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Phase-Sensitive Fiber-Optic Parametric Amplifiers and their Applications

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Abstract: The basics and recent progress in nonlinear fiber-based phase-sensitive parametric amplifiers is discussed. In addition, their potential use as in-line amplifiers, resulting in significant link performance improvement potential, is highlighted.

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1. Introduction

Phase sensitive amplification (PSA), relying on the $\chi^{(2)}$ and $\chi^{(3)}$ (four-wave mixing, FWM) nonlinear process can be implemented with different gain medium (e.g. optical fiber [1], periodically-poled lithium-niobate [2] or silicon [3]) and in different implementations (e.g. interferometric, non-interferometric, degenerate or non-degenerate idler, and with one or two pump waves). Common to all implementations is that the relative phase relation among all involved waves in the PSA dictates the performance in terms of gain as well as noise figure (NF). Perhaps the most intriguing property is the possibility to approach a 0 dB NF for the in-phase component [4]. In our work, we have primarily focused on the use of highly nonlinear solid core fibers as gain medium in phase-sensitive fiber-optic parametric amplifiers (PS-FOPA) implemented in a single pump non-degenerate idler configuration, thus having three input waves; pump, signal and idler. In 2010, we demonstrated the lowest NF reported to date at high gain (1.1 dB at 26 dB gain) of any optical amplifier [5]. Here we will discuss some fundamental properties of PSA and their potential use in various applications, most notably in optical transmission links.

2. PSA concepts

Two key building blocks of FOPAs are the specifically designed highly nonlinear fiber (HLNF) that should not only have low dispersion near the operating wavelength but also low attenuation and be easy to splice to other types of fibers and the high power single-frequency pump laser with low intensity noise and small spectral linewidth. For PS-FOPAs, in addition, idler(s) satisfying appropriate phase conditions have to be generated and, in practice, optical phase locked loops (PLL) are often needed to maintain optimal conditions in presence of environmental disturbances. Figure 1 shows conceptually a single-pump implementation of a PS-FOPA.

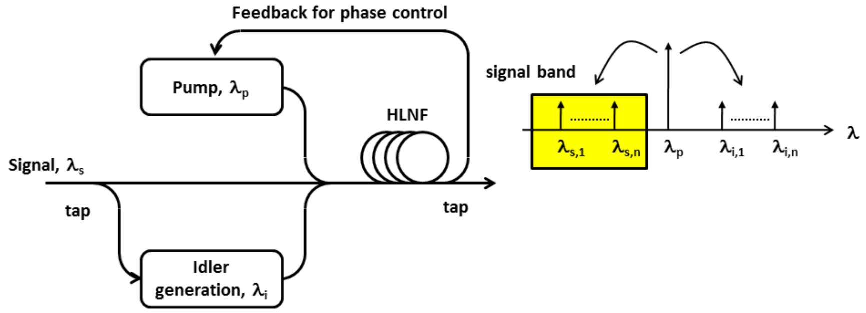

Fig. 1. Conceptual schematic of a single-pump, two-mode PS-FOPA in a non-degenerate-idler configuration.

Here, the signal and idler wavelengths are symmetrically located around the pump, the so-called non-degenerate-idler configuration in which multiple signal-idler pairs can interact with the pump making the scheme compatible with the use of several DWDM channels. A fraction of the signal could be tapped off and used as a seed to generate an appropriate idler wave that must not only have the correct optical phase but also contain the encoded data from the signal. The control of the relative phase relation among the different waves can be implemented with a feedback control loop (by e.g. maximizing the gain) as illustrated in the figure. The phase sensitive amplification is dictated by the relative phase among the interacting waves. The input/output optical field relation of a FOPA at perfect phase matching is given by [6]:

$$\begin{bmatrix} A_{s,out} \\ A^*_{i,out} \end{bmatrix} = \begin{bmatrix} \cosh(\gamma P L_{eff}) & i\sinh(\gamma P L_{eff}) \\ -i\sinh(\gamma P L_{eff}) & \cosh(\gamma P L_{eff}) \end{bmatrix} \begin{bmatrix} A_{s,in} \\ A^*_{i,in} \end{bmatrix} \tag{1}$$

Here, γ is the nonlinear coefficient of the fiber, P is the pump power, and L_{eff} is the effective length of the fiber. Clearly, in the case of no idler present at the input, one will be generated, and the signal phase is conserved. Solving this equation, assuming for simplicity that the signal and idler powers are equal, one finds the expression for signal gain as:

$$G_s = 1 + 2\sinh^2(\gamma P L_{eff}) + 2\sinh(\gamma P L_{eff})\cosh(\gamma P L_{eff})\sin(\theta_{rel}) \tag{2}$$

The quantity θ_{rel} is the relative phase among the three waves. In the case of figure 1 it is given by $\theta_{rel} = 2\phi_p - \phi_s - \phi_i$. It is seen from this equation that only signal phases satisfying $\theta_{rel} = \pi/2$ are fully amplified while those resulting in $\theta_{rel} = -\pi/2$ will be parametrically attenuated. By blocking the idler wave, the gain becomes phase insensitive (θ_{rel} is always zero, assuming perfect phase matching, as a local idler wave with $\phi_i = 2\phi_p - \phi_s$ is generated within the fiber) and is then simply given by:

$$G_s = 1 + \sinh^2(\gamma P L_{eff}) \tag{3}$$

It can be noted that under the condition of high gain, in this case the gain is 6 dB smaller than in the PS-FOPA phase-adjusted for maximum gain.

