Signal Regeneration Techniques for Advanced Modulation Formats

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Abstract: We review recent results on all-optical regeneration of phase encoded signals based on phase sensitive amplification achieved by avoiding phase-to-amplitude conversion in order to facilitate the regeneration of amplitude/phase encoded (QAM) signals.

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1. Introduction

Phase noise introduced during transmission, which originates both from optical amplifiers and nonlinear interactions between channels, represents a significant limiting factor to data transmission when advanced modulation formats such as (differential) phase-shift keying, (D)PSK, or quadrature phase shift keying, QPSK, are used [1]. Consequently, the development of all-optical techniques capable of eliminating phase (and ideally amplitude as well) noise from multi-level phase signals is of great interest.

Phase regeneration can be divided into two broad categories: direct regeneration, which operates on the premise that a signal has already been degraded in phase, and therefore signal quality can only be improved by suppressing these phase perturbations; and indirect regeneration, which acts by suppressing amplitude fluctuations which could seed phase noise after subsequent transmission (so called phase preserving amplitude regeneration). However, the latter process must not create significant added phase noise, to make it worthwhile. Direct regeneration can be classified either as format conversion based regeneration, which relies on optical techniques to convert the optical PSK signal to one or more OOK signals before regenerating its amplitude (without the requirement to be phase-preserving) and converting it back on to the phase of a noise-free optical carrier [2], or phase sensitive amplification (PSA) based regeneration, which has been widely recognized as an effective way to regenerate phase-encoded signals thanks to its phase squeezing capabilities [3-6]. PSA-based regeneration of any M-ary PSK signal (where M is the number of phase levels used) can be achieved through a careful coherent addition of the (M-1)-th phase harmonic of the signal with the signal itself via four-wave mixing (FWM) in highly nonlinear fibers (HNLFs) [5,6] or multi-stage frequency mixing in periodically-poled lithium niobate (PPLN) waveguides [7], such that the signal phase transfer function takes the form of a staircase function. We will refer to this scheme as a single-harmonic PSA system. However, despite successfully regenerating phase, such systems tend to exhibit a strong phase-dependent gain, thereby partially converting phase noise into amplitude noise unless gain saturation is achieved, consequently grossly limiting the benefit of the regeneration in the first instance, especially if multi-level amplitude and phase shift keyed signals, such as quadrature amplitude modulation (QAM) signals, are to be regenerated.

We have recently proposed and experimentally demonstrated a simple modification to this scheme to suppress such phase-dependent gain, whilst maintaining good phase squeezing capability [8,9]. This can be achieved by mixing the (M-1)-th and the –(M+1)-th phase harmonics together with the original signal. We will refer to this scheme as a dual-harmonic PSA system.

In this presentation, we will discuss the principle of the dual-harmonic PSA system and review the key results obtained so far, highlighting the benefit of this scheme in long-haul fiber optic links especially when QAM signals are transmitted.

2. Dual harmonic PSA scheme

In the conventional PSA scheme, multiple FWM processes (usually in HNLFs) are simultaneously exploited: (i) generation of new harmonics with phases bearing integer multiples of the original signal and (ii) coherent addition of two of them through a dual-pump non-degenerate PSA, see Fig.1, to obtain a signal transfer function as follows:

$$Ae^{i\theta(t)} \propto e^{i\phi(t)} + m_1 e^{-i(M-1)\phi(t)} \ , \quad (1)$$

where A and $\theta(t)$ are the output signal electric field amplitude and phase, respectively, $\phi(t)$ is the input phase and m_1 is the phase harmonic weight. Considering M=4 (i.e. 4-PSK signal being QPSK), this function can be achieved by coherently mixing the original signal with its conjugated 3rd (M-1) phase harmonic. An example of experimentally measured and simulated transfer function that corresponds to this case is reported on the right hand side of Fig.1.

