# PSA and PSA-Based Optical Regeneration for Extending the Reach of Spectrally Efficient Advanced Modulation Formats

J.-Y. Yang[1], Y. Akasaka[1], M. Ziyadi[2], A. Mohajerin-Ariaei[2], Y. Cao[2], A. Almaiman[2], I. Kim[1], S. Takasaka[4], R. Sugizaki[4], J. Touch[3], A. E. Willner[2], and M. Sekiya[1]

1) Fujitsu Laboratories of America, 2801 Telecom Parkway, Richardson, TX 75082, USA
2) Department of Electrical Engineering, University of Southern California, Los Angeles, CA 91801, USA
3) Information Sciences Institute, University of Southern California, Marina del Rey, CA 90266, USA
4) Fitel Photonics Laboratories, Furukawa Electric Co., 6 Yawatakaigan-dori, Ichihara, Chiba, Japan
Email: jeng-yuan.yang@us.fujitsu.com

**Abstract — We investigated various PSA schemes for phase regeneration and compared applicability to QPSK and higher-level formats. We demonstrated a polarization-diversity PSA to support a dual-polarization signal. Optical parametric amplifier may be one of the solutions to squeezing amplitude noise.**

## I. Introduction

Spectrally efficient modulation enables high-capacity networks, but their transmission distance is hampered by high receiver OSNR thresholds and low optical noise tolerance. The optical reach of 16QAM may be limited to a few hundred kilometers, requiring expensive OEO regenerators. To make these formats practical, their optical reach must be increased.

It is difficult to reduce the OSNR threshold, so it is preferable to suppress accumulated optical noise. One approach reduces the optical amplifier's noise figure (NF). Common optical amplifiers (EDFA, optical parametric amplifier (OPA), etc.) have a minimal NF of 3dB [1-4]. To further reduce NF, phase-sensitive amplification (PSA) is of great interest because of its ideal NF of 0dB (i.e., the quantum limit). Another approach squeezes the optical signal's phase/amplitude noise, e.g., using PSA. PSA-based optical regenerators have attracted significant recent interest [5-14].

To make PSA-based optical regenerator practical to use, some challenges need to be overcome, including (i) immunity to signal's state of polarization and residual chromatic dispersion, (ii) applicability to 16QAM and higher-order formats, (iii) highly nonlinear device that can be immune to effects of SBS, pump phase modulation, temperature drift etc., and (iv) phase drift caused by environmental conditions. Comparisons of Pros/Cons between $\chi^{(2)}$ and $\chi^{(3)}$ nonlinear devices have been discussed in [4-6]. Our research motivation aims to investigate practical solutions to these challenges.

This paper highlights our research on optical phase regeneration for multi-level PSK and a polarization-diversity PSA for single- and dual-polarization formats. It describes a non-PSA based phase regenerator with an OPA based amplitude regenerator [15]. We continue researching novel solutions to remaining challenges.

## II. Regeneration of Optical Phase Noise

Fig. 1(a) illustrates the concept of dual-conjugate-pump degenerate PSA phase regenerator. Two conjugate pumps can provide the desired gain response for phase regeneration,

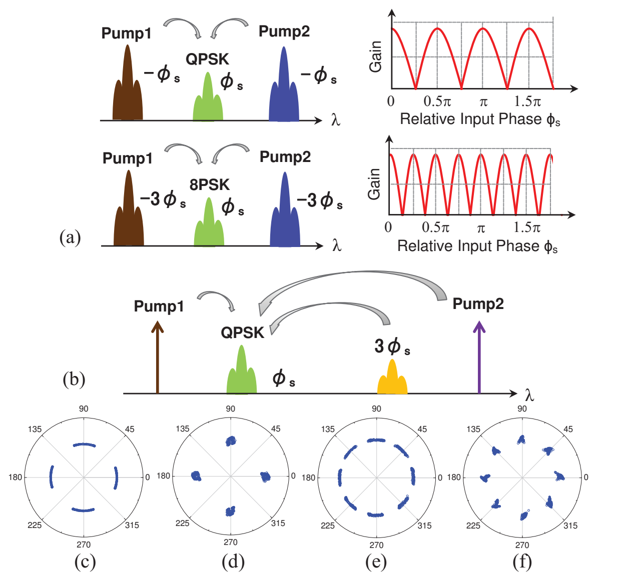


Fig. 1: (a) Degenerate scheme and transfer function for phase regeneration of QPSK/8PSK. (b) Non-degenerate scheme for phase regeneration of QPSK. (c) Non-regenerated QPSK (25Gbaud) with phase noise. (d) Phase-regenerated QPSK via degenerate scheme. (e) Non-regenerated 8PSK (25Gbaud). (f) Phase-regenerated 8PSK via degenerate scheme.

