Phase-Sensitive Amplifiers in Optical Transmission System

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Abstract *We first introduce the fundamental concepts of phase-sensitive parametric amplifiers and their implementation with highly nonlinear optical fibers. We then discuss their ability to amplify without excess noise and mitigate nonlinear transmission fiber impairments resulting in enhanced performance in fiber- and free-space communication links.*

Introduction

Optical communication link performance is fundamentally limited by noise. In addition, in optical fiber systems, the transmission fiber nonlinearities impose limitations that are very difficult to mitigate. Therefore, the signal power into each span of a link should be optimized such that the degradations caused by noise and nonlinearity are of similar importance. Optical amplification is essential in all long-haul fiber systems, and erbium-doped fiber amplifiers (EDFA) are widely used with the purpose to maintain a large enough signal-to-noise ratio (SNR) throughout the link. However, the noise figure (NF) of EDFAs and all other known phase-insensitive amplifiers such as Raman- and semiconductor amplifiers is limited to at best 3 dB at high gain, which results in generation of excess noise. Phase sensitive parametric amplifiers (PSA) are, however, an exception to this and can fundamentally reach NF = 0 dB[1], with 1.1 dB being experimentally demonstrated[2]. In[3], it was shown theoretically that the use of a fiber link relying on distrusted PSA provides the best possible link noise figure. The basis of the operation of PSAs is either the second-order susceptibility, $\chi^{(2)}$ (three-wave mixing) or the third-order susceptibility $\chi^{(3)}$ (four-wave mixing, FWM) in a material exploiting a nonlinear process where the energy of incoming photons is not changed (elastic scattering). The former process has been implemented in e.g. the $LiNbO_3$ platform[4], while the latter in the highly nonlinear optical fiber (HNLF) platform. Recent reviews of optical-fiber-based PSAs and their applications can be found in[5,6]. There are different implementations (e.g. interferometric, non-interferometric, degenerate or non-degenerate, single- or dual-frequency pumps). Common to all implementations is that the relative phase relation among the involved waves dictates the performance in terms of gain as well as noise figure (NF).

PSA basics

We consider here $\chi^{(3)}$-based amplifiers implemented with HLNFs. Let us start by first considering a phase-insensitive implementation of a parametric amplifier (PIA) which in many ways are similar to the phase-sensitive version of such amplifiers. While PIAs also rely on FWM (which is phase sensitive), only a pump and signal are present at the input. The resulting gain is, however, independent of the signal and pumps phase, while a conjugate copy of the signal wave, the idler, is created in the HNLF with a relative phase to sustain the gain. The gain can be large with a broad gain spectrum under proper conditions; most importantly, the phase-matching condition, which implies that the group velocity dispersion should be small in the fiber (and slightly anomalous at the pump wavelength). PIAs and PSAs can be pumped with a single- or dual-pump configuration, the latter being capable of providing flat and large gain bandwidth. Fig. 1 shows calculated gain spectra for a dual-pump PIA.

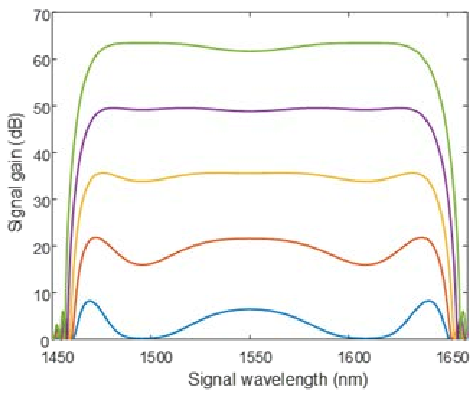

Fig. 1: Calculated gain spectra of a fiber-based parametric amplifier. The pump power ranges from 0.2-1 W (bottom to top) in a 500 m long HNLF with a nonlinear coefficient of 16 $W^{-1}km^{-1}$. The average wavelength of the two pumps was 0.3 nm above the zero-dispersion wavelength of the HNLF.