In the new proposed scheme, the same FWM processes are used, but the coherent addition happens among three waves, the signal and two phase harmonics, see Fig.2. The signal transfer function is then modified as follows:

$$Ae^{i\theta(t)} \propto e^{i\phi(t)}+m_2e^{-i(M-1)\phi(t)}-m_2e^{i(M+1)\phi(t)} \quad . \quad (2)$$

The opposing signs in harmonic weights cause the amplitude response of the harmonics to interfere destructively, while their phase responses combine constructively. This maintains a similar phase staircase transfer function as in the single harmonic system, while the amplitude response as a function of input phase flattens. Considering again the QPSK example, this can be achieved by coherently mixing the original signal with its conjugate 3rd and non-conjugated 5th (-(M+1)) harmonics. An example of an experimentally measured and simulated transfer function is reported on the right hand side of Fig.2. Full system-level simulations comparing the performance of single and dual-harmonic PSA designs on three modulation formats (QPSK, 8-PSK and star 8-QAM) have shown that the BER can be reduced by as much as 2 orders of magnitude after regeneration in the middle of the link [8].

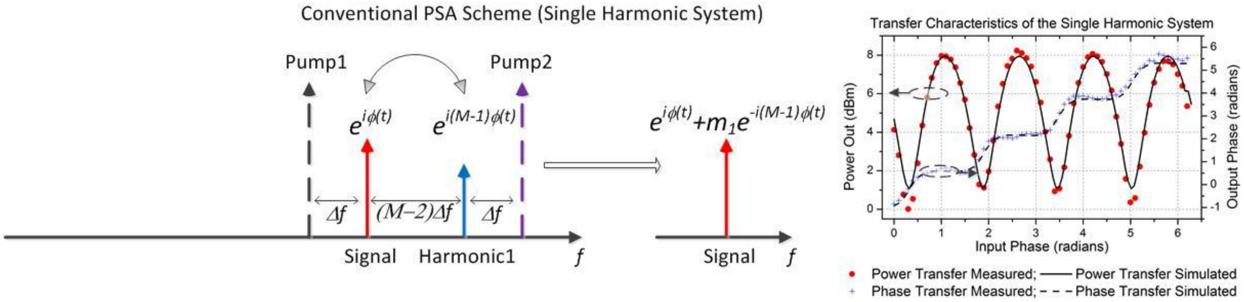

Fig. 1: Single-harmonic PSA scheme operation principle and an example of corresponding measured (red circles and blue crosses) and simulated (solid and dashed lines) signal transfer functions (for pump powers of 17.4dBm, signal power of 6.4dBm and m_1=0.38).

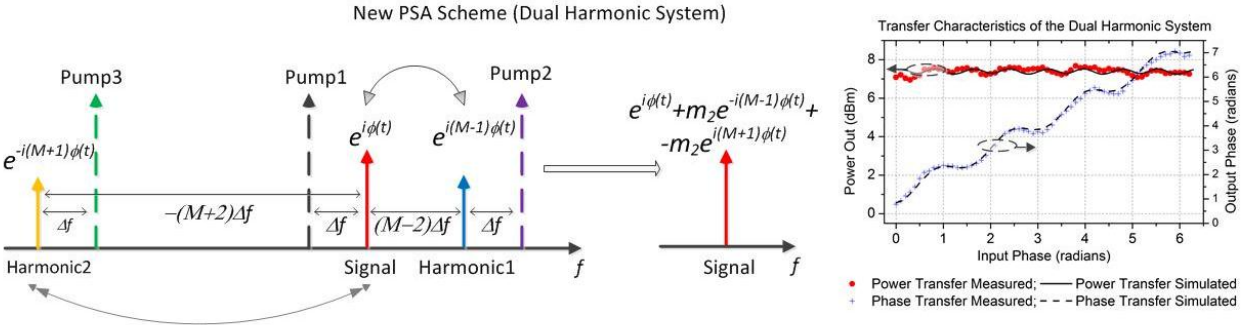

Fig. 2: Dual-harmonic PSA scheme operation principle and an example of corresponding measured (red circles and blue crosses) and simulated (solid and dashed lines) signal transfer functions (pump powers of 15.3dBm, signal power of 7.3dBm and m_2=0.14).

3. Conclusion

We have reviewed a new phase regeneration scheme based on PSA without significant phase to amplitude conversion achieved by mixing two phase harmonics of a M-ary PSK signal with the signal itself.

4. References

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