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Applications of nonlinear four-wave mixing in optical communication

Peter A. Andrekson

Department of Microtechnology and Nanoscience, Chalmers University of Technology, Gothenburg, Sweden

A R T I C L E I N F O

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A B S T R A C T

In this paper I will briefly review some applications of nonlinear four-wave-mixing in optical fibers and silicon-nitride waveguides. This includes ultrafast all-optical waveform sampling and 'noiseless' phase-sensitive optical amplification which have been demonstrated to enable signal recovery at very low optical powers.

1. Introduction

In the late 1980s and 1990s extensive experimental research was ongoing dealing with the promise of using optical solitons in optical fiber communication links. This was largely based on the instrumental contribution of Akira Hasegawa and Fred Tappert proposing their existence already in 1973 [1]. The reason for the long delay until demonstrating their use in optical fiber links was the lack of suitable optical amplifiers which are needed to sustain the balance between dispersion and nonlinearity as the pulse propagate in the lossy fiber. The invention of the erbium doped amplifier in the late 1980 s [2] made this possible. The most prominent experimental groups were at AT&T Bell Laboratories (mainly L.F. Mollenauer, see e.g. [3]) and at Nippon Telegraph and Telephone Corporation (mainly M. Nakazawa, see e.g. [4]). I also worked on soliton transmission experiments at Bell Labs and for example reported the first observation of soliton collisions in erbium-doped fiber-based fiber transmission links [5] and demonstrated soliton pulse transmission over 9000 km in 1991 [6].

Meanwhile, other nonlinear optical fiber phenomena also attracted attention and possible applications were explored. One such phenomena is four-wave mixing (FWM) which has resulted in several interesting applications, perhaps the most obvious one being translating information carried by an optical wave at one wavelength to a newly created wave at some other wavelength. As these nonlinear processes in optical fiber glass are extremely fast, they can be utilized to circumvent the so-called electronic bandwidth 'bottleneck' by implementing ultrafast all-optical functionalities.

In this short review of selected examples, I will highlight the use of FWM being implemented with specific objectives; Ultrafast all-optical sampling for waveform monitoring and 'noiseless' phase-sensitive optical parametric amplifiers which can be used to build very sensitive optical receivers. While these examples were implemented in optical fibers, we have also recently demonstrated the first continuous wave operation of compact parametric amplifiers based on low-loss silicon nitride waveguides which will also be discussed here.

E-mail address: peter.andrekson@chalmers.se.

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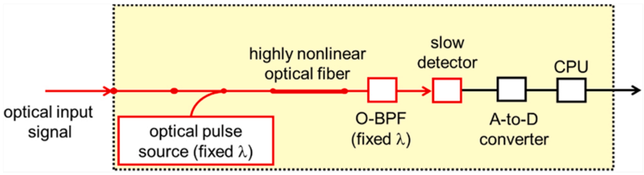

Fig. 1. Principle of all-optical sampling of optical waveforms. O-BPF: optical bandpass filter, CPU: central processing unit.

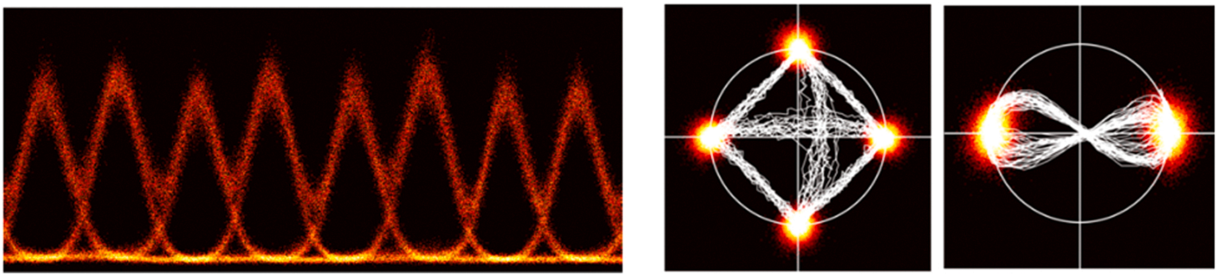

Fig. 2. Examples of signals captured with optical sampling. Left: Eye diagram of a 640 Gb/s return-to-zero waveform (like solitons). Right: Constellation diagrams of 10 Gbaud QPSK data and 40 Gbaud BPSK data, respectively.

