Experimental Demonstration of Phase-Sensitive Regeneration of a 20-40 Gb/s QPSK Channel without Phase-Locked Loop using Brillouin Amplification

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Abstract *We experimentally demonstrate all-optical phase-sensitive regeneration of a 20-40Gb/s QPSK signal without a phase-locked loop by amplifying the fourth-harmonic using Brillouin amplification. We observe up to 65% reduction in phase noise and 3.4 dB gain at BER of* 10^{-4}.

Introduction

Phase-dependent data modulation formats have become highly popular in optical communication systems due to the tolerance to nonlinear effects and spectral efficiency [1]. Phase-modulated data channels may benefit from optical regeneration, potentially to avoid full optical-electrical-optical conversion in a long-distance system [2]. One promising technique to all-optically clean a QPSK signal's phase noise (Φ_{noise}) is to add the signal and its third-harmonic conjugate using phase-sensitive (PS) processes [3]. For example, PS-based regeneration of QPSK data occurs using nonlinear wave mixing in a highly nonlinear fiber (HNLF) when two pumps are used to mix and add the signal to its third-harmonic. Therefore, the part of the signal that has a different phase from the QPSK phase states will be "squeezed".

However, such regeneration mixing is only efficient when the addition is coherent and phases are locked. Various QPSK regeneration approaches were demonstrated including: (a) the use of a phase stabilization feedback loop (i.e. phase-locked loop (PLL)) [4-8], and (b) wave mixing of a signal with its delayed harmonics and their conjugates, which alters the data pattern [9].

In this paper, we demonstrate a phase-sensitive regeneration of a 20-40 Gb/s QPSK channel without the need for a phase-locked loop using Brillouin amplification (BA). Signal's higher harmonics are generated in a HNLF, similar to [4-7], but we then benefit from the narrow bandwidth nature of Brillouin amplifier (~10MHz) [10,11] to amplify the fourth-harmonic in a SMF. Because amplification occurs without a path separation, phase relationships between the pump, signal, third-harmonic and amplified fourth-harmonic remain locked allowing stable phase regeneration without the phase-locked loop and without changing the data pattern. We examine regeneration at different phase noise levels, and we observe up to 65% reduction in the phase noise, 3.4 dB gain and stable phase regeneration.

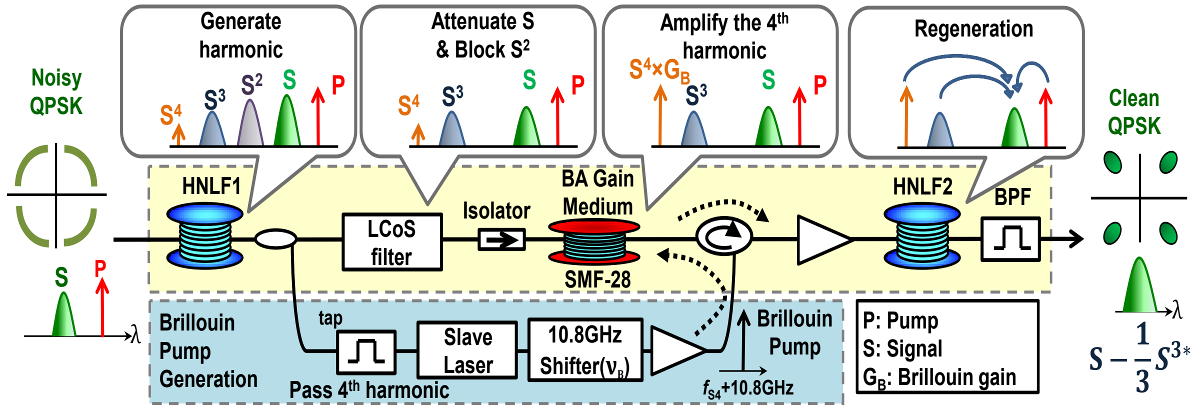

Fig. 1: Concept of QPSK regeneration without phase-locked loop using Brillouin amplification. Signal's higher harmonics are firstly generated in HNLF1, and afterwards S is attenuated in the LCoS filter along with blocking S^2. Next, the 4th harmonic (S^4) is amplified in a SMF-28 using Brillouin amplifier counter propagating pump. The Brillouin pump is generated by tapping S^4 and using a slave laser to ensure stable frequency-locking needed for Brillouin interaction. Because S^4 is amplified in the SMF and P, S, and S^3 also propagate in the same SMF, phase relationships remain locked allowing stable regeneration process.

