage of providing electronic processing functions such as forward-error correction (FEC), which may improve significantly the repeater/regenerator spacing.

In this paper we experimentally demonstrate for the first time the phase regeneration property of a novel synchronous 10.66Gbit/s DPSK OEO regenerator by emulating Gaussian phase noise using an arbitrary waveform generator (AWG) and a 40Gbit/s phase modulator covering the whole bandwidth (BW) of the DPSK signal. A low-cost distributed-feedback (DFB) laser was injection-locked to the extracted carrier which was extracted by stripping off the modulation from a 10.66Gbit/s DPSK signal in a feed-forward manner based on a recently published carrier extraction scheme [9]. This regenerator synchronizes the wavelength of the regenerated data signal to the wavelength of the incoming signal. A narrow line-width laser was used at the transmitter which enabled the low-cost DFB laser used at the regenerator to have the same narrow linewidth characteristics as the transmitter laser after injection locking. This is advantageous if coherent detection is used at the receiver-end or when precise frequency control is required for the regenerated signal. The proposed scheme can be developed further to provide important functionalities which are important for different applications such as carrier distributed networks and multi-carrier add-drop multiplexers.

2. Experimental setup

The experimental setup of a 10.66Gbit/s synchronous DPSK regenerator system is shown in Fig. 1. A DPSK transmitter as shown in the top blue box consisted of a fiber laser that was used to generate a carrier signal at a wavelength of ~1553.65nm with a linewidth of ~5kHz. A Mach-Zehnder modulator (MZM) biased at null-transmission was used to modulate the optical carrier with a 10.66Gbit/s electrical data stream with a pseudo random bit sequence (PRBS) length of 2^{31}-1 resulting in an optical 10.66Gbit/s DPSK signal.

A 40Gbit/s phase modulator (V_π = 4.7V) was driven by an electrical Gaussian phase noise signal generated from a 24GS/s arbitrary waveform generator (AWG) to emulate random phase noise variations as shown in the top green box. This was used to study the effect of phase noise on the DPSK regenerator performance. A variable optical attenuator (VOA) was placed before the regenerator and used to vary the input power to an erbium doped fiber amplifier (EDFA) allowing control of the input OSNR. The EDFA was followed by an optical tunable band pass filter with a bandwidth of 0.3nm, a second EDFA in automatic power control mode (APC), and a tunable optical filter with a bandwidth of 1nm. The filtered DPSK signal was used in a carrier extraction circuit as shown in the bottom red box in Fig. 1.

The basic function of the carrier extraction system was to strip the data modulation off the incoming DPSK signal by re-modulating it with a complementary data pattern and provide the demodulated DPSK signal. In the carrier extraction circuit the filtered 10.66Gbit/s DPSK signal was split in two paths (path (a) and path (b)) using a 3dB coupler as shown in Fig. 1.

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The signal in the path (b) was fed to a 10.66Gbit/s DPSK demodulator consisting of a 1-bit delay asymmetric Mach-Zehnder interferometer (AMZI). Following the demodulator was a balanced photodiode that detected the differentially demodulated signal which was then amplified and reshaped using a limiting amplifier. The received electrical signal then passed to a differential encoder which restored the original logic sequence before being amplified by a modulator driver to $2V_{\pi}$. The amplified electrical signal was used to drive a DPSK modulator consisting of a MZM biased at null-transmission in path (a) which was used to reverse the phase modulation of the received data signal thus resulting in a continuous phase for the carrier signal. A short piece of single mode fiber and an optical delay line were used in path (a) to ensure that the delays in both paths (a) and (b) were matched and proper carrier extraction was achieved.

At the output of the MZM the extracted carrier signal contained intensity modulation at the eye crossing due to the use of MZM's for data encoding. This resulted in spectral components with a 10.66GHz spacing appearing on the spectrum of the extracted carrier. The extracted carrier was also further degraded by the finite OSNR of the incoming DPSK signal. By injection-locking a DFB laser to the extracted carrier, the OSNR of the extracted carrier was improved and the residual modulation was eliminated therefore producing a high quality regenerated carrier. The DFB laser used in the experiment had a self heterodyne free running line-width of ~475kHz half width half maximum. When injection-locked the linewidth of the regenerated carrier was improved and followed that of the transmitter laser. The regenerated carrier was then passed to a second MZM that was modulated by the received DPSK signal. The output of the second MZM was the regenerated DPSK signal.