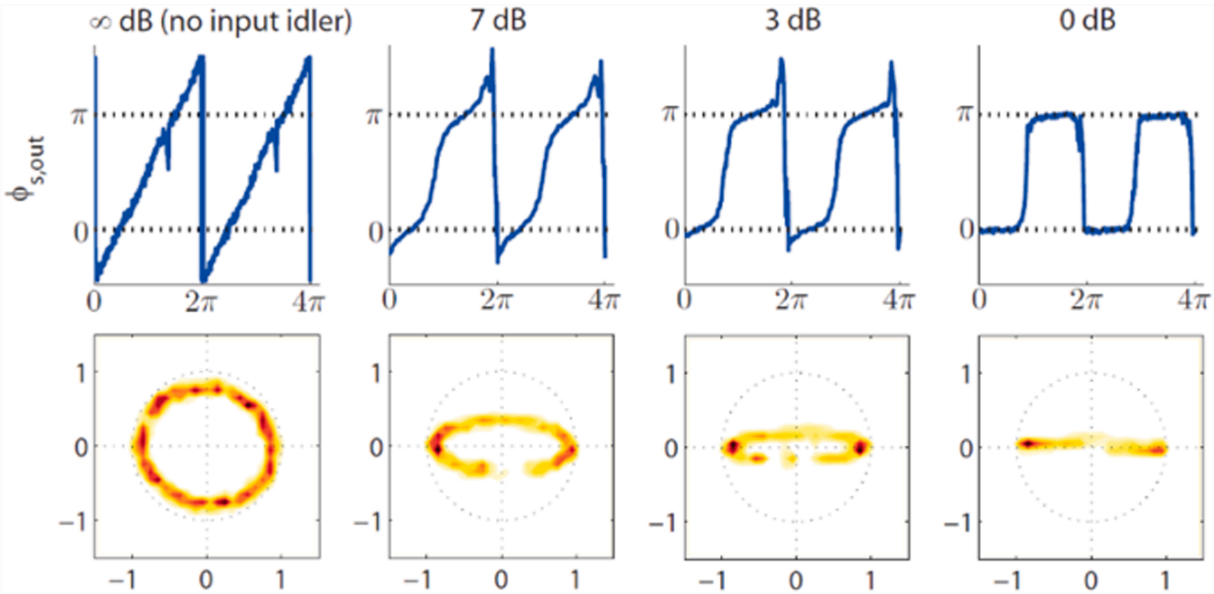

Fig. 3. Example of optical phase squeezing in a phase-sensitive parametric amplifier. The signal power level relative to that of the idler is indicated in dB. The top row shows temporal traces of the output versus input phase and bottom row shows the corresponding constellation diagrams.

2. Optical sampling for waveform monitoring

If there is a need to carefully observe an optical waveform it makes sense to do this with an optical means, in the same way as monitoring an electrical wave with electronics. With FWM-based sampling there are no concerns with ringing artifacts (e.g., due to impedance mismatch) in contrast to using a high-speed photo diode and a high-bandwidth electrical oscilloscope to capture the information. In addition, with FWM-based sampling the temporal resolution can be very high as it is mainly dictated by the duration of the optical sampling pulse [7]. Fig. 1 illustrates the operating principle in which a highly nonlinear optical silica fiber is used to facilitate FWM.