In practice, polarization-mode dispersion, higher-order dispersion, stimulated Raman scattering, dispersion variations along the fiber, and amplified spontaneous emission will all degrade the performance to some extent, but a bandwidth of significantly more than 100 nm is feasible. A remarkably simple approximate expression of the peak gain is:

$$G_{peak} = \frac{1}{4} e^{(4\gamma\sqrt{P_{P1}P_{P2}}L)} \quad (1)$$

where P_{p1} and P_{p2} are the pump powers, γ and L are the nonlinear coefficient and effective length of the HNLF, respectively.

For PSAs, both a signal and idler wave are present at the input, and the peak gain is 4 times higher, a result of the coherent superposition of the signal and idler waves. The noise, however, adds incoherently and the resulting signal SNR is actually improved by 6 dB after amplification compared to when using an EDFA, which is equivalent to a NF = ½. However, as the idler needs to be present at the input as well, this results (in the case of equal signal and idler power) in a quantum-limited NF = 1 (0 dB).

While parametric amplifiers are compatible with DWDM signals, it should be pointed out that in most applications, due to the presence of the idlers, only about 50% of the optical gain spectrum is available for the signals, which may be considered as a loss of spectral efficiency (note the discussion below, however). As FWM is a polarization-dependent process, so are PSAs, and methods to deal with this may need to be considered, depending on the application in mind, e.g. using polarization-diversity or vector-PSAs[7].

We now briefly discuss the difference in capacity of a conventional system with PIAs, e.g. EDFAs and one based on PSAs, keeping in mind the need for the idler in PSA links which do not carry any additional information. The relative capacity of these can be expressed (ignoring nonlinear transmission impairments) as:

$$\frac{C_{PSA}}{C_{PIA}} = \frac{1\log_2(1+4SNR)}{2\log_2(1+SNR)} \quad (2)$$

Here, SNR is the SNR in the PIA-based link. For PSAs, the signal SNR is 4 times higher and the presence of the idler is accounted for by the factor of 2 in the denominator. At very high SNR, the PSA will suffer from a factor of 2 reduction in capacity relative to that of PIA-based systems (since the log-terms then are then approximately equal). However, at very low SNR, $\log_2(1+SNR) \cong SNR/(\ln 2)$ and what is outside and inside of the logarithm are equally important for the capacity. Therefore, in this regime, PSAs have a up to twice the capacity of PIAs. Fig. 2 illustrates this where it is also indicated that the PSA and PIA system capacities are equal at SNR_{PIA} = 3 dB, or equivalently at a spectral efficiency of 1.58 bit/s/Hz.

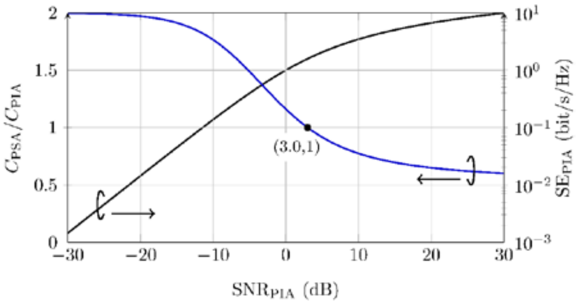

Fig. 2: Relative capacity of PSAs vs. SNR

PSAs in fiber communication links

PSAs are useful both as in-line amplifiers and as preamplifiers in receivers. Fig. 3 shows how this could be implemented. At the transmitter, idlers containing phase conjugated copies of the signals can be generated in an HLNF using FWM. Once the signal has reached its destination, the idlers are not needed anymore.

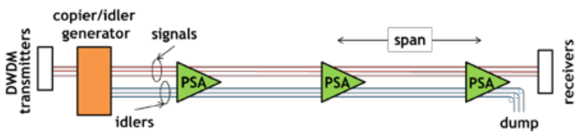

Fig. 3: Schematic of PSA-based fiber link.