Concept

The concept of an all optical QPSK regenerator using Brillouin amplification is shown in Fig.1. A QPSK signal (S), which is degraded with phase noise, is combined with a CW pump (P) and both are sent into a highly nonlinear fiber (HNLF1) to generate higher harmonics; S^2,S^3,S^4. Then, the second-harmonic (S^2) is blocked and S is attenuated in a Liquid Crystal on Silicon (LCoS) filter. Afterwards, the fourth-harmonic (S^4) gets amplified in the SMF with gain (G_B) using the counter propagating Brillouin pump. In order to ensure frequency locking between S^4 and the BA pump (<10MHz), we generate the appropriate frequency-locked BA pump by tapping S^4 and setting a slave laser to frequency-lock to it. The slave laser CW output is then frequency up-shifted by ν_B (10.8GHz), amplified, and sent into the SMF as a counter propagating Brillouin pump; where: ν_B is the Brillouin gain frequency shift of an SMF. At the output of the SMF, the P, S , S^3, and $S^4\times G_B$ are amplified using an EDFA and sent into HNLF2 for phase regeneration, and because S^4 is not separated from the other harmonics, its phase will remain locked to them, which can be explained in [12]. In the phase regeneration stage, QPSK phase is squeezed when the conjugate of the third-harmonic (S^{3}*) is created through FWM as $\varphi_{S3^*}=\varphi_{pump}+\varphi_{S4}-\varphi_{S3}$ and destructively added to the signal as $S-\frac{1}{3}S^{3*}$.

Experimental Setup

The experimental setup is depicted in Fig.2(a). We modulate a 1-kHz line-width laser at 1553.9 nm with QPSK data at 20Gb/s and 40Gb/s using 2^{31}-1 PRBS pattern in an I/Q Mach-Zehnder modulator (MZM). Phase noise is loaded using a phase modulator driven by 5.5 GHz tone. The signal and a CW pump at 1553.1 nm are amplified, combined in a 50/50 coupler, and then sent together into a 357 m HNLF1 (ZDW=1556 nm), with signal and pump power levels of ~ 20dBm. Then, the HNLF1 output (as in Figh.2(b)) goes into an LCoS filter which is used to attenuate S, block S^2, adjust relative phases and compensate for delays that will be induced by dispersion walk-off in the upcoming 500m SMF (Fig.2(c)). Afterwards, LCoS output is sent into the SMF and SMF output is shown in Fig.2 (d) before and after amplifying S^4. We generated the BA pump by selecting S^4 in a BPF and adjusting a slave laser to frequency-lock to it using temperature controller in the BA pump generation tap. The slave laser output is then frequency up-shifted in a MZM biased at null and fed with a ν_B=10.805 GHz tone. Next, we use a sharp filter to pass only the upper tone needed for BA, which is boosted in an EDFA and filtered before reaching the 500m SMF. We operate the BA pump EDFA at ~27 dBm corresponding the operating point shown in Fig.2(e). Figure.2(f) shows the spectrum of S^4 after the SMF which is captured using 10MHz OSA where the S^4 is found to enjoy ~40 dB gain while higher harmonics of phase noise don't gain amplification. Finally, P, S, S^3, and S^4 are amplified in an EDFA, set to 26 dBm, and sent into the regeneration stage of HNLF2. HNLF2 has ZDW=1545nm and was operating with SBS=-10 dBm. Regeneration stage output is shown in Fig.2(g) along with showing the case of blocking S that can illustrate the generated S^{3}* at 1553.1nm with 10 dB less power than signal (~1/3 difference in magnitude to satisfy the regeneration equation). Finally, we filter the regenerated output signal and send it to an 80 Gsample/s coherent receiver for analysis.