which may be more applicable to high-level PSK. We discussed its configuration in [13]. In contrast, as depicted in Fig. 1(b), the conventional non-degenerate PSA scheme [6] needs a much higher-order idler that may have limited applicability to >8 phase levels. Fig. 1(c-e) show simulated constellation diagrams of 25-Gbaud/s QPSK and 8PSK at PSA input (non-regenerated) and PSA output (regenerated). For 8PSK, input phase noise varies with a range of $21.6^0$ and a standard deviation (STD) of $7.6^0$. Output phase noise is squeezed to STD of $2.4^0$. For QPSK, input noise varies with a range of $36^0$ and STD of $12.1^0$. Output STD is reduced to $3.6^0$.

As shown in Fig. 2, we also experimentally investigated a polarization-diversity PSA structure to verify phase regeneration of DP-BPSK/QPSK [14]. A PPLN crystal is used in PSA stage, neglecting the need for SBS suppression. In Fig. 3(a), phase noise on BPSK/QPSK is reduced after regeneration for both polarizations. Fig. 3(b) shows improved BER by 3.6 dB and 0.4 dB OSNR at BER of 1e-3.

978-1-4799-7468-9/15/$31.00 ©2015 IEEE 

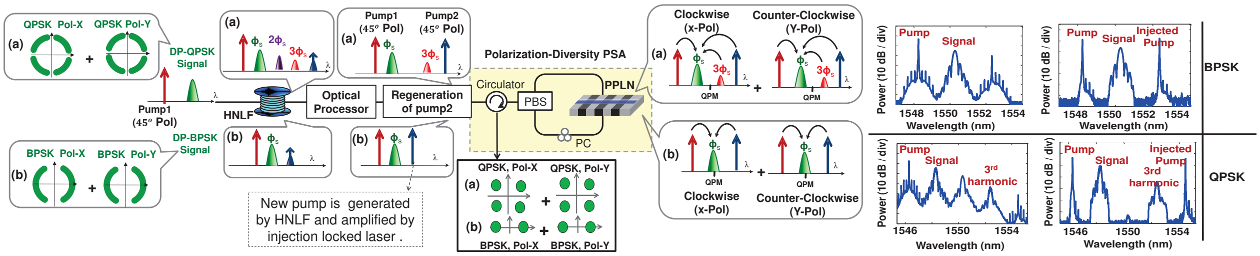


Fig. 2: Conceptual diagram of phase regeneration of dual-polarization signals by using a polarization-diversity PSA: (a) QPSK and (b) BPSK. Note that a non-degenerate scheme is applied to QPSK while a degenerate scheme is applied to BPSK. Right figures show the experimental optical spectra.

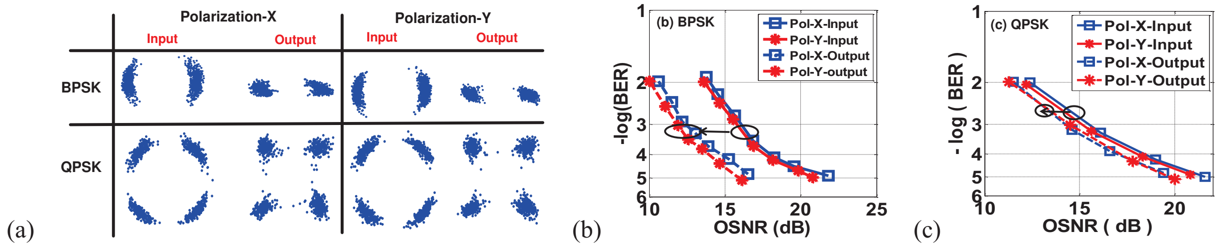


Fig. 3: Experimental results of DP-BPSK/QPSK regeneration. (a) Constellations of both polarizations. (b) BER measurements of DP-BPSK signals. (c) BER measurements of DP-QPSK signals.