The FWM process will create an idler wave at a frequency $2\omega_p$-ω_s with ω_s being the signal wavelength and ω_p being the pump wavelength. The power of the idler wave is proportional to the signal power and is quadratically dependent on the pump power. Thus, if a pulsed pump is used, a sample of the signal wave is obtained at the idler frequency only when the pump is present. If the repetition

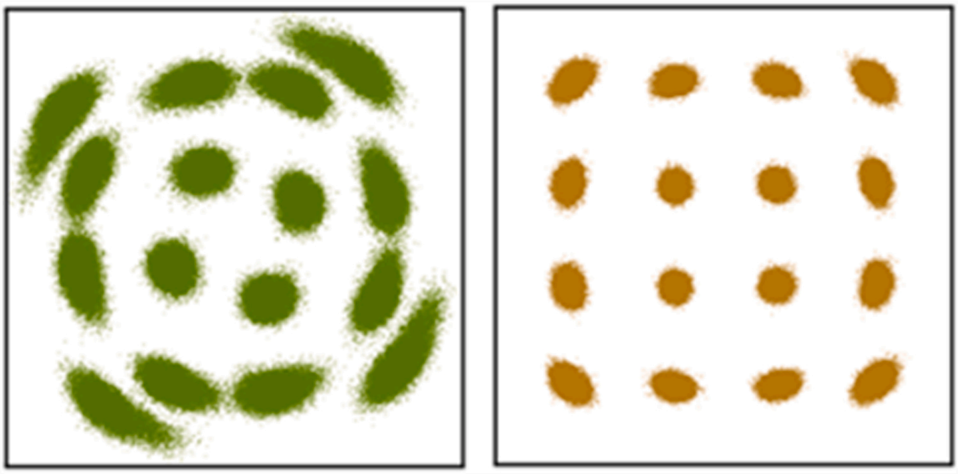

Fig. 4. Constellation diagrams of 16-QAM modulated data being transmitted over 160 km fiber. Left: conventional amplification. Right: PSA amplification.

rate of the pulse source is low, one can use low bandwidth detection to capture the samples and then synthesize the waveform in accumulative fashion if the waveform to be studied is repetitive (this is referred to as equivalent-time sampling). Fig. 2 (left) shows a measurement example of a so-called eye pattern of soliton-like pulses encoded with binary information at a bit rate of 640 Gbit/s which is far above what can be achieved with optoelectronic detection, while constellation diagrams of phase-encoded signals are shown on the right. The concept can be extended to real-time sampling and to phase-sensitive sampling (right) in which the filtered idler is detected with a coherent receiver which captures the full amplitude and phase data (as shown in Fig. 2, right). A review of all-optical FWM-based sampling can be found in [8].

The described principle of FWM-mixing-based sampling can be applied to any optical wavelengths with very high resolution limited by the sampling pulse duration and the properties of the nonlinear component being used. Silicon-nitride is a promising platform for this. Not only is it compact, but it can also be dispersion engineered and cover wavelength from visible to IR, i.e., well beyond what is possible with silica fibers.

3. Phase sensitive parametric optical amplifiers

Four-wave mixing can also serve to create significant optical parametric amplification [9]. A simple rule of thumb is that significant gain (say 20 dB) can be expected with a nonlinear phase shift of at least π rad,.i.e., $\gamma \cdot P \cdot L_{eff} > \pi$ where γ is the nonlinear coefficient, P is the optical pump power and L_{eff} is the effective loss length of the device. A very interesting case is when both a signal wave and an idler wave is entering the amplifiers. If one can control the relative phase among these waves and the pump wave, it is possible to achieve larger gain due to coherent superposition (with some properties like that of coherent detection, while here the output is an optical wave, not a photocurrent). Remarkably, this implementation has a quantum-limited noise figure (NF) of 1 (0 dB), thus effectively not adding any excess noise in the amplification process. This contrasts with all other known optical amplifiers (e.g., based on stimulated emission) that suffer from a quantum-limited NF of 3 dB. In [10], we demonstrated a NF = 1.1 dB experientially in a fiber-based phase-sensitive amplifier (PSA) with 26 dB gain. Such amplifiers can be implemented in different ways, for example in a way to make the gain independent of the modulation format being used or in a way to allow phase squeezing. Fig. 3 shows an example of the latter. Here the signal and idler phase are periodically changed with triangular shape using a phase modulator. The PSA output was monitored as the idler power was increased (with 0 dB in the figure representing equal power of the signal and the idler). When the powers are equal near-perfect phase squeezing is observed as signal output can only reach two phase states.

