The Impact of Zero-Dispersion Wavelength Fluctuations in >110 nm Fiber Optical Raman+Parametric Amplification

Vitor Ribeiro[(1)], Vladimir Gordienko[(1)], Chandra Gaur[(1)], N.J. Doran[(1)]

[(1)] Aston Institute of Photonic Technologies, Aston University, Birmingham, B4 7ET, UK , v.ribeiro@aston.ac.uk

Abstract *In this paper numerical results supported by experimental results, demonstrate that zero-dispersion wavelength fluctuations are found to be the main reason for the gain bandwidth limitation even in fiber optical parametric amplifiers employing ultra-short (25 m) gain fibres.*

Introduction

The invention of erbium-doped fiber amplifiers (EDFAs) was a great step forward, about 30 years ago, building the strongly connected society, that we live nowadays. With the widespread of internet and with the decrease of the cost per bit, it supported the creation of new applications and allowed to connect remote places that were not connected to the remaining world up to that time. The question how long they will be around, still remains, however it is the mission of the scientific community to build up new devices that can technically be prepared to make its substitution. Fiber-optical parametric amplifiers (FOPAs) are one of the best options, when one thinks about the limitations EDFAs have in terms of bandwidth. Moreover FOPAs have the potential to offer low noise figures and instantaneous gain. As it is generally known four-wave mixing (FWM) is present at any wavelength opening opportunities for FOPAs to be deployed as an amplifier at distinct wavelength windows not covered by any conventional amplifiers.

Recently a set of works have been published to demonstrate the best capabilities of FOPAs, related with bandwidth and gain flatness assisted with Raman gain[3] and experimental studies have been done in order to study FOPAs use, in high-capacity (dense) wavelength division multiplexing (D)WDM communications[1,4,5]. Issues normally related with FOPAs, such as polarization sensitivity and nonlinear crosstalk have been dealt carefully in order to turn FOPAs a more attractive solution[1,4,5].

In this paper we present numerical results supported by experimental results, that show that the main bandwidth limitation in short-length FOPAs assisted with Raman gain, when bandwidth exceeds about 100 nm is the zero-dispersion wavelength (ZDW) fluctuations. It is well known that ZDW fluctuations can limit the bandwidth of FOPAs. However a numerical study supported by experimental studies in the frame of ZDW fluctuations in very short amplifiers has never been done to the best of our knowledge. In fact accordingly to theory[6] it is expected that only short-scale fluctuations take action in short FOPAs and that they are less detrimental in general than long-scale fluctuations[6,7]. However we show that there is still room to improve in fiber fabrication in order to take advantage of the full bandwidth that FWM can offer. We show that this problem can be nearly neglected if ZDW fluctuations are reduced to nearly one third, thus higher-order dispersion takes over the process and limits the gain bandwidth.

Numerical model

The model used in this paper takes into account polarization effects, Raman interaction and computes ZDW fluctuations by using a normal distribution with mean λ_p and standard deviation δ, with a correlation length of 1 m. This allowed to model short-scale fluctuations which is believed to be the only ones taking action in short length FOPAs. We model our fiber accordingly to the model in[8], however we made a common substitution[6], $|\underline{A_k(z)}\rangle = |A_k(z)\rangle \exp(jL_k(\omega)z)$, where $k = s{,}i$, z is the propagation distance, and $L_k(\omega)$ is the Taylor expansion of the propagation constant at the ZDW $(n \geq 2)$. Moreover by assuming the total electrical field to be $|\underline{A(z{,}t)}\rangle = |\underline{A_i(z)}\rangle \exp(-j\omega t) + |\underline{A_s(z)}\rangle \exp(j\omega t) + |\underline{A_p(z)}\rangle$ we free the equations in[8] from the slow computing terms. While the model in[8] just take into consideration narrow bandwidth FOPAs (i.e. $L_k(\omega) = 0$) with these substitutions we extended it to model broadband amplifiers. Therefore $L_k(\omega)$ is given by,

$$L_i^s(\omega) = \left[j \sum_{n=2}^{+\infty} \frac{\beta_{(\omega_0)}^{(n)}}{n!} (\pm\omega)^n \right]. \tag{1}$$

