# Phase regeneration of optical signals

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***Abstract*- We present recent advances in phase-sensitive amplification technology and its application to the regeneration of phase-encoded signals. Using a combination of parametric effects in fibers and optical injection locking of lasers, it is possible to observe phase regeneration in signals with multiple levels of phase encoding.**

## I. INTRODUCTION

Signals travelling over long transmission distances in an optical fiber generally suffer from noise, which is introduced both directly from the optical amplifiers included in the transmission link, as well as from the nonlinear interaction between signals co-propagating in the same fiber. Signal regenerators are therefore required to clear the transmitted signals from the accumulated noise and condition them before they can be re-transmitted. Signal regeneration is currently performed in commercial systems using optical-electrical-optical (O/E/O) conversion; such regenerators include a full receiver and transmitter per optical channel. However, considerations relating to the energy and cost efficiency of O/E/O systems often make all-optical solutions attractive. The use of optical nonlinearities in fibers has long been considered for these purposes. A notable example is the Mamyshev-regenerator which employs self-phase modulation in an optical fiber followed by spectral filtering in order to regenerate intensity modulated signals [1]. However, it is the regeneration of phase-encoded signals that is becoming ever more interesting in modern high-speed transmission systems, where the use of such modulation formats is favored for the resilience they offer to transmission-induced impairments and their prospect for achieving a high spectral efficiency [2]. In this case, phase noise represents a significant source for errors, since it can directly distort the value of the transmitted symbols.

Parametric effects in fibers, such as four-wave mixing, are particularly interesting in this respect, since unlike self-/cross-phase modulation, they can support phase modulation formats. In addition, parametric effects can allow phase-sensitive operation, i.e. it is possible to control the efficiency of the mixing process between two or more waves by adjusting the relation between their optical phases. In the work described here, we demonstrate the regeneration of phase-encoded signals by making use of phase-sensitive amplification (PSA) based on parametric processes in highly nonlinear optical fibers (HNLFs). Suitable combinations of such processes allow even the regeneration of signals with multiple levels of phase encoding, by effectively quantizing the phase at the output of the system to a corresponding number of levels.

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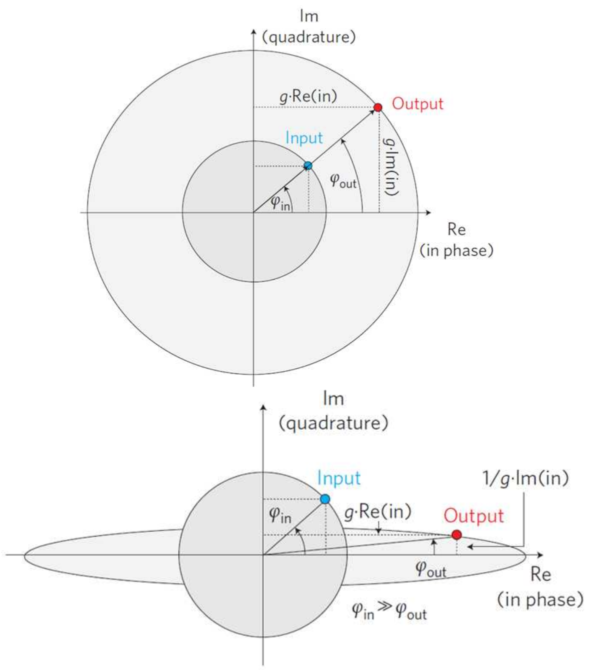


Figure 1. Phase-insensitive (PI) versus phase-sensitive amplification (taken from [3]).

## II. BASIC PRINCIPLE

The difference between conventional (PI) and phase-sensitive amplification can be conceptually understood by the diagram shown in Fig.1. Whereas in a PI amplifier the intensity of a signal experiences amplification regardless of its phase, in a PSA only those components whose phase is aligned to a certain reference value experience amplification. Any out-of-phase components can be made instead to experience de-amplification by the same amount. The significance of this effect, e.g. for the regeneration of (differential) phase shift-keyed ((D)PSK) signals becomes apparent in the diagram, where only those signals with a phase aligned along the 0-π axis are amplified, whereas any departure from this axis (representing phase noise here) results in de-amplification.