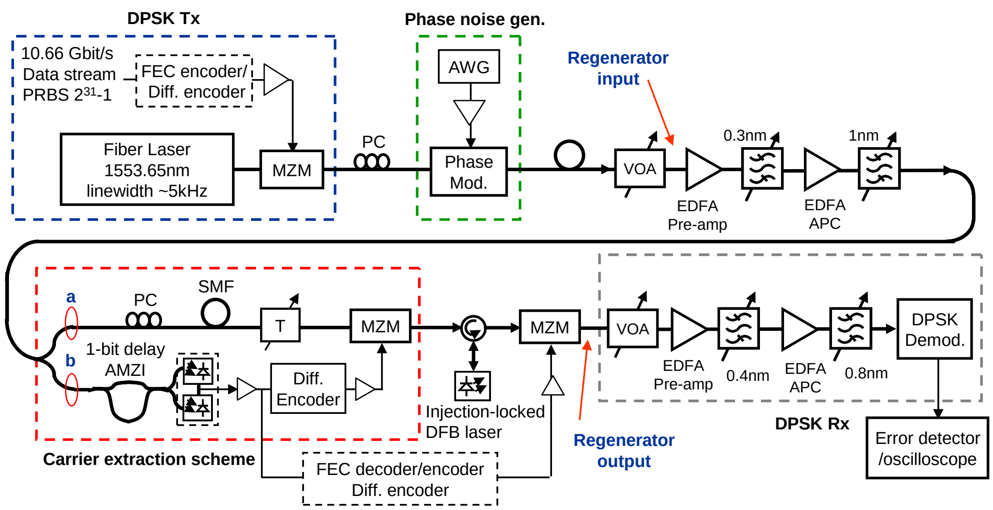

Fig. 1. Schematic of a synchronous DPSK regenerator system.

For a practical system a differential encoder would be required at the transmitter and before the regenerator MZM. In this paper the experimental measurements were performed without the differential encoder which was made possible due to the properties of the PRBS data used in the system. Since the signal is regenerated in the electrical domain, optional FEC encoders/decoders could also be used. Also for the regenerator to be employed in a real transmission system an automatic polarization controller/tracker [10] would be required as is the case with other regenerators that are polarization sensitive. To characterize the performance of the regenerated DPSK signal, another pre-amplified DPSK receiver was used as shown in the grey box on the bottom right of Fig. 1. It consisted of a VOA, pre-amplifier EDFA, 0.4nm filter, APC EDFA, 0.8nm filter, and a DPSK demodulator (1-bit delay AMZI, balanced photodiode and linear electrical amplifier). An Agilent 86100C high speed oscilloscope (12.4GHz BW plug-in) in eye diagram mode was used to measure the electrical

#142108 - $15.00 USD Received 3 Feb 2011; revised 23 Mar 2011; accepted 25 Mar 2011; published 29 Apr 2011

eye SNR. A 10Gbit/s error detector was used to measure the bit error rate (BER). To measure the constellation diagrams, the DPSK demodulator box was replaced by a coherent receiver consisting of a 90° optical hybrid (Kylia) with its local oscillator input connected to a tap of the transmitter laser. The output of the 90° optical hybrid was connected to two balanced photodiodes to recover the in-phase (I) and quadrature (Q) signal components. The received I and Q signals were amplified and captured using a 50Gsamples/s (16GHz 3-dB BW) real-time oscilloscope and then processed offline and re-sampled to 1 Sample/bit using MATLAB.

3. Results

Figure 2(A) shows the optical spectrum (measured with a resolution bandwidth of 0.01nm) of the (a) received DPSK signal measured at the input of the carrier extraction system showing no carrier component, (b) the generated extracted carrier measured at the output of the carrier extraction system showing the 10.66GHz modulation sidebands, (c) the injection-locked DFB laser output (regenerated carrier), and (d) the regenerated DPSK signal. It is clear from the injection-locked DFB laser signal (c), that the OSNR of the extracted carrier is improved and the residual intensity modulation has been eliminated. Figure 2(B) shows the performance of the carrier extraction system, which was evaluated by measuring the self-heterodyned line-width of the injection-locked laser against different levels of input powers measured at the input of the regenerator. Figure 2(B) also confirms that the DFB laser which was injection-locked to the extracted carrier had a constant measured linewidth of ~6.5kHz for an input power > –42dBm and a measured linewidth below 140kHz for an input power > –44dBm.