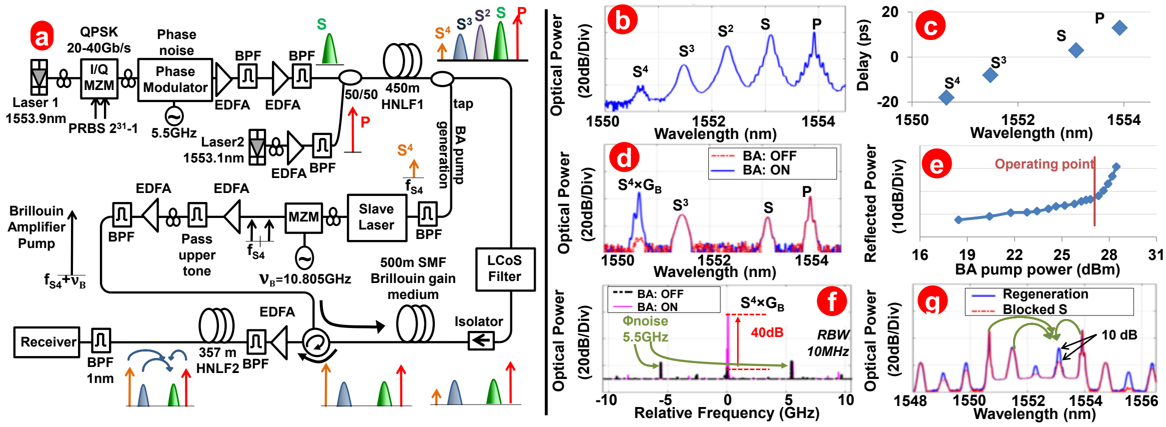

Fig. 2: (a) Experimental setup. (b) Spectrum after generating the higher harmonics in HNLF1. (c) Applied delay in LCoS to compensate the dispersion induced walk-off in the 500m SMF between P,S,S^3, and S^4. (d) Spectrum after the 500m SMF when BA is on and off. (e) The BA's pump operating power point at ~27 dBm. (f) Spectrum of the 4th harmonic with 10MHz resolution showing that S^4 gets 40 dB gain while the Φnoise doesn't get any gain. (g) HNLF2 output when system is regenerating, and when S is blocked to observe the ~10 dB power difference between S and S^{3}* (i.e., 1/3 magnitude difference to satisfy the QPSK regeneration equation $S-\frac{1}{3}S^{3*}$)

