

Saturation Effects In Degenerate Phase Sensitive Fiber Optic Parametric Amplifiers

Joseph Kakande⁽¹⁾, Francesca Parmigiani⁽¹⁾, Radan Slavík⁽¹⁾, Lars Grüner-Nielsen⁽²⁾, Dan Jakobsen⁽²⁾, Søren Herstrøm⁽²⁾, Periklis Petropoulos⁽¹⁾ and David J. Richardson⁽¹⁾

⁽¹⁾ Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK
Tel.: +44-2380594524, Fax +44-2380593142, e-mail: jkk@orc.soton.ac.uk

⁽²⁾ OFS, Priorparken 680, 2605 Brøndby, Denmark.

Abstract *We experimentally study saturation effects in degenerate phase sensitive amplifiers, revealing and explaining a gain regime suitable for all-optical signal processing functions such as phase regeneration.*

Introduction

Four wave mixing (FWM) based phase-insensitive fiber optical parametric amplifiers (PI-FOPAs) when operated in the linear gain regime have been demonstrated to achieve low (albeit quantum limited) noise¹, flat, high and wide gain bandwidths² exceeding those achievable using the ubiquitous erbium doped fibre amplifier (EDFA). To date though, these devices have been plagued by detrimental effects such as stimulated Brillouin scattering (SBS), cross gain modulation (XGM) via pump depletion and intra-channel crosstalk due to spurious four wave mixing products. PI-FOPAs can also be operated in the nonlinear gain regime to perform all-optical amplitude processing of input signals. The predominant effect utilised is gain saturation which can be used to perform amplitude regeneration of high speed signals³⁻⁵.

The recent resurgence of interest in the use of the entire complex field for optical signalling has meant that the capability of the FOPA to manipulate signal phase is becoming increasingly relevant. Phase sensitive (PS) operation can be achieved by having the signal and idler fields present at the input to the FOPA. In particular, in the degenerate PS-FOPA, two

strong pumps spaced equally apart in frequency from a signal wave (in this case the signal and idler fields can be considered to be at the same frequency). Degenerate PS amplification is characterised by a sinusoidal phase-to-amplitude transfer function and a step phase-to-phase transfer characteristic⁶. This configuration is particularly useful because the gain (and phase step) is periodic in 180° with the signal phase, which is ideal for phase regeneration of binary phase shift keyed (BPSK) optical signals^{7,8}. Achieving saturation via increasing pump and signal powers in FOPAs is often limited by the SBS thresholds of the highly nonlinear fibre (HNLF) used. For PI-FOPAs, the use of phase dithering to increase the SBS threshold is the most common solution to this problem. In PS-FOPAs however, phase dithering is not desirable as it distorts the signal phase, limiting the corresponding regenerative properties. Short lengths of highly nonlinear Bismuth-Oxide fibre have previously been used to experimentally study the gain properties of the degenerate PS-FOPA⁷. In this paper, we utilise a novel high SBS threshold HNLf to experimentally study the nature and cause of saturation effects in the degenerate PS-FOPA configuration.

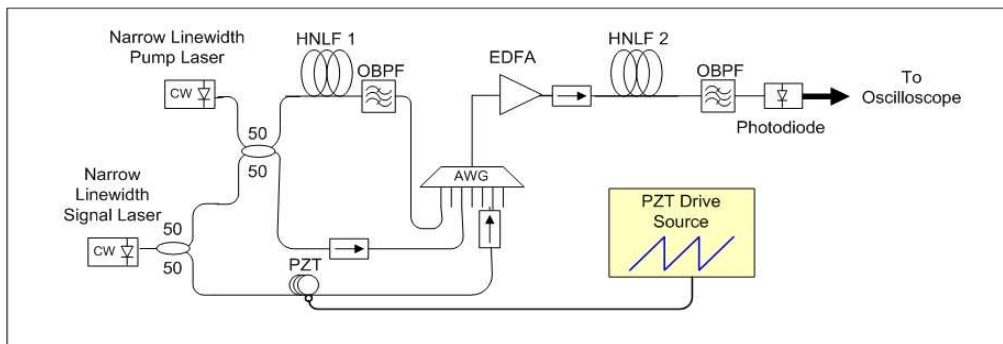


Fig. 1: Experimental setup of degenerate PS-FOPA. OBPF: Optical Bandpass Filter

Experimental setup and results

The experimental setup is shown in Fig. 1. Two narrow linewidth signals 200 GHz apart were mixed in a Ge-doped HNLF (OFS, Denmark) generating an idler wave. The HNLF length, dispersion, nonlinear coefficient and attenuation were 500m, 0.09ps/nm/km, $11.5\text{W}^{-1}\text{km}^{-1}$ and