3. PSAs as in-line amplifiers in transmission links

Clearly, if 0 dB NF amplifiers could be used as in-line amplifiers, it would be significantly beneficial as the overall transmission link NF would improve. In fact, it has been shown that the link NF can be improved by up to 6 dB compared with the use of ideal EDFA in-line amplification, if implemented as a cascade of a copier stage (serving to generate idlers containing also the signal information) and assuming that the noise from the copier can be neglected in the output signal (which is the case for long-haul transmission). The link NF is thus entirely limited by the span losses. For a fixed modulation format, this concept allows the signal power in the link to be reduced a factor of four compared with the traditional approach, thus reducing the degrading impact of transmission fiber nonlinearities.

Figure 2 illustrates the concept that we have proposed [7]. The copier can be straightforwardly implemented by using the FWM process e.g. in a HNLF and requires no active control. It should be understood that the only purpose of the idlers is to facilitate near-noiseless amplification of the signals in the in-line PSAs and once the signals and idlers have reached their destination, only the signal waves are recovered with traditional direct detection or coherent detection receivers. The figure also illustrates some details in terms of the in-line PSA implementation. Before all waves can be input to the HLNF, the cw pump wave needs to be regenerated, which can be achieved with injection locking in which a slave laser tracks the phase and frequency of the pump wave [8]. A PLL is also needed at this point to ensure proper phase relation. The signal and idler waves can be separated from the pump wave and combined with the amplified wave from the slave laser with low-loss WDM couplers ensuring that the "black box" NF of the PSA is kept very small.

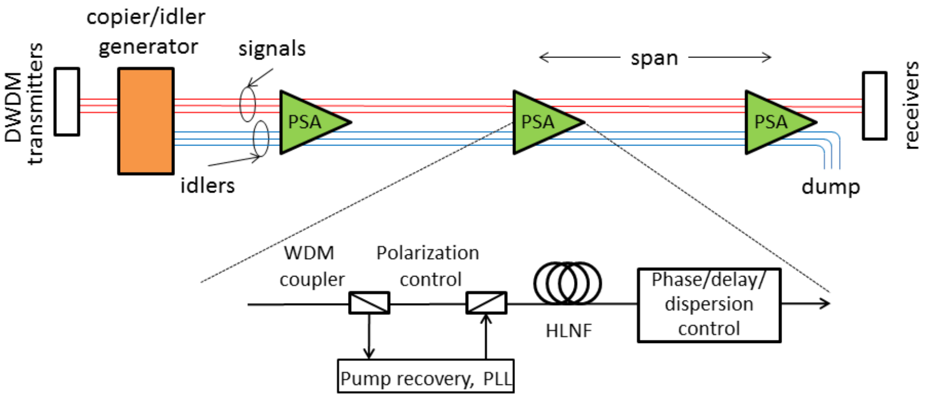

Fig. 2. Illustration of the use of PSA in DWDM transmission links.

There is also a need for periodic (possibly at each PSA stage) dispersion, time delay, polarization, and static phase control among the waves, but this can be implemented at the PSA output, thus not impacting the NF. In addition to being compatible with free running DWDM lasers, this scheme is suitable for advanced modulation formats, e.g. m-QAM, which is a result of the idler being conjugated with respect to the signal [5, 9].

In terms of benefits with this approach, the 6 dB link NF improvement, which was confirmed experimentally by emulating the transmission fiber span loss with a lumped loss (thus eliminating the need for pump recovery) in [9], can be used to increase overall reach by a factor of four or increase the span length, or increase the number of bits/symbol in multilevel modulation formats by approximately 2 b/s per polarisation (as the OSNR needed increases approximately by 3 dB for each added b/S [10]) or a combination of the above. It should also be pointed out that the above scheme is compatible with the use of distributed Raman amplification which, together with lumped PSAs would form a very low link NF. Recently, we demonstrated a direct comparison of a PS-FOPA versus an EDFA as preamplifier in a real fiber transmission experiment over 80 km with 10 GBd QPSK signals [11]. The results show approximately 2 dB better sensitivity for the PSA when comparing with the EDFA in which two optical WDM channels carrying identical data were detected simultaneously (to emulate the PSA case of signal + idler carrying same data). Our experiments further suggest a large degree of tolerance against nonlinear impairment caused by self-phase modulation in the transmission fiber [12].

As seen in figure 1, only a certain fraction of the available low-loss transmission band in fiber is available for signal transmission due to the need for idler transmission, but PSAs allows for an interesting trade-off between bandwidth usage and noise performance. In addition, FOPAs have been demonstrated to have an effective gain bandwidth larger than 100 nm [13], thus by far surpassing the available bandwidth in EDFAs.

4. Challenges

There are several challenges to overcome before the full prospects of phase-sensitive FOPAs can be understood and implemented in real systems. In many experimental demonstrations, active mitigation of stimulated Brillouin scattering (SBS) by use of pump phase modulation is needed. This degrades the performance of FOPAs in several ways and should ideally be avoided. FOPAs are inherently single polarization amplifiers; however, in principle this can be resolved by using dual-orthogonal polarization pumping. Injection-locking is a candidate for optical carrier recovery and our recent results on this aspect are very promising.

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