Finally by algebraic manipulations this leads into the following expressions,

$$\begin{aligned}
\partial_z|A_p\rangle &= S_p|A_p\rangle \\
\partial_z|A_s\rangle &= j\left(\vec{\beta}\cdot\vec{\sigma}\right)\omega|A_s\rangle + (X_p+R_f)|A_s\rangle + \\
&\quad + F_f|A_i^*\rangle \exp(-kz) \\
\partial_z|A_i\rangle &= -j\left(\vec{\beta}\cdot\vec{\sigma}\right)\omega|A_i\rangle + (X_p+R_i)|A_i\rangle + \\
&\quad + F_i|A_s^*\rangle \exp(-kz)
\end{aligned} \tag{2}$$

where the 2×2 $\left(\vec{\beta}\cdot\vec{\sigma}\right)$ matrix is related to birefringence and is defined in the following form

$$\vec{\beta}\cdot\vec{\sigma} = \begin{bmatrix} \beta_1 & \beta_2 \\ \beta_2 & -\beta_1. \end{bmatrix} \tag{3}$$

By truncating the Taylor expansion of $L_k(\omega)$ to $n\leq4$, $k=\beta^{(2)}\omega^2+\beta^{(4)}\omega^4$ with $\beta^{(2)}=\beta^{(3)}(\omega_p-\omega_0)$, $\omega_p=\frac{2\pi c}{\lambda_p}$ and $\omega_0=\frac{2\pi c}{\lambda_0}$. The modulus of birefringence is set to be constant over the bandwidth of the amplifier. The parameters c, λ_p and λ_0 are the speed of light, the pump wavelength and the ZDW, respectively. The birefringence is modeled based on the random modulus model[9]. Birefringence change slightly the gain spectrum across a batch of measurement rounds (also observed experimentally), so we had to apply an average in our results. This is more pronounced in 50 m FOPAs. We neglected the zero-order propagation constants and therefore $\Delta\beta_k=\beta_k^{(0)}-\beta_p^{(0)}=0$. The remaining parameters are defined as follows[8],

$$\begin{aligned}
S_p &= j\frac{\gamma_K}{3}(2\langle A_p|A_p\rangle \mathrm{I} + |A_p^*\rangle\langle A_p^*|) + \\
&\quad + 2j\frac{\gamma}{3}\frac{\chi_R(0)}{\chi_K}\langle A_p|A_p\rangle \\
X_p &= 2j\frac{\gamma}{3}(\langle A_p|A_p\rangle \mathrm{I} + |A_p\rangle\langle A_p| + |A_p^*\rangle\langle A_p^*|) \\
F_{s,i} &= j\frac{\gamma}{3}(\langle A_p^*|A_p\rangle \mathrm{I} + 2|A_p\rangle\langle A_p^*|) + \\
&\quad + j2\frac{\gamma}{3\chi_K}\chi_R(\Omega_i^s)|A_p\rangle\langle A_p^*| \\
R_{s,i} &= j\frac{2\gamma}{3\chi_K}(\chi_R(0)\langle A_p|A_p\rangle \mathrm{I} + \chi_R(\Omega_i^s)|A_p\rangle\langle A_p|)
\end{aligned} \tag{4}$$

where I is the identity matrix, $\frac{\chi_R}{\chi_K}$ is related to the fractional strength of the Raman response $\chi_R(\omega)$ to the Kerr χ_K response. The imaginary and real parts of $\chi_R(\omega)$ can be found in[10]. We define $\Omega_i^s=\pm\omega$. The remaining parameters are defined in Tab. 1.