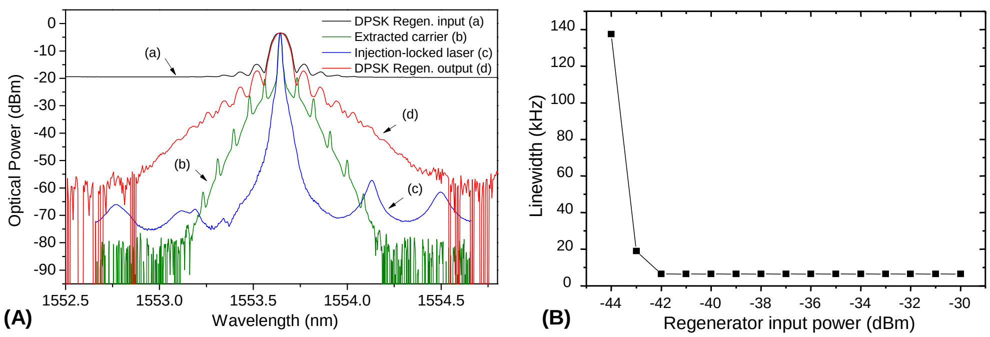

Fig. 2. Optical spectrum of the (a) DPSK signal, (b) extracted carrier, (c) injection-locked DFB laser, and (d) regenerated DPSK signal (A). Measured self-heterodyned linewidth for the ILL vs. regenerator input power (B).

Figure 3(A) shows the captured eye-diagram of the demodulated DPSK signal measured at different received power levels at the input and output of the regenerator. Figure 3(B) shows the electrical SNR of the demodulated DPSK signal for the input and output ports of the regenerator as a function of the regenerator input power.

#142108 - $15.00 USD Received 3 Feb 2011; revised 23 Mar 2011; accepted 25 Mar 2011; published 29 Apr 2011

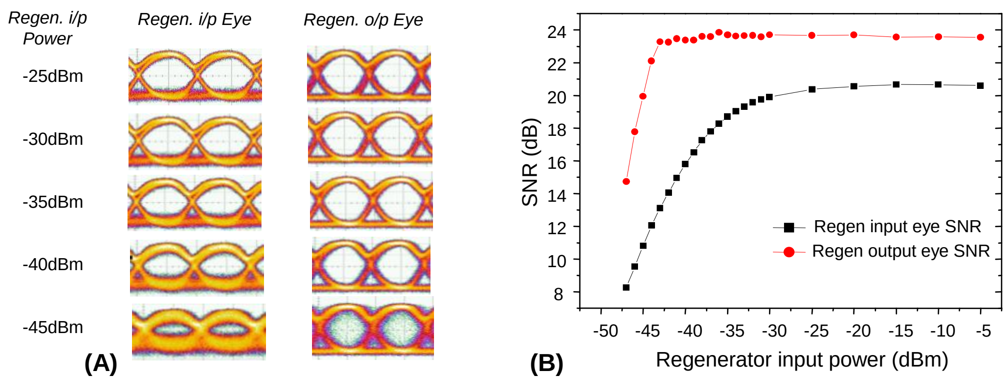

Fig. 3. Eye-diagrams of 10.66Gbit/s demodulated DPSK signals at the input and output of the DPSK regenerator at different regenerator input power levels (A). Electrical measured SNR for the input and output of the regenerator at different regenerator input power levels (B).

The SNR was measured using the built in measurement function of an Agilent 86100C high speed oscilloscope (12.4GHz BW plug-in) in eye diagram mode. Error free performance was achieved at regenerator input powers > −39dBm. It should be noted that the electrical SNR measurement technique used in the oscilloscope does not take into account the error floor which arises from the DPSK errors caused by the OSNR degradation. Therefore it would not be accurate to have a direct correspondence between the electrical measured SNR and the measured BER at such low input powers < −39dBm due to deviation from the Gaussian statistics of the output of any regenerator.

Since the proposed regenerator is for DPSK signals, the assessment of the phase noise performance is important. In order to emulate the effects of phase noise and evaluate phase regeneration properties of the DPSK regenerator, a phase noise emulation system was introduced before the regenerator as shown in Fig. 1. The phase noise emulation system was based on a phase modulator driven by a Gaussian signal generated from an AWG. The sampling rate of the AWG was 24GS/s and the amplitude of the noise signal was varied to emulate different levels of random phase noise. The electrical bandwidth of the electrical Gaussian random noise signal applied to the phase modulator was measured to be ~12 GHz using a 50GHz BW RF spectrum analyser (RBW = 300kHz, VBW = 100kHz) as shown in Fig. 4(A). This random signal covers the whole BW of the DPSK signal and emulates all the possible frequency noise components.