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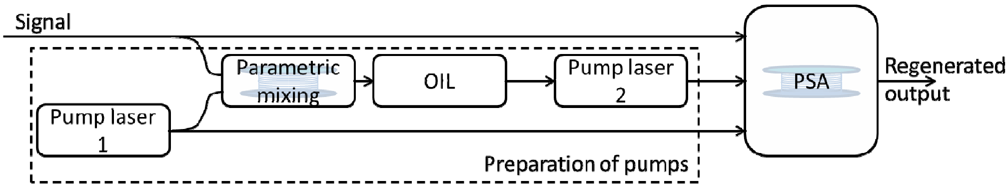


Figure 2. Block diagram of the PSA-based regenerator.

Parametric effects in optical fibers have long been studied for their application in PSA operation (see e.g. [4]), and indeed the proof-of-principle of regeneration of DPSK signals based on these effects has been demonstrated [5]. The complexity in the operation of PSA-based regenerators lies mainly on the fact that all of the waves involved in the process need to be phase-locked relative to each other. This requirement has usually been addressed in laboratory demonstrations by generating all of the signals together, e.g. in a separate PI optical parametric amplifier (OPA). In contrast, the configurations described below allow the pump sources to be independent of the signal, therefore the PSA-based system can be located at a remote node, as required in regeneration applications.

## III. Experiments

A generic block diagram of our regenerator is shown in Fig.2. The PSA in the regenerator is a dual-pump fiber OPA. The two waves acting as the pumps are generated locally, and are phase-locked relative to each other and the incoming signal by means of an additional PI-OPA stage. This mixes the light from Pump laser 1 and the signal and generates a tone which is phase-locked to these two and has the same wavelength as Pump laser 2. The parametrically generated tone is then used to optically injection-lock (OIL) Pump laser 2, which is consequently also phase-locked to the other two waves [3, 6]. A programmable phase filter controls the phase of the signal at the PSA input relative to that of the two pumps, thereby controlling the gain and phase response of the output signal. Gain saturation of the PSA ensures that both amplitude- as well as phase-regeneration is achieved. The technique benefits crucially by the use of dispersion-shifted HNLFs with a high stimulated Brillouin scattering threshold as well as from narrow linewidth laser sources that are used as the low-noise pumps for the PSA.

By selecting the suitable harmonic from the parametric mixing process (Fig.2) to be used as the tone to be injected to Pump laser 2, it is possible to control the number of phase levels allowed at the regenerator output, thereby adjusting the system operation for different modulation formats [7]. This is demonstrated in Fig.3, which shows example constellation diagrams for operation either with DPSK or differential quaternary phase shift keying (DQPSK) signals. The diagrams show that even large amounts of phase noise can be mitigated.

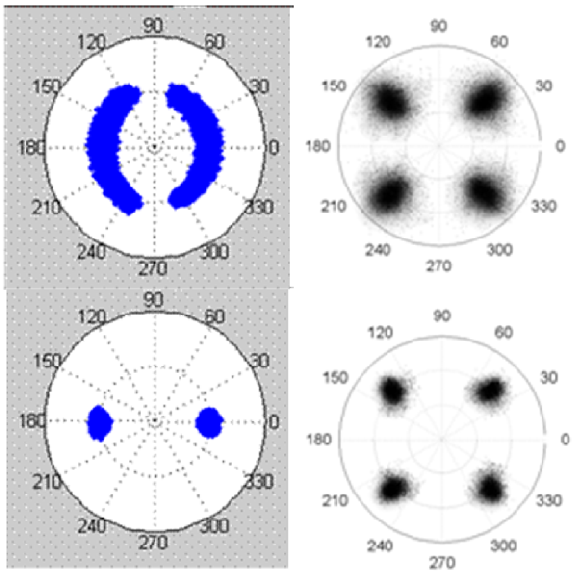


Figure 3. Constellation diagrams at the input (top) and the output (bottom) of the regenerator for DPSK (left) and DQPSK (right) signals.

## IV. Conclusions

PSA techniques represent a powerful signal processing tool for phase-encoded signals. Important developments in fiber and laser technologies allow for the implementation of practical systems.


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