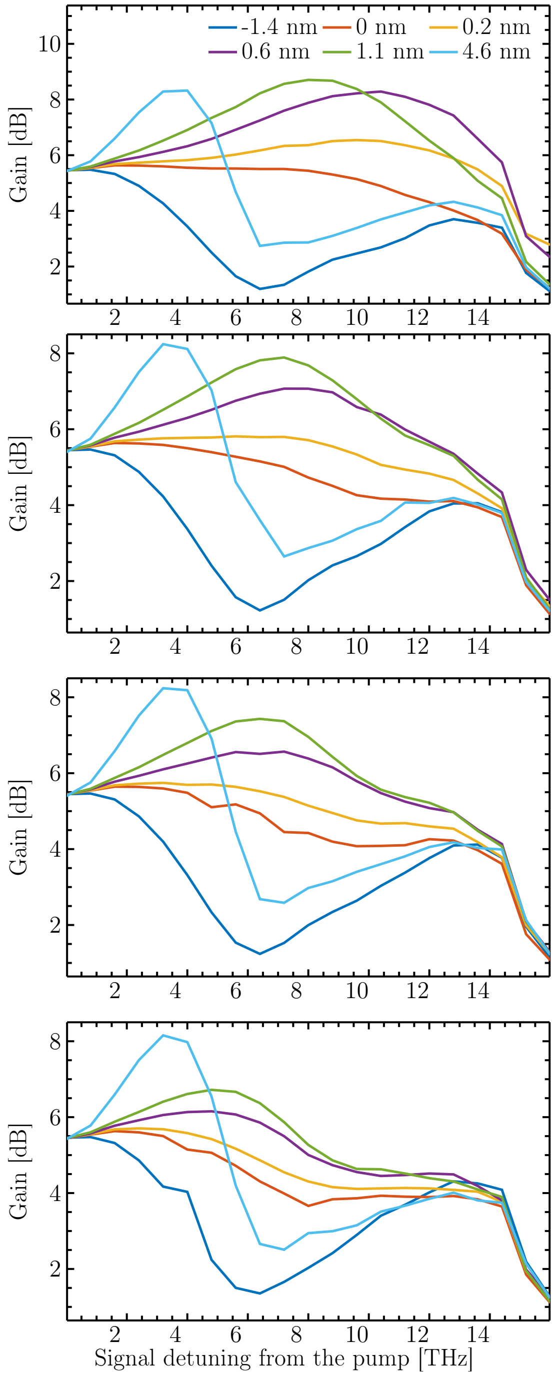

Fig. 1: Numerical results of the gain as a function of signal detuning from the pump frequency for several values of standard deviation δ of ZDW fluctuations. Each curve represents the wavelength separation between the wavelength of the pump λ_p and the ZDW λ_0. a)$\delta=0.08$ nm, b)$\delta=0.22$ nm, c)$\delta=0.3$ nm and d)$\delta=0.45$ nm.

Results and Discussion

In Fig. 1 we show a set of results where the standard deviation δ of the ZDW fluctuations varies. It is no surprise that with the increase of the standard deviation of the ZDW fluctuations the bandwidth of the spectrum is reduced, however its impact on short-length FOPAs has never been measured to the best of our knowledge. Moreover it is believed that the impact of ZDW

Tab. 1: Setup parameters (unless otherwise stated)

Symbol	Value	Units
λ_p	varying	nm
λ_0	1551.4	nm
P_p	5	W
γ	9.6	W^{-1}km^{-1}
β_3	0.0651	ps^{3}km^{-1}
β_4	1×10^{-5}	ps^{4}km^{-1}
X_k	2.22	
L	25	m

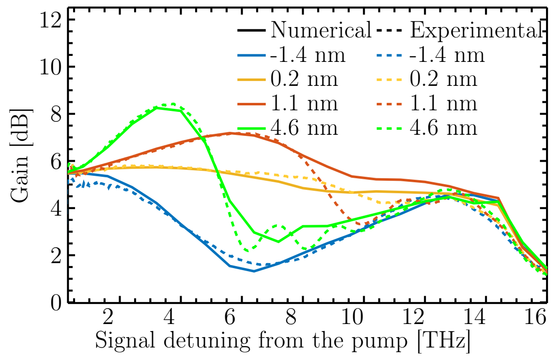

Fig. 2: Numerical results of the gain as a function of signal detuning from the pump frequency. Each curve represents the wavelength separation between the pump wavelength λ_p and the ZDW λ_0. In this case $\delta = 0.37$ nm results as the best fitting to our experimental results

fluctuations is less detrimental in short FOPAs[7], however we show in Figs. 1 a) to d) that there is still room to improve in fiber manufacture, in order to take advantage of the whole bandwidth FWM has to offer. We predict that with ZDW fluctuations of about $0.1-0.15$ nm the impact of ZDW fluctuations in short-length FOPAs can be nearly neglected. In Fig. 1 a) we can see a high broadband gain is achieved when $\lambda_p - \lambda_0 = 0.6$ nm. This is the result of the compensation of a negative $\beta^{(2)}$ with a positive $\beta^{(4)}$. However when ZDW fluctuations increase its standard deviation, as shown in Figs. 1 b) to d), this high broadband gain is compromised leading to the reduction of the gain bandwidth available. Most of the Raman gain occurs for frequencies higher than 10 THz.

In Fig. 2 we show numerical results supported by experimental results that demonstrate that the ZDW fluctuations of our 25 m long FOPA have a standard deviation of 0.37 nm. In addition with this value of ZDW fluctuations and with the parameters of Tab. 1 we could fit our experimental results to our numerical results. This demonstrates the level of ZDW fluctuations involved in our experiment, which can guide future experiments with short length FOPAs in order to circumvent this issue.

Conclusions

We conclude that zero-dispersion wavelength (ZDW) fluctuations are still a considerable factor of impairment in short-length fiber optical parametric amplifiers (FOPAs). We predict that in order to take advantage of the bandwidth four-wave mixing has to offer ZDW fluctuations shall be reduced to nearly one third.

Acknowledgements

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