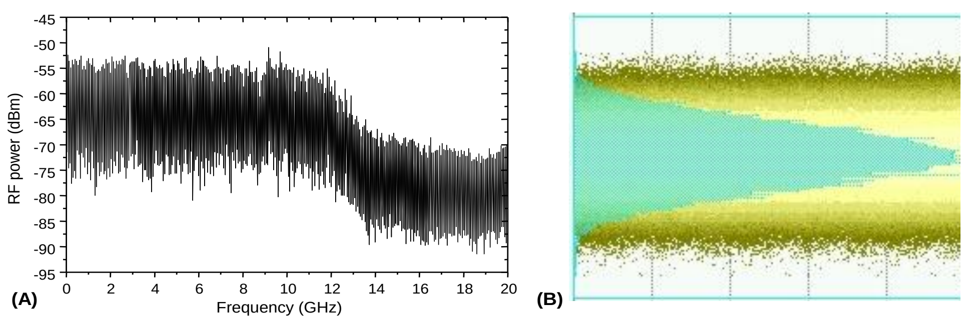

Fig. 4. Measured RF spectrum (A) and histogram (B) of the electrical Gaussian noise signal applied to the phase modulator.

The standard deviation and the peak-to-peak amplitude of electrical Gaussian signal applied to the phase modulator were measured using a high speed oscilloscope (24GHz BW plug-in) for different driving amplitude levels as shown in Fig. 4(B). These measured values were used to estimate the amount of phase noise generated by the phase modulator and

#142108 - $15.00 USD Received 3 Feb 2011; revised 23 Mar 2011; accepted 25 Mar 2011; published 29 Apr 2011

introduced to the DPSK signal before the regenerator. As the phase modulator used is a 40Gbit/s modulator, we believe that the V_π was sufficiently flat up to 12GHz.

Table 1. Phase Noise (PN) Estimated for Different Applied Voltage Cases

	Applied electrical voltage (V)		Estimated Phase Noise* (Degree)	
Case	peak-to-peak	Std. Dev. (σ)	peak-to-peak	Std. Dev. (σ)
PN 0	0	0	0	0
PN 42	1.1	0.145	42.1	5.6
PN 56	1.46	0.190	55.9	7.3
PN 61	1.6	0.209	61.2	8
PN 69	1.8	0.233	68.9	8.9
PN 80	2.1	0.273	80.4	10.5
PN 98	2.56	0.336	98	12.9

*PN noise estimated using the phase modulator V_π (PN = V × 180°/4.7).

It should be noted that the power and OSNR at the input of the regenerator were kept constant and only the amount of phase noise was varied, therefore the phase noise is assumed to be the dominant degradation factor. The amplitude of the electrical noise signal was varied in different steps resulting in several possible phase noise levels applied to the system as shown in Table 1. The main parameters used to describe the phase noise applied in this experiment are the standard deviation and peak-to-peak values measured in degrees.

Figure 5(A) shows the BER performance and penalty observed for a 10.66Gbit/s DPSK signal at the input of the regenerator with different levels of phase noise. For the phase noise levels PN 0-69, it was possible to achieve error free performance for input powers >-30dBm. While for higher phase noise degradations (PN 80 and PN 98) an error floor of 3×10^{-10} and 1×10^{-5} respectively was observed. However, as well known, the regenerator improves the electrical SNR performance but cannot remove the error floor unless the data sequence is known a-priori [11] as shown in Fig. 5(B) where the input power applied to the regenerator was −5dBm but the error floor at high phase noise values was replicated. As for a phase noise degradation of 69° (PN 69) a receiver sensitivity (BER = 10^{-9}) improvement (phase regeneration) of ~6.5 dB was achieved for the regenerated DPSK signal. We believe that the same performance could be achieved as long as no errors occur, which indicates that the regenerator could also operate with the same performance at input power levels ≥ −30dBm. It should also be noted that the main function of the carrier extraction system is to remove the data phase modulation, but the phase noise introduced from different sources will be passed on to the extracted carrier and to the injection-locking stage. Since it is known that by operating the injection-locked laser at low input powers the phase-phase transfer function will show a LPF behavior (e.g. <1GHz BW), which will suppress the high frequency phase noise components, therefore improve the performance.