These amplifiers have been used in optical fiber communication links demonstrating significant reach increases due to the lower NF, but also due to their ability to mitigate the transmission-fiber-induced nonlinear signal distortion (due to self-phase modulation). Fig. 4 shows constellation diagrams of such an example with a 40 Gb/s, 16-QAM signal is being transmitted over 160 km [11]. On the left, using conventional optical amplification in the transmission link, clear nonlinear distortion is visible, while when using a PSA (right) the signal is improved significantly, a result of the coherent superposition of the signal and idler in the PSA. A recent review of fiber-based PSA can be found in [12].

4. Sensitive optical receivers

The PSA discussed above has several possible applications mainly because of its excellent noise properties. In deep-space optical communication the receiver sensitivity is one of the three fundamental metrics that dictate the data throughput. The other two are the available optical power in the transmitter and the aperture sizes being used (these will dictate the loss of link caused by diffraction) and

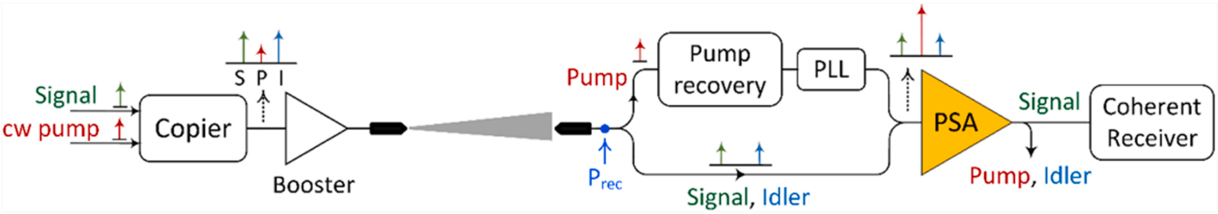

Fig. 5. A free-space optical link using a low-noise PSA preamplified receiver for ultimate sensitivity.

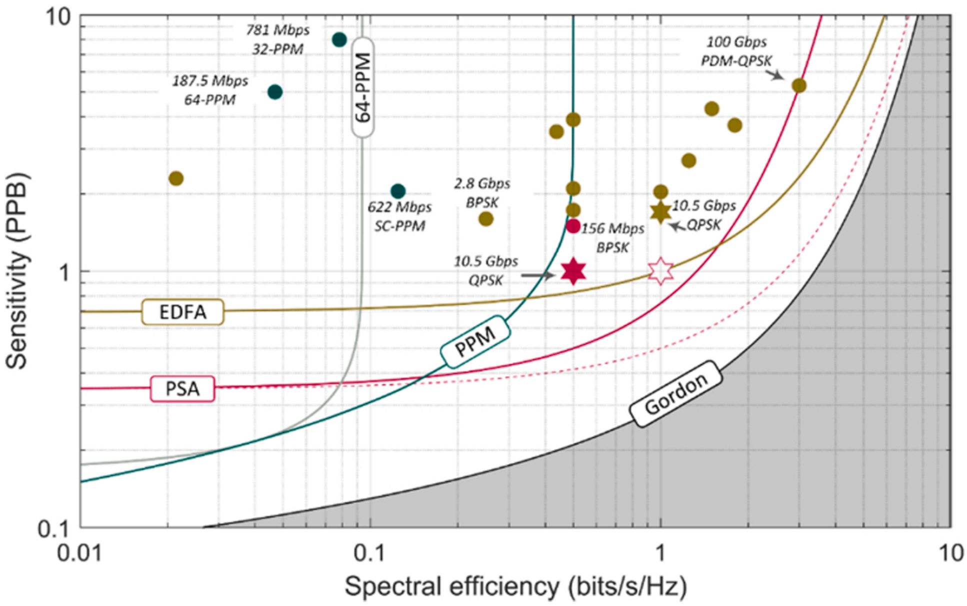

Fig. 6. Experimental data (marks) and theoretical limits of receiver sensitivity for various modulation format. From [13].