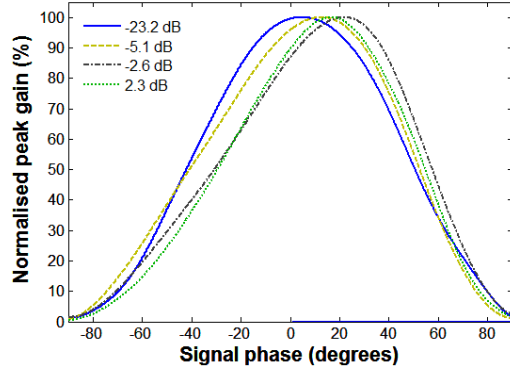


Fig. 2: Saturation characteristics as signal-to-pumps ratio is varied for PS-FOPA (total power of 29 dBm).

0.83dB/km respectively. The idler was filtered out, in so doing generating a third wave locked in frequency and phase to the two signals at the HNLF input. The three waves spaced 200 GHz apart could then be used as the two pumps and signal for the PS-FOPA. A variable attenuator allowed control of the signal power relative to the pumps. The degenerate PS-FOPA utilised a novel high SBS threshold strained aluminosilicate HNLF (OFS, Denmark). The length, dispersion, polarization mode dispersion, nonlinear coefficient and attenuation of the fiber were 177m, -0.13ps/nm/km, $0.11\text{pskm}^{-0.5}$, $7.1\text{W}^{-1}\text{km}^{-1}$ and 15dB/km, respectively. The high SBS threshold meant that in excess of 1W per pump could be coupled into the fibre.

The phase of the signal wave was modulated using a 50 kHz ramp function applied to a piezo-electric fibre stretcher. The choice of the ramp frequency was chosen to correspond to the resonant frequency of the piezo-electric stretcher used, allowing the phase to be swept by many multiples of 180° for a peak-to-peak drive voltage of under 100V. The three waves were then combined, amplified in a high power polarization maintaining EDFA to a fixed total power, and then launched into the degenerate PS-FOPA. Following the parametric interaction, the signal at the PS-FOPA output was filtered, attenuated and coupled into a low power photodiode. The electrical signal from the photodiode was then observed using a high speed digital oscilloscope. Post-processing was then carried out to eliminate high-frequency noise and normalise the gain curves.

The normalised signal gain curves for a total

power of 29 dBm (pumps and signal combined) coupled into the fibre are shown in Fig. 2. At this moderate pump power, for low input signal

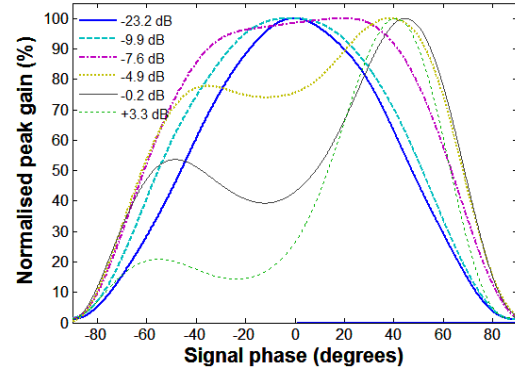


Fig. 3: Saturation characteristics as signal-to-pumps ratio is varied for PS-FOPA (total power of 32 dBm).

levels (solid curve in Fig. 2) the gain curve is sinusoidal with relative signal input phase as expected from theory⁹. As the signal power increases, the curves accumulate a skew, with the gain peak seemingly detuned in phase from the central phase position. Because each curve is captured for a fixed signal power at the PS-FOPA input, this differs from PI saturation because a nonlinear dependence on input signal phase exists. In this case, every point on the curve experiences a gain shift due to the alteration of the phase matching condition by the variation in the signal/pump power proportions during propagation. As the signal and pumps propagate down the fibre in which the PS interaction occurs, at every point a nonlinear contribution to the phase matching exists as a result of self- and cross-phase modulation (SPM and XPM respectively). Because the gain is dependent on the signal phase, the absolute powers and therefore the nonlinear phase matching varies with the input phase. For strong signal levels, this phase dependent behaviour leads to a modification of the gain characteristic, and ultimately to gain saturation.

For applications such as the regeneration of binary phase shift keyed (BPSK) signals, a crucial requirement would be that the PS gain curves have a flat-top, minimising the transfer of phase to amplitude noise. To obtain such flattening, it was necessary to increase the total power coupled into the PS-FOPA to 32 dBm. A selection of the resulting gain curves are shown in Fig. 3. At the lowest signal level assessed a sinusoidal gain curve is obtained indicating the absence of significant gain saturation (thick solid line in Fig. 3). As the signal power is increased, the gain curve is seen to acquire a flat-top (dashed-dotted line in Fig. 3). Increasing the signal power further reveals that the flattening is

in fact due to the growth of a second peak in the gain curve that detunes in phase from the central position as the signal level is increased.