PSAs can be used to extend the reach in a fiber communication system in two ways: 1) Maintaining a higher SNR throughout the link due to the low NF. This has been shown to give a reach extension up to 4 times (i.e. a link NF increase of 6 dB) in the linear transmission regime of a many-span link. 2) As the signal and idler propagate together in the fiber, they experience the same amount of self-phase modulation (SPM) which can partially be cancelled out in the process of coherent superposition in each of the in-line PSAs. This can thus result in a reach extension much larger than 4 times if operated in the nonlinear regime (which of course is normally the case)[8]. An example[9] of experimental results illustrating the nonlinearity mitigation capability is shown in Fig. 4. Here, the maximum single-span loss is determined (BER <10^{-3}) as a function of launched power. We note that for a 4-QAM modulation format, the optimum launch power is 2 dB higher with PSAs than with conventional amplifiers resulting in a 7.7 dB larger allowable span loss, 6 dB of which is related to the lower noise. In fact, the relative benefit of the PSA increases with higher modulation order as can be seen in the figure showing the 64-QAM results. The reason is that PSAs are particularly effective in mitigating smaller nonlinearities, while higher-level formats are more sensitive to nonlinearities.

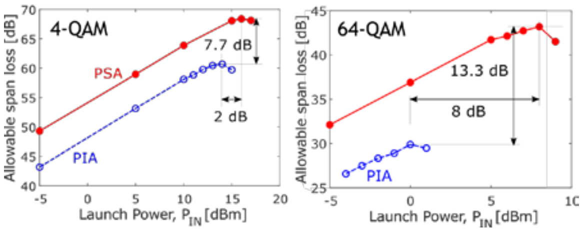

Fig. 4: Allowable single span loss vs. span input power, comparing PSA and PIA at 10 Gbaud with different modulation formats.

PSAs in free-space communication links

In very long free-space links (e.g. to the moon and beyond), the main transmission channel impairment is the beam-diffraction-induced channel loss. As the losses can be very high, it is not unlikely that the received SNR can be below 3 dB, with PSAs thus providing the best capacity. Here, dispersion and nonlinearities are not important, making PSA-based links simpler to implement compared to their fiber system counterpart. PSAs can here serve as ultra-low noise pre-amplifiers in cohrerent receivers. In these links, the optical spectral efficiency (SE, expressed in bits/s/Hz or bits/symbol) is not necessarily a critical aspect. However, the *electrical* SE can be a limiting factor (as dictated by the analogue hardware bandwidth) depending on the targeted bit rate and the modulation format used. A schematic of a free-space link with a PSA receiver is shown in Fig. 5.

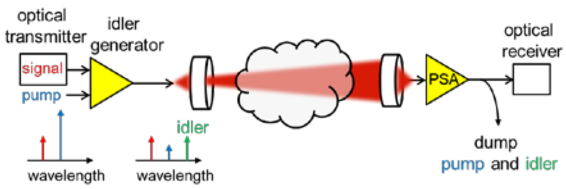

Fig. 5: A PSA-based free-space link

In this example, the needed idler is generated at the transmitter (similar to Fig. 3). While the idler generator causes excess noise, this becomes insignificant relative to the vacuum noise if the channel loss is large enough. The needed CW pump wave for the PSA in the receiver is sent along with the modulated signal/idler waves at a power level much lower than the signal (which is important as it would otherwise impact the power budget) and is recoved at the receiver using injection locking. At the receiver, the PSA amplifies the signal-idler pair, after which only the signal (or the idler) needs to be recovered. This approach provides the best possible coherent receiver sensitivity, and a record ”black-box” sensitivity (bit-error-rate $<10^{-6}$) of 1 photon-per-infomation-bit was recently observed using 4-QAM modulation at 10.5 Gbit/s[10].

Conclusions

Phase-sensitive parametric amplifiers have the unique property of a quantum-limited noise figure of 0 dB. This can be valuable not only in communication systems, but anywhere where noise is a key performance limitation. In optical fiber links, PSA are also capable of mitigating impairments caused by transmission fiber nonlinearities.

Acknowledgements

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