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# Towards Wide-Bandwidth Ultra-Flat FOPAs

Vladimir Gordienko<sup>1</sup>, Marc Stephens<sup>1</sup>, and Nick Doran<sup>1</sup>

<sup>1</sup>Aston Institute of Photonic Technologies, Aston University, B4 7ET, Birmingham, UK

Tel: (44) 121 204 3512, e-mail: gordienv@aston.ac.uk

## ABSTRACT

Fibre optical parametric amplifiers (FOPAs) offer the potential for high gain and >100 nm bandwidth at arbitrary wavelengths for increased transmission capacity. We will cover the main principles of the FOPA and discuss our approach to obtaining broad flat gain and performance improvement via simultaneous Raman amplification.

**Keywords:** optical parametric amplifiers, broadband amplifiers, Raman scattering.

## 1. INTRODUCTION

Modern optical transmission systems are approaching the nonlinear Shannon limit, and techniques are being explored to extend performance beyond it [1]. An alternative way of enhancing capacity is to increase the transmission bandwidth (BW). Some fibres, such as OFS AllWave® allow low-loss (<0.32 dB/km) transmission over a wide range (1310 - 1625 nm). This presents an available BW of 44 THz, with only ~9 THz covered by C and L-band Erbium-doped fibre amplifiers (EDFAs). The development of amplifiers capable of providing one-stage amplification over the full transmission band would offer a fivefold transmission capacity increase.

The most promising amplifiers capable of operating in that window are the fibre Raman amplifier (FRA) and the FOPA. However, the gain BW of FRA has so far been limited to ~100 nm, and requires multiple (>5) pumps [2]. Conversely, a single-pump FOPA with a total gain BW >30 THz has been demonstrated [3]. Additionally, the FOPA has a higher gain coefficient than FRA, and the FOPA can operate in a phase-sensitive regime enabling noise figures below 3 dB [4]. However, the FOPA still has numerous challenges – for example, the unidirectional nature of the gain prohibits backward pumping and means pump noise can transfer to signals. Secondly, the FOPA suffers from four-wave mixing between signals leading to crosstalk. Thirdly, pump power is limited by stimulated Brillouin scattering (SBS), and techniques used to mitigate it (such as pump dithering) cause signal degradation [5]. Finally, it is difficult to obtain polarization insensitive gain, although recent progress has been made [6].

This paper reviews the FOPA principle and recent achievements of wide gain BW operation suitable for signal amplification. We will explore how Raman gain from the parametric pump can be used to extend FOPA gain BW.

## 2. BROADBAND FOPA

The single-pump FOPA gain coefficient depends on pump power  $P$ , fibre nonlinearity  $\gamma$  and propagation constant mismatch between pump, signal and idler  $\Delta\beta$  as shown in (1) [7]. The nonlinear medium is typically a Highly Nonlinear Fibre (HNLF). Considering co-polarized waves, the maximum gain coefficient  $g_{\max} = \gamma P$  is achieved when  $\Delta\beta = -2\gamma P$ . This condition is termed ‘phase-matched’. When  $\Delta\beta$  is in a range from 0 to  $-4\gamma P$ , but not equal to  $-2\gamma P$  parametric gain is strongly reduced. For  $\Delta\beta$  outside of this range, the FOPA gain coefficient is imaginary.

$$g = \sqrt{-\Delta\beta \cdot (4\gamma P + \Delta\beta)} / 2 \quad (1)$$

$$\Delta\beta = \beta_s + \beta_i - 2\beta_p = \beta^{(2)} (\Delta\omega_s)^2 + \frac{\beta^{(4)}}{12} (\Delta\omega_s)^4 \quad (2)$$

Equation (2) defines  $\Delta\beta$  for the single-pump FOPA, where  $\beta_s$ ,  $\beta_i$ , and  $\beta_p$  are propagation constants of signal, idler and pump waves respectively, and  $\beta^{(2)}$  and  $\beta^{(4)}$  are second- and fourth-order derivatives of  $\beta_p$  (higher orders ignored), and  $\Delta\omega_s$  is the angular frequency offset between the signal and the pump.