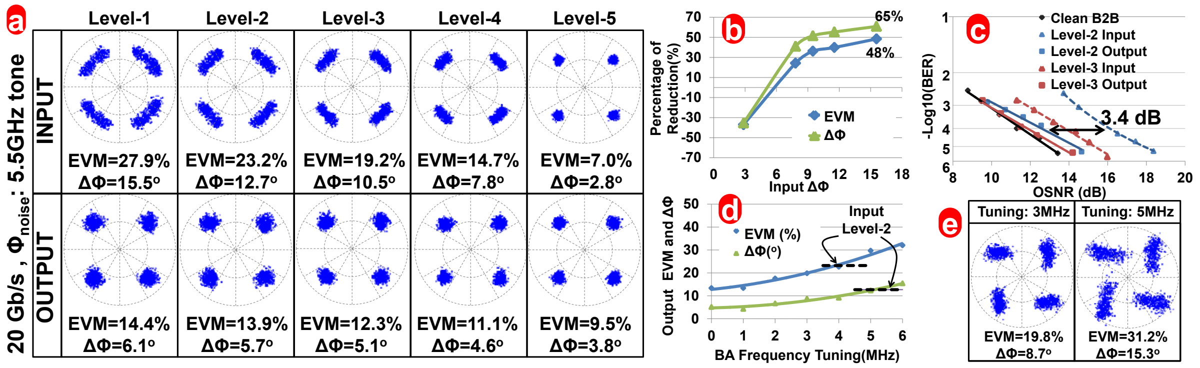

Fig. 3: (a) Constellations before and after the regeneration system for 20Gb/s QPSK loaded with 5.5GHz tone phase noise. (b) Percentage of EVM and $\Delta\Phi$ reduction corresponding to different $\Delta\Phi$ input levels. (c) BER performance before and after the system for two scenarios. (d) Tuning the BA pump from its optimal frequency shift and studying effect on the case of regenerating level-2. (e) Examples of the effect of tuning BA frequency on the constellation.

Results

First, we vary the phase noise to different levels and record the constellations, error-vector-magnitude (EVM) and phase noise variance ($\Delta\Phi$) values for 20Gb/s signal at the system input and output in Fig.3(a). Also, we calculated the EVM and $\Delta\Phi$ percentage of reduction corresponding to each input $\Delta\Phi$ in Fig.3(b) where we observe reductions of up to 65% in $\Delta\Phi$ and 48% in EVM for the high phase noise scenario. In Fig.3(c) we measure the BER and observe up to 3.4 dB improvement for phase noise level-2. Then, we study the effect of tuning the BA pump frequency from the optimal shift and record the regeneration performance when input $\Delta\Phi$ is at level-2 in Fig.3(d) and find that EVM will exceed the input EVM level after 4MHz of tuning. Examples of the effect of tuning the frequency on constellation are presented in Fig.3(e) where tuning the BA pump frequency adds phase shift to the regeneration process.

We compare the regeneration performance when the input $\Delta\Phi$=~10° for 20 and 40 Gb/s and we examine the regeneration under broadband phase noise (generated by ASE and a photodiode) in Fig.4(a). It can be noticed that the regeneration performance slightly degraded for the 40Gb/s case compared to the 20Gb/s. Finally, we study the regeneration performance over an hour without adjustments or a PLL in Fig.4 (c) and (d) for the 20 Gb/s QPSK with 5.5 GHz phase noise. In this test, When the input EVM and $\Delta\Phi$ were 19.2% and 10.5°, respectively, the mean output EVM and $\Delta\Phi$ were 13.0% and 5.4°, respectively.

Acknowledgments

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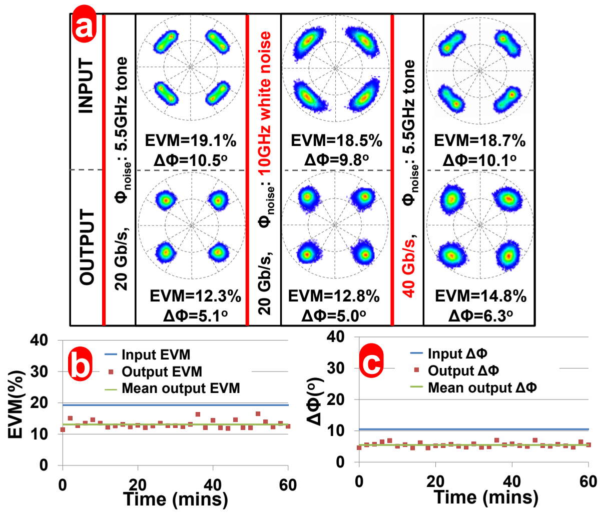

Fig. 4: (a) Regenerating 20 Gb/s signal with different types of Φ_{noise} and regenerating a 40 Gb/s channels with input $\Delta\Phi$=~10°. (b),(c) EVM and $\Delta\Phi$ free-running stability test over an hour without PLL for regenerating the case of 20 Gb/s with 5.5GHz noise of $\Delta\Phi$=10.5°.

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