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Transmission Systems With Low Noise Phase Sensitive Parametric Amplifiers

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Abstract *We review and present the recent research on phase-sensititve amplifiers, and describe how they can be used in transmission systems.*

Introduction

With the introduction of the remarkably successful Erbium-doped fiber amplifier (EDFA) in the early 90:s, the role of optical amplification in fiber communications was firmly established. This changed fiber link design in a profound way of making optical, rather than electrical, noise the dominant noise source in amplified fiber links.

The success of the EDFA led to a number of other fiber amplifier technologies being investigated and developed, for example doped-fiber amplifiers based on Thulium, Ytterbium or Praseodymium dopants, or the use of fiber nonlinearities such as Raman scattering or the Kerr-effect. The fiber-optic parametric amplifier (FOPA) is based on the latter, and has a number of unique features. It is unidirectional, it has an ultrafast response, and it has a gain bandwidth determined by the fiber dispersive properties, which thus can be tailored by designing the dispersion. This tutorial will describe the most recent results on parametric amplifiers, with emphasis on *phase-sensitive* operation, with focus on their use in fiber transmission systems.

The Kerr effect and four-wave mixing

Parametric amplification in nonlinear $\chi^{(3)}$ materials like silica fibers is based on the Kerr-effect, which physically means that the refractive index in the fiber increases with the instantaneous intensity of the light. If two waves with different frequencies (ω_1 and ω_2) co-propagate in such a medium they will interfere and create a moving grating, from which a third wave ω_3 may scatter, thereby generating a fourth wave at ω_4 - hence the name *four-wave mixing* (FWM). The fourth wave will be generated at a frequency that is Doppler-shifted from the scattering wave, at a frequency $\omega_4 = \omega_3 + \omega_2 - \omega_1$. For the process to be efficient also the corresponding Bragg condition $\beta_4 = \beta_3 + \beta_2 - \beta_1$ must be satisfied, where β_k are the propagation constants of wave k. This is the classical picture of FWM. The quantum mechanical picture is deceptively simpler: two "pump" photons ($\hbar\omega_2$ and $\hbar\omega_3$) are annihilated and two new photons, "signal" and "idler" ($\hbar\omega_1$ and $\hbar\omega_4$) are created[1]. Photon energy conservation $\omega_2 + \omega_3 = \omega_1 + \omega_4$ corresponds to the Doppler formula, and momentum conservation $\beta_2+\beta_3 = \beta_1+\beta_4$ to the Bragg formula. *Degenerate pumping* ($\omega_2 = \omega_3$), where only a single intense pump is used, symmetrically between the signal and idler wave, is a common special case and the idea behind the copier-PSA scheme discussed below.

Parametric amplification

In order to realize parametric amplification a suitable nonlinear material platform is required, and the most successful so far - in terms of performance - is the highly nonlinear fiber, HNLF. This fiber is compatible with, i.e. can be spliced with low losses to, conventional standard single mode fiber (SMF), but it has around 10 times higher nonlinear coefficient, in addition to low attenuation and dispersion zero around 1550 nm, which makes it an ideal parametric amplifier building block. In order to realize FWM with high efficiency in the conversion of pump power to the signal and idler (which we will henceforth denote *parametric gain*) an intense, continuous-wave (CW), pump is required. The interaction between the three waves, (pump, signal, idler) is modeled by three coupled equations[1–3], that are *phase sensitive*, i.e., depend coherently on the phase difference between the three waves. In the limit of an undepleted pump, the vector $\vec{E}$ of the signal and conjugate idler amplitudes in and out from the parametric amplifier can be written in vector form as $\vec{E}_{out} = K\vec{E}_{in}$, where $\vec{E}_{in/out} = \left(E_{s,in/out} \quad E^*_{i,in/out}\right)^T$, and K is the transfer matrix. Since an equal amount of signal and idler photons are created in the parametric process, the power difference must be conserved, i.e., $C = |E_s|^2 - |E_i|$ must be the same at input and output, which is known as the *Manley-*

Rowe invariant. In matrix from this can be written $C = \vec{E}^H J \vec{E}$, where $J = diag(1, -1)$ is a diagonal matrix. By applying this condition to the transfer matrix K we obtain[4] $K^H J K = J$, from which one may show that K must have the form[5] $K = \begin{pmatrix} \mu & \nu \\ \nu^* & \mu^* \end{pmatrix}$ where μ, ν are complex coefficients related by $det(K) = |\mu|^2 - |\nu|^2 = 1$. If the idler wave is absent, the signal will be amplified a factor $G = |\mu|^2$, which we call the *phase-insensitive (PIA) gain*. This gain is maximized at a specific wavelength, given by the phase-matching condition, and then approximately equal to $G = \cosh^2(\gamma P_p L)$, where γ is the fiber nonlinear coefficient, P_p is the pump power, and L is the fiber length. By using up to a few Watts of CW pump power, parametric gains of 20-40 dB can be regularly achieved[2].

For such intense CW pump powers, the stimulated Brillouin scattering (SBS) needs to be suppressed, which in most cases is done by phase modulating the pump or changing the fiber parameters by applying a temperature or strain gradient[2]. Recently[6] such a strained fiber produced 10 dB of gain, which is the the highest reported parametric gain without pump phase-modulation.