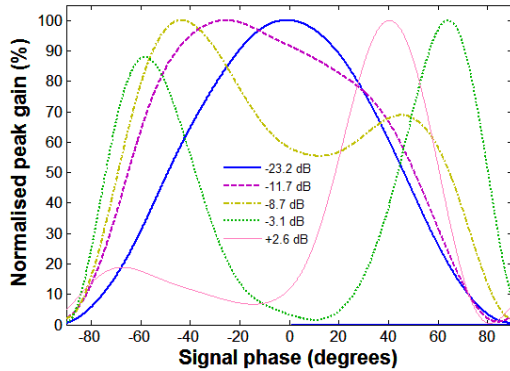


Fig. 4: Saturation characteristics as signal-to-pumps ratio is varied for PS-FOPA (total power of 33 dBm).

The total signal power was then increased further to 33 dBm and the gain curves obtained are shown in Fig. 4. The gain curve goes from sinusoidal at low signal levels to skewed at moderate power levels, as previously discussed. At high signal levels, though, it is possible to have two separate peaks in the gain curve for a 180° change in the input signal phase, contrasting with a single peak for lower power levels. This can be seen in the dotted line in Fig. 4. This points further towards the saturation effect stemming from a modification of the nonlinear phase matching condition and not just from pump power depletion. For 0° input phase as an example, the gain goes from maximum for the signal 23.2 dB lower than the pumps, to minimum at -3.1 dB, and then starts to increase again for stronger signal levels. The ability to tune the periodicity of the phase response as well as the peak gains of a PSA by saturation opens up a whole new host of applications, an example being the phase regeneration of QPSK and M-PSK signals.

In the dotted line in Fig. 4, the peaks have a 14% difference in power. To obtain two equal peaks, the signal level and the total power into the PSA were varied and the results are shown in Fig. 5. Generating dual peaks can be achieved by increasing the signal level beyond -8 dB in proportion to the total power coupled into the PSA. It is also worth pointing out that for a total power of 32 dBm (Fig. 3 thin solid line) the spacing between the peaks was approximately 90° , despite a peak to peak variation of 50%. At 33 dBm (dotted line Fig. 5) the spacing between the peaks was 70° without significantly compromising the phase sensitive swing (97%). Finally moving to 34 dBm (solid line Fig. 5) this reduced to 52° with equal gain peaks. These studies suggest that by optimising the signal and

pump powers further it should be possible to achieve the desired gain shape, such as the 90° spacing required for regeneration of QPSK signals in a single PS-FOPA.

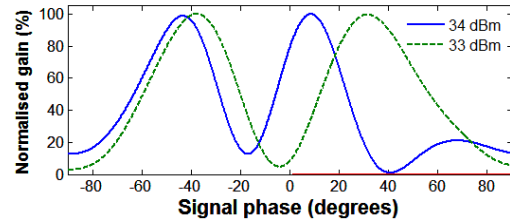


Fig. 5: PS-FOPA saturation optimised to achieve two gain peaks within a 180° signal phase period.

Conclusions

We have experimentally studied saturation effects in PS-FOPAs showing the impact of the nonlinear phase matching term on the gain characteristics. The ability to experimentally access this high saturation regime stems from the very high SBS threshold levels for the HNLF used, allowing access to a flat top regime suitable for BPSK phase regeneration, as well as a further saturation regime characterised by multiple gain peaks within a 180° signal phase periodicity.

Acknowledgements

We would like to thank OFS Denmark and Eblana Photonics Inc., Dublin, Ireland, for respectively providing HNLFs and lasers used in the experiment. This research has received funding from the European Communities Seventh Framework Programme FP/2007-2013 under grant agreement 224547 (PHASORS).

References

- [1] A. Durecu-Legrand et al., *Photonics Technology Letters*, IEEE 17, 1178 (2005).
- [2] J. M. C. Boggio et al., *Photonics Technology Letters*, IEEE 21, 612 (2009).
- [3] C. J. McKinstrie, S. Radic, and A. H. Gnauck, *Opt. Photon. News* 18, 34 (2007).
- [4] K. Inoue, *Electronics Letters* 36, 1016 (2000).
- [5] P. Kylemark et al., *Lightwave Technology, Journal of* 24, 3471 (2006).
- [6] A. Bogris, and D. Syvridis, *IEEE Photonics Technology Letters* 18, 2144 (2006).
- [7] K. Coussore, and G. F. Li, *IEEE Photonics Technology Letters* 19, 864 (2007).
- [8] Parmigiani F. et al. *Proc. OFC'10, PDPC3* (2010).
- [9] R. Tang et al., *Optics Express* 13, 10483 (2005).