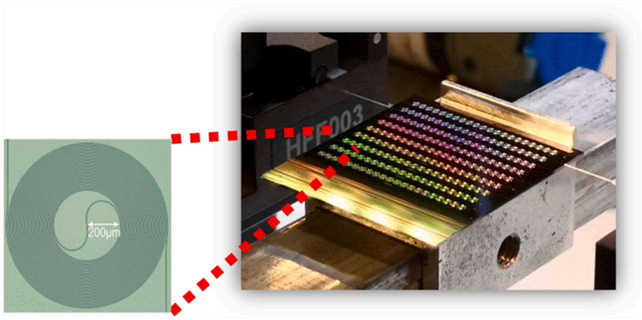

Fig. 7. Nonlinear silicon nitride waveguides formed with several spirals to reduce the footprint. Each waveguide is 1.4 m long, while the length of the chip is 2 cm.

are constrained only by engineering limitations. However, the sensitivity is fundamentally limited by vacuum noise. By using a PSA-preamplified optical receiver it is possible to simultaneously achieve excellent sensitivity (defined as the number of received photons per information bit (PPB) needed for error-free digital communication) and spectral efficiency (defined as the bandwidth needed to transmit at a certain bit rate, being expressed in bit/s per Hz). Fig. 5 illustrates the concept of such a free-space link. An idler, containing the phase-conjugated data in the signal wave is created at the transmitter using FWM in an optical fiber. This allows modulation-format independence in the PSA preamplifier in the receiver (here QPSK modulation at 10 Gb/s was used). All three waves are being transmitted in the link. To keep the power budget as large as possible it is important that the power in the transmitted pump wave (containing no information) is kept as low as possible. Therefore, a refined version of optical injection locking was used for PSA pump recovery.

This approach was used to experimentally demonstrate a record ‘black box’ sensitivity of 1 PPB at 10 Gb/s [13]. The theoretical limit is $\ln(2)/2 \approx 0.35$ PPB using a PSA and coherent detection. Fig. 6 summarizes the sensitivity and spectral efficiency with different modulation formats and approaches; coherent detection and photon counting using the pulse-position modulation (PPM) format being widely considered in the space communication community. The ultimate limit was described already in 1962 by Jim Gordon [14] who extended the capacity limit presented by Claude Shannon in [15] (the two capacities converge at high spectral efficiency or equivalently at high power, where the particle nature of light can be ignored). PPM can in theory reach the best sensitivity at low power but comes at the expense of very small spectral efficiency thus liming the bit rate that can be used due to hardware constraints.

5. Silicon-nitride-based parametric amplifiers

There are several material systems beside the optical fiber that can be fabricated to form a nonlinear waveguide with properties useful for parametric amplification. Silicon nitride (SiN) is of interest since it is transparent in a broad range of wavelengths with many possible applications aside from communication (spectroscopy, sensing, quantum technology) and because they can be fabricated with very low loss (i.e., allowing a large L_{eff}). Fig. 7 shows a picture of an in-house fabricated chip with nine such waveguides, each being 1.4 m long using 20 concatenated spiral waveguides. The dispersion was engineered to be anomalous with a value of $\beta_2 = -36$ ps^2/km and the nonlinear coefficient was approximately 1 W^{-1}m^{-1}.

With such a chip, we recently demonstrated the first reported continuous-wave operation of chip-based parametric amplifier relying of FWM [16]. In phase-sensitive mode, the chip NF was 1.2 dB, and the gain was 9.5 dB. Waveguide losses are essential to reach such performance and were in these dispersion-engineered chips as low as 1.4 dB/m. With lower insertion loss it is expected that a NF well below 1 dB is possible [17]. With the advantages of low noise and a small monolithic footprint, CW-pumped silicon nitride based parametric amplifiers may open previously unattainable possibilities in optical communications [18], ultrafast spectroscopy [19], and quantum optics and metrology [20].

6. Summary

I have briefly given some background of nonlinear four-wave mixing based optical parametric amplifiers in $\chi^{(3)}$ materials and provided some examples of applications. In phase-sensitive mode, these amplifiers can reach an unprecedented noise figure of 0 dB which can help lead to significant improvements in various optical science experiments and applications. The silicon-nitride is a promising nonlinear material platform as it is transparent across a very broad spectral range thus, in principle, allowing the design of such amplifiers for a range of applications beyond optical telecommunication.

Declaration of Competing Interest

I declare no conflict of interest.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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