Phase sensitive amplifiers

If both waves (signal and idler) are present the interaction given by the matrix K above is *phase sensitive*, i.e., the two waves will be coherently superposed, as in interferometry. Practically this is difficult to realize, and requires phase-locking between the pump, signal and idler waves. The three waves can be generated by either using a "copier" (as discussed below), as was originally used by Tang et al.[7] or by phase-locked lines from a single laser source by e.g. external modulation, as used in the pioneering work by Bar-Joseph[8]. A two-mode PSA with equal signal and idler powers will experience a maximum (minimum) gain of $G_{max/min} = (|\mu| \pm |\nu|)^2 = \exp(\pm 2\gamma P_p L)$. One can show that in a PSA, one signal quadrature will exhibit a gain G_{max} and the other an attenuation equal to $1/G_{max}$. The phase modulation used to suppress SBS is problematic in such experiments, and may distort observations (especially of the attenuation), but phase sensitive gains of over 30 dB has been observed[9].

Noise in amplifiers

Even before the EDFA became established, the fundamental limits of optical amplification was established in key works by, e.g., Yamamoto & Haus[10], and Caves[11]. On a fundamental level, these limits come from the Heisenberg uncertainty relation between the two quadratures of the optical field, as well as the amplification of vacuum fluctuations. All amplifiers add noise, which seen at the input has a power spectral density of half a photon per mode[12]. For phase-insensitive amplfiers this leads to an added noise that degrades the SNR relative to a shot noise limited input (i.e. a coherent state), so the resulting noise figure becomes $NF_{PIA} \approx 2 - 1/G$, where G is the PIA gain. For a PSA this generalizes to $NF_{PSA} \approx 2 - 1/\sqrt{G_1 G_2}$, where $G_{1,2}$ are the gain for the respective quadratures, but since their product is 1 for the PSA, as we saw above, we have $NF_{PSA} = 1$. In quantum mechanics this is known as *squeezing*, since it maintains the total Heisenberg uncertainty of the coherent state but redistributes the noise between the quadratures[10]. In amplified links, however, the PSA does indeed add noise, but at a lower rate than PIAs,[12] as will be explained next.

The Copier-PSA scheme

A powerful way to realize a PSA transmission link is to generate the idler wave in a parametric amplifier, and "copier" or "idler generator" at he transmitter[7,12,13], as shown in Fig. 1. Then the pump, signal and idler waves will be automatically phase locked to each other, irrespective of the signal phase. This means that an arbitrary modulated signal can be phase-sensitively amplified along the link if all three waves are transmitted, and also, that several signal wavelengths can be used with their corresponding idlers and a common pump[13]. Compared to a PIA, the copier-PSA scheme will provide 6 dB higher gain for the same added noise power[12,13], which is due to the coherent superposition of the two signal waves, whereas the noise around each wave are uncorrelated. In experiments, typically 5.5 dB of sensitivity gain could be realized[13]. Ideally, for a linear amplified link, this should translate to a 4-fold increase of the transmission distance[12]. In connection with this we should also mention the four-mode PSA, from which one expects a 16-fold (12 dB) increase in sensitivity over the PIA, whereas a 10.3 dB gain difference was seen in experiments[14]. The PSA was also used in a demonstration of the highest-sensitivity reported[15] of 10 Gb/s OOK data, reaching a sensitivity of -41.7 dBm for a BER= 10^{-9}.

In practical implementations the copier-PSA

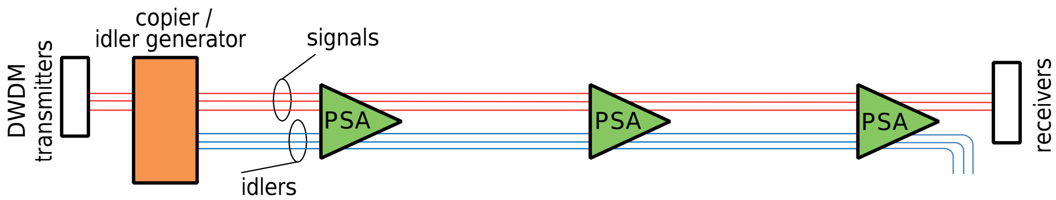

Fig. 1: Transmission system base on the copier-PSA scheme. The idlers are only used as internal modes.

scheme is challenging as it requires full phase synchronization at each amplifier in the link, which require per-span dispersion compensation and phase tracking. The pump recovery requires special attention, and injection locking to a local PSA pump laser has proven successful.

The copier-PSA scheme has one additional benefit, and that is its ability to compensate nonlinear distortions from, e.g., self-phase modulation[16]or nonlinear phase noise[17]. The scheme relies on the fact that the signal and conjugate signal receives conjugated nonlinear phase shifts, that cancel out in the coherent superposition process. An example of 16-QAM constellation is shown in Fig 2.

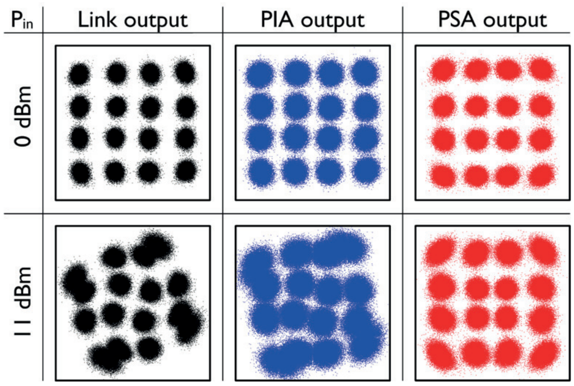

Fig. 2: Linear (upper row) and nonlinear (lower row) transmission of 16-QAM data through a link, and after with PIA/PSA.[16]

Olsson recently demonstrated[18] the first recirculating loop experiment, based on high-gain PSAs in the copier-PSA configuration, that showed and increased transmission distance of around 4 times compared to a PIA-based link. The possibility to tolerate a nonlinear phase shift of 5.8 radians at a BER of 10^{-3}, makes this demonstration one of the most nonlinear transmission experiments ever performed, while also demonstrating the potential of the PSA-based links.

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