#142108 - $15.00 USD Received 3 Feb 2011; revised 23 Mar 2011; accepted 25 Mar 2011; published 29 Apr 2011

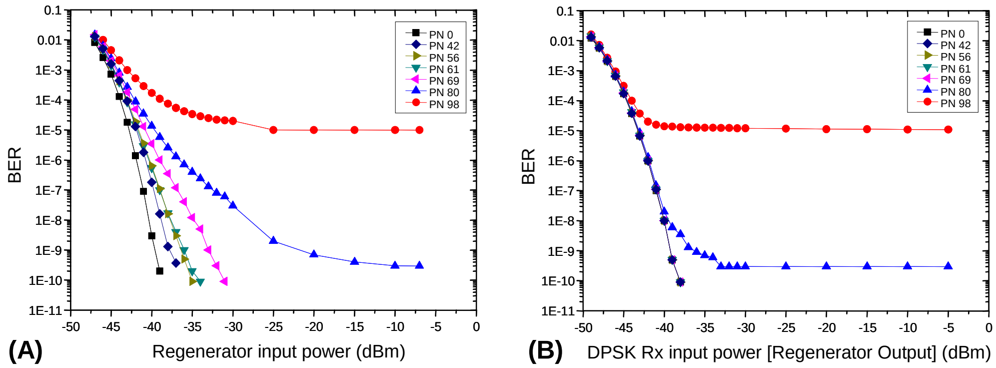

Fig. 5. BER measurements vs. optical power for differentially demodulated 10.66Gbit/s DPSK signals before regeneration with phase noise added (A), and after regeneration (B).

Phase regeneration was also quantified through eye diagram measurements after differential detection (Fig. 6 (top)), and constellation diagrams of the DPSK signal after coherent detection (Fig. 6 (bottom). The constellation diagrams shown in Fig. 6 (bottom) were plotted with 100000 bits for the DPSK signal measured at the input and output of the regenerator for different levels of phase noise. It should be noted that since Gaussian noise was used, and due to the limited number of samples measured, it is difficult to see the points causing the errors due to the phase noise induced from the tails of the Gaussian noise signal. This caused a BER error floor for higher phase noise levels. Using other types of phase noise (non-Gaussian sinusoidal) would make the degradation clearly observed on the constellation diagram [7,8] but would not cover the whole BW of the data signal.

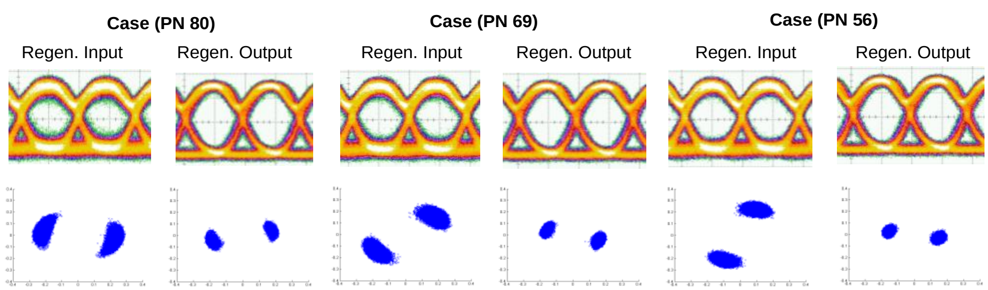

Fig. 6. Measured eye diagrams for the differentially detected DPSK (top) and coherently detected DPSK signal constellation diagrams (bottom) at the input and output of the regenerator for different input phase noise levels.

4. Conclusions

We experimentally demonstrated for the first time a novel Synchronous DPSK OEO regenerator for 10.66Gbit/s DPSK signals. The scheme uses a carrier extraction scheme with an injection-locked laser to synchronize the regenerated signal wavelength to the incoming signal wavelength. This enables using a single narrow line-width laser at the transmitter and a low cost laser at the regenerator. The regenerated signal is frequency locked to the transmitter laser and has the same narrow linewidth characteristics. Stable low linewidths of ~6.5kHz for input powers >-42dBm were obtained. Phase regeneration was also observed by degrading the DPSK signal at the input of the regenerator using a Gaussian noise emulator that covered the whole bandwidth of the DPSK signal. Phase regeneration of ~6.5 dB was achieved for the regenerated DPSK signal with peak-to-peak phase noise degradation of 69° applied to the input signal. The proposed carrier extraction system enables DPSK regeneration maintaining a narrow linewidth which is useful if coherent detection is used at the final receiver end and

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offers the possibility to regenerate multi-carrier signals when combined with a comb generator.

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