$$G(z) = \left| \frac{\gamma P}{g} \sinh(gz) \right|^2 + 1 \quad (3)$$

The signal gain  $G$  can be approximated by (3), where  $z$  is the propagation distance. Figure 1 shows a typical single-pump FOPA gain spectrum calculated using (3). Unless  $\beta^{(2)}$  is very small when pump is very close to zero-dispersion wavelength  $\lambda_0$ , the  $\beta^{(2)}$ -term dominates over the  $\beta^{(4)}$ -term in (2) over a wide range around the pump. In this case  $\Delta\beta$  takes a parabolic shape and changes quickly across the range where gain coefficient is real. It results in a significant gain variation (GV) across the gain spectrum (Fig. 1). Near the pump  $\Delta\beta$  is close to zero, so moderate quadratic gain is observed. As signal detuning from the pump increases,  $\Delta\beta$  reaches a value of  $-2\gamma P$  and gain increases up to its maximum featuring an exponential gain growth. Further increase of signal

detuning from the pump leads to phase mismatch and the gain correspondingly reducing to near zero. Note that gain magnitude is defined by nonlinear phase shift  $\gamma PL$ , where  $L$  is HNLF length. Overall, even though the FOPA can provide high gain and wide BW, typically the GV across the spectrum is very high. Therefore, not only would high loss gain flattening filters be required for broadband operation, but significant penalties would be induced due to nonlinear crosstalk occurring between excessively amplified signal channels near the gain peak.

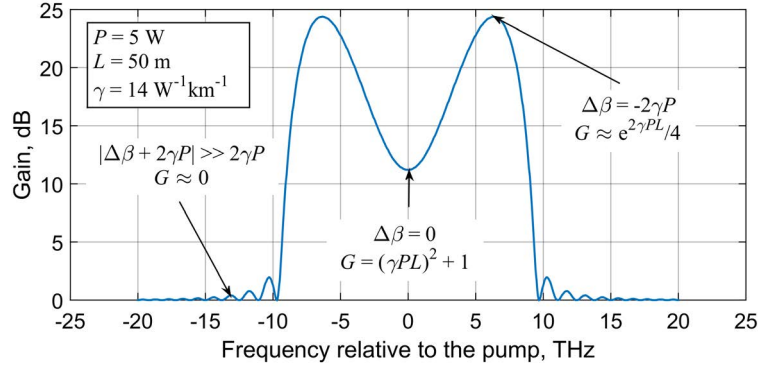


Figure 1. Example analytical FOPA gain spectrum from Eq. (3).

A flat and broad gain spectrum can best be achieved using short lengths of HNLF. This approach requires much higher pump power to obtain high gain, but has two advantages. First, wider gain BW can be obtained due to the higher pump power whilst keeping the peak gain the same. Secondly, short fibres suffer less from longitudinal dispersion fluctuations, giving more control over the gain spectrum shape when tuning pump wavelength. Thus, by positioning the pump very close to  $\lambda_0$  at the anomalous dispersion side of HNLF possessing positive  $\beta^{(4)}$  coefficient, the two terms in Eq. (2) can be cancelled out over a wide range. In this way  $\Delta\beta \approx 0$  and gain is not phase-matched, but gain is almost constant over wide BW.

## 2.1 Experimental setup

Figure 2 shows the setup for an experimental study of single-pump broadband FOPA gain spectra. A continuous pump wave generated from a 100 kHz linewidth tuneable laser was phase modulated with radio frequency (RF) tones at 100 MHz, 320 MHz and 980 MHz to mitigate SBS. The pump was amplified by a high-power EDFA and filtered using a circulator and a tuneable fibre Bragg grating (FBG) to remove EDFA noise from the pump, and to combine the pump with a signal probe. The pump and signal were guided into various lengths of dispersion stable HNLF [8]. The key datasheet parameters of the HNLF were:  $\lambda_0 = 1550.5 \pm 1$  nm,  $\gamma = 14 \text{ W}^{-1} \cdot \text{km}^{-1}$ , dispersion slope  $S = 0.044 \text{ ps} \cdot \text{nm}^{-2} \cdot \text{km}^{-1}$  and  $\beta^{(4)} \sim 10^{-56} \text{ s}^4 \cdot \text{m}^{-1}$ , measured at 1550 nm. To accurately measure the FOPA gain [9], a depolