# Bit-Rate-Tunable Regeneration of 30-Gbaud QPSK Data Using Phase Quantization and Amplitude Saturation

A. Mohajerin-Ariaei[(1)], Y. Akasaka[(2)], J.-Y. Yang[(2)], M. R. Chitgarha[(1)], M. Ziyadi[(1)], Y. Cao[(1)], A. Almaiman[(1)], J. D. Touch[(3)], M. Tur[(4)], M. Sekiya[(2)], S. Takasaka[(5)], R. Sugizaki[(5)], C. Langrock[(6)], M. M. Fejer[(6)], and A. E. Willner[(1)]

(1) Department of Electrical Engineering, University of Southern California (USC), 3740 McClintock Ave., Los Angeles, CA 90089, USA, mohajera@usc.edu
(2) Fujitsu Laboratories of America, 2801 Telecom Parkway, Richardson, TX 75082, USA
(3) Information Sciences Institute of USC, 4676 Admiralty Way, Marina del Rey, CA, 90292, USA
(4) School of Electrical Engineering, Tel Aviv University, Ramat Aviv 69978, Israel
(5) Fitel Photonics Laboratories, Furukawa Electric Co., 6 Yawatakaigan-dori, Ichihara, Chiba, Japan
(6) Edward L. Ginzton Laboratory, 348 Via Pueblo Mall, Stanford University, Stanford, CA 94305, USA

**Abstract** *We propose an all-optical regeneration consisting of a phase quantizer based on delay and summation of higher harmonics and an optical amplitude squeezer. We experimentally demonstrate phase noise reduction of 40% and OSNR-gain of 3dB at BER $10^{-3}$ for 30-Gbaud QPSK signals.*

## Introduction

Multi-level formats have become quite important in optical communication systems. In particular, quadrature-phase-shift-keying (QPSK) encodes data on the phase of optical carrier wave and is spectrally efficient. In QPSK systems, changes in phase or amplitude can cause a decrease in data's signal-to-noise ratio, causing a system power penalty. For different applications, there is the desire for optical regeneration, in which the data-point constellation has a lower error-vector-magnitude (EVM) and the system has a lower power penalty[1].

Different approaches have been used for optical regeneration of QPSK signals. In general, these techniques have required the use of a feedback loop to stabilize the phase within the regenerator[2]. One recently published approach that did not require a phase feedback loop to improve QPSK signal's performance was the use of phase quantization derived from the generation, delay and summation of higher harmonics of data signal[3]. Receiver's sensitivity improvement for this phase-noise mitigator was ~1.5dB for ~35 degrees of phase noise. One drawback of this approach was that phase noise was partially converted into amplitude noise, thus limiting system performance. A laudable goal is to add amplitude noise mitigation, such that a combined phase/amplitude noise mitigator can further improve the system performance.

In this paper, we demonstrate a bit-rate-tunable phase and amplitude noise mitigation scheme based on phase quantization and amplitude saturation. Utilizing differentially delayed signal and its conjugated third

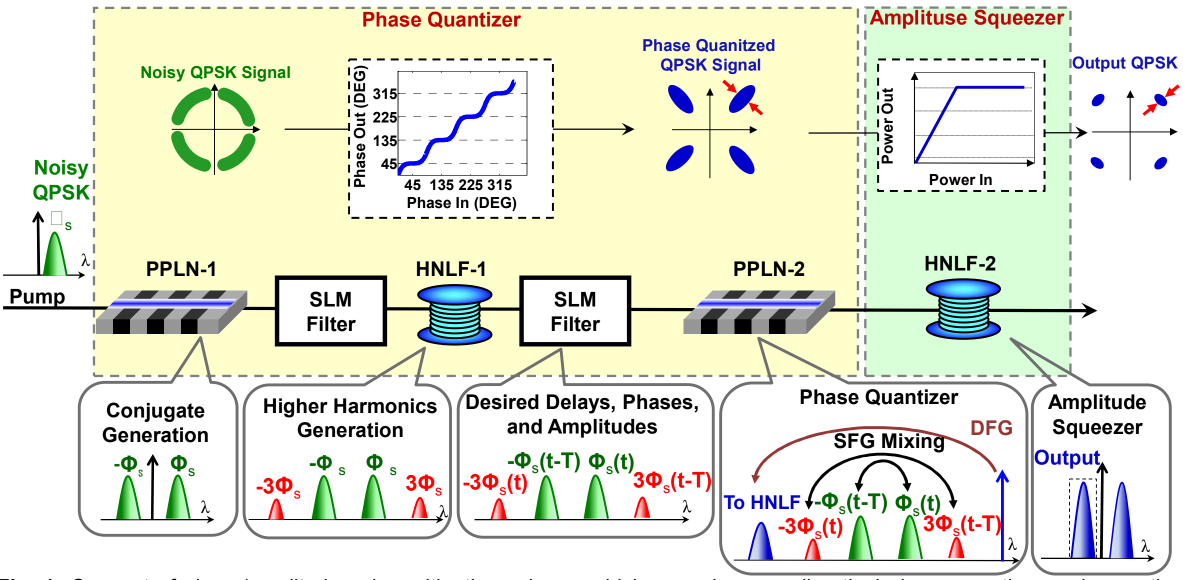


**Fig. 1:** Concept of phase/amplitude noise mitigation scheme which comprises an all-optical phase quantizer and an optical amplitude squeezer. Phase quantizer's staircase phase transfer function can result in phase squeezing by generating third harmonics of signal, applying the relative delays and amplitudes between harmonics, and then mixing the nonlinear products. The residual amplitude noise can be suppressed by amplitude squeezer operated in saturation regime.

harmonics, phase noise is suppressed. Then the partially converted noise to amplitude is squeezed by using an optical parametric amplifier operated in saturation regime. The system could be tuned for different baud rates by adjusting the amount of delay. System performance improvement is successfully verified by the analyses of constellation, EVM at 30 and 20 Gbaud signals. At 30-Gbaud, phase noise range reduction of around 40% and OSNR gain of 3dB at BER $10^{-3}$ can be achieved.

## Concept

Fig. 1 depicts conceptual diagram of our phase and amplitude noise mitigation method, which comprises two stages: optical phase quantizer and optical amplitude squeezer. The input/output phase profile of phase quantizer and the input/output amplitude profile of amplitude squeezer enable suppressing noise in phase and amplitude directions, respectively. In phase quantizer, a QPSK signal contaminated with phase noise along with a CW pump are injected into a periodically-poled Lithium Niobate (PPLN) waveguide to generate a phase conjugate copy of signal. The signal and conjugate copy are sent into a highly nonlinear fiber (HNLF) to generate the third harmonics of signal. The signal and harmonics are sent into an in-line spatial light modulator (SLM) phase and amplitude programmable filter to apply appropriate delays, amplitudes, and relative phases. The amount of the delays can be adjusted based on signal baud rate[3]. To suppress signal's phase noise, a staircase phase transfer function can be built by coherently mixing products of harmonics in the second PPLN. To compensate the residual noise which is partially converted from the phase to the amplitude of signal, phase quantizer's output along with a CW pump will be sent to a second HNLF. HNLF's gain profile is designed to work in the saturation regime for

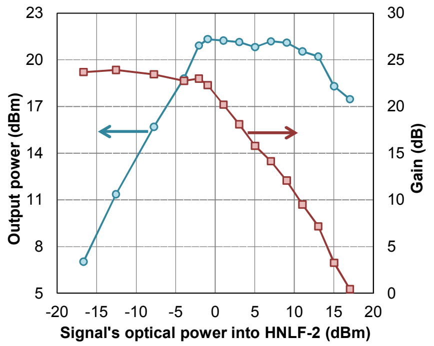


**Fig. 3:** Power and gain profiles for HNLF-2. Operation in saturation regime results in amplitude noise sqeezing.

squeezing the amplitude noise.

## Experimental setup

Fig. 2 illustrates the experimental setup of phase and amplitude noise mitigation scheme. One I/Q modulator is used to generate 20/30-Gbaud QPSK (PRBS $2^{31}$-1). This signal is amplified by EDFA and phase modulated with amplified spontaneous emission (ASE) source to emulate phase noise. Various levels of phase noise can be generated by adjusting the attenuator before the photo-detector (PD). The noisy signal is amplified and coupled with an CW pump around 1551.5nm and injected into PPLN-1 to generate the phase conjugate of signal. PPLN-1's output is then sent to a SLM filter for adjusting amplitudes. The adjusted signal and its conjugate copy are amplified and sent to 450m HNLF-1 (ZDW at 1555 nm) to generate the third harmonics of signal through degenerate four-wave mixing. The signal and the generated harmonics are then sent to another SLM filter to apply appropriate delays, amplitudes, and relative phases. The resulting signals are amplified and coupled with another CW pump around 1543nm and sent to PPLN-2 to mix signal and its conjugate copy as well as the third harmonic and its conjugate through cascaded processes of second harmonic generation followed by difference frequency generation

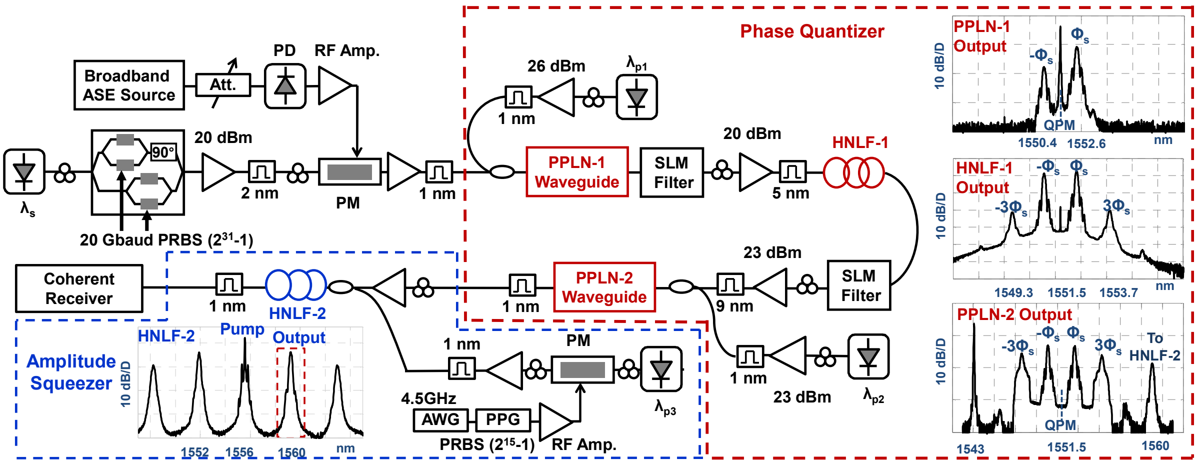


**Fig. 2:** Experimental setup of phase and amplitude noise mitigation. PM: Phase modulator, HNLF: Highly nonlinear fiber, PPLN: Periodically poled Lithium Niobate, SLM: Spatial light modulator, PD: Photo-detector, VOA: Variable optical attenuator.

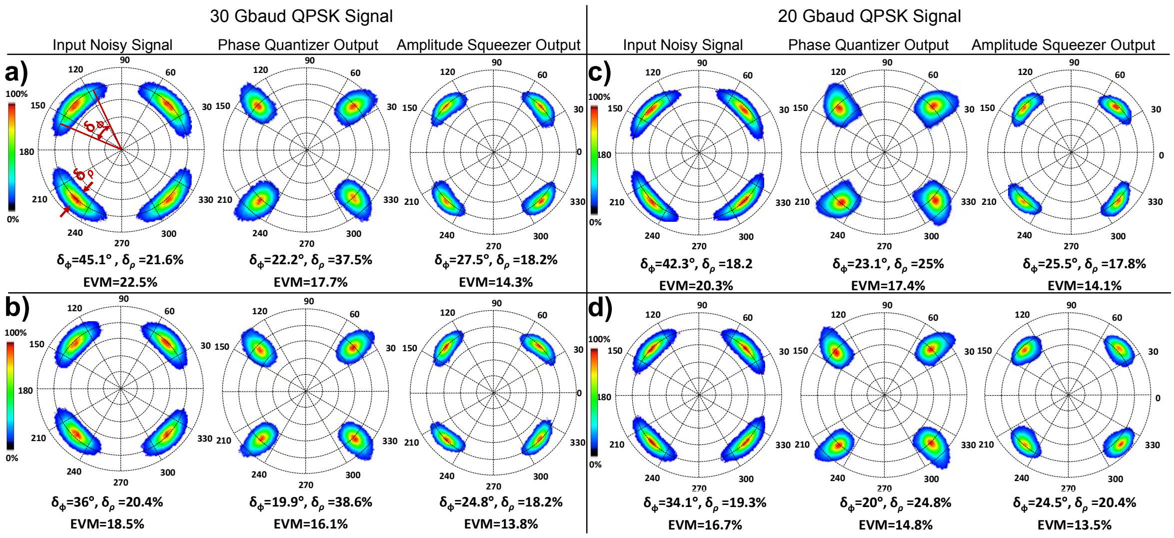


**Fig. 4:** The input and output constellation diagrams of the phase noise mitigation systems for 30 Gbaud (a, b) and 20 Gbaud (c, d) QPSK signals impaired by different values of phase noise.

(cSHG-DFG). The phase quantized output signal is amplified and coupled with an amplified CW pump at 1556.3nm and injected into a 700m dispersion stable HNLF-2 (ZDW at 1551.5 nm)[4]. A CW pump is phase modulated with 4.5 GHz PRBS ($2^{15}$-1) data to suppress stimulated Brillouin scattering. Fig. 3 shows measured gain and power profiles of HNLF-2. A quite wide range of signal power from about 0 to 10dBm can be squeezed within 0.4dB deviation. Finally, the output signal is captured by a coherent detector, without applying any equalizer, in order to measure the phase noise range, EVM, and BER of the system.

## Result and discussion

The system performance is assessed using 20- and 30-Gbaud QPSK signals, respectively. Fig. 4 shows the constellation diagrams of input noisy signal, output of phase quantizer, and output of amplitude squeezer. These results are obtained for different values of phase noise. For comparing the phase noise range between various constellation diagrams in Fig. 4, the parameter δφ is defined to quantify the phase deviation from the corresponding expected value. In addition, the parameter δρ is defined as the percentage of amplitude deviation from the expected value. The phase quantizer can significantly reduce the amount of phase noise degree; δφ is decreased by ~50% in Fig. 4(a). However, in the phase quantizer output, the phase noise is partially converted to amplitude noise; δρ is increased by ~70% in Fig. 4(a). This amplitude noise is successfully suppressed by the amplitude squeezer, and δφ is decreased by ~40% and δρ is decreased by ~16% in comparison to the input noisy signal in Fig. 4(a). As a result, the amount of EVM between the input signal and the output of amplitude squeezer in Fig. 4(a) is decreased by ~36%. In general, Fig. 4 shows that the phase quantizer is capable of suppressing the phase noise, particularly for high levels of phase noise; however, the partial amount of phase noise is converted to amplitude noise. This noise can be successfully squeezed in the amplitude squeezer operated in saturation regime.

Fig. 5 shows the BER of the noise mitigation system at 30Gbaud QPSK signals for two different levels of phase noise, i.e., δφ ~46° and 37°. This scheme results in ~3dB OSNR gain at a BER of $10^{-3}$.

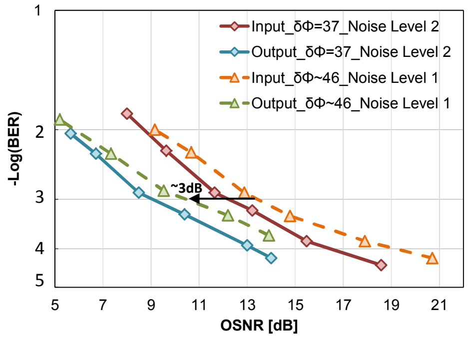


**Fig. 5:** BER versus OSNR for two different levels of phase noise ($\delta_\varphi$~46°, 37°), showing ~3dB OSNR gain at BER of $10^{-3}$.

## Acknowledgements

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## References

[1] K. Solis-Trapala et al., “Tunable optical parametric regenerator assessment in a 43 Gb/s RZ-DPSK signal transmission link,” PTL 26, 629 (2014).

[2] J. Kakande et al., “Multilevel quantization of optical phase in a novel coherent parametric mixer architecture,” Nat. Photon. 5, 748–752 (2011).

[3] A. Mohajerin-Ariaei et al., “Experimental demonstration of all optical phase noise mitigation of 40-Gbits/s QPSK signals by mixing differentially delayed nonlinear products,” OFC’14, paper W3F.3 (2014).

[4] S. Takasaka et al., “Nonlinear optical fiber nonlinear optical device, and optical signal processor,” European Patent EP-1-988-411-A1.