## III. Regeneration of Optical Amplitude Noise

A non-PSA-based bit-rate-tunable phase and amplitude noise mitigation approach was experimentally verified [15]. In this approach, phase quantization was achieved by combining the differentially-delayed signal and its conjugated third in a PPLN and amplitude saturated using a fiber OPA, which can avoid the need for phase stabilization, but which modifies the signal encoding [16]. Fig. 4 shows the constellation diagrams of a noisy input 30Gbaud QPSK, phase quantizer output, and amplitude squeezer output. The phase quantizer significantly reduces phase noise and δφ is decreased by ~50% in Fig. 4(a). At the phase quantizer output, phase noise is partially converted to amplitude noise and δρ is increased by ~70%. This amplitude noise is successfully suppressed by the amplitude squeezer, and δφ and δρ are decreased by ~40% and ~16%. The EVM between the input signal and amplitude squeezer output is decreased by ~36%. Fig. 4(b) shows another example for which the phase quantizer is capable of suppressing high levels of phase noise; however, partial phase noise is converted to amplitude noise which can be squeezed in amplitude squeezer operated in saturation regime. We continue investigating this scheme's scalability to multi-level QAM signals (e.g., 8QAM/16QAM) [17].

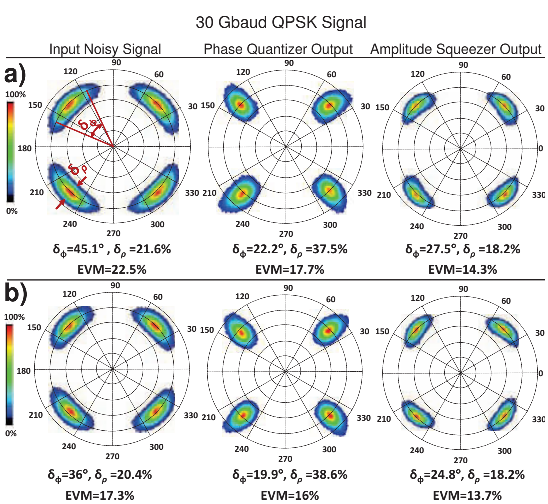


Fig. 4: Input/output constellation diagrams of phase noise mitigation for 30 Gbaud (a, b) QPSK signals impaired by different values of phase noise.

## IV. Conclusion

PSA has obtained lots of interest since it may provide the functionalities of optical regeneration of phase and amplitude noise as well as optical low-noise amplification and so on. Many research teams, including us, have been working on overcoming the crucial challenges in order to turn PSA into a practical tool. This paper highlighted our recent research work including optical phase regenerator for multi-level PSK, a polarization-diversity PSA for SP/DP formats, and an OPA based amplitude regenerator. We expect that more novel solutions are required to overcome the remaining limitations.

We would like to acknowledge the support of NSF and CIAN.

## References


[1] M. Vasilyev, Optics Express 13(19), 7563 (2005).
[2] Z. Tong et al., Nature Photonics, 5, 430 (2011).
[3] S. L. I. Olsson et al., OFC'2014, paper Th.1.H.3 (2014).
[4] T. Umeki et al., Optics Express 22(3), 2473 (2014).
[5] R. Slavik et al., Nature Photonics 4, 690 (2010).
[6] J. Kakande et al., Nature Photonics 5, 748 (2011).
[7] M. Gao et al., ECOC'2013, paper We.3.A.5 (2013).
[8] A. D. Ellis, OFC'13, paper OW4C1 (2013).
[9] T. Ritcher et al., ECOC'2013, paper We.3.A.2 (2013).
[10] T. Roethlingshoefer et al., Optics Express 22(22), 27077 (2014).
[11] J.-Y. Yang et al., ECOC'2012, paper P.130 (2012).
[12] Y. Akasaka et al., OECC'2013, paper ThO3-3 (2013).
[13] J.-Y. Yang et al., ECOC'2013, paper P.3.9 (2013).
[14] M. Ziyadi et al., CLEO'2014, paper Stu2J.3 (2014).
[15] A. Mohajerin-Ariaei et al., ECOC'2014, paper P.3.20 (2014).
[16] J. Touch, et al. USC/ISI Tech. report ISI-TR-690 (2014).
[17] Y. Cao et al., OFC'2015, paper W2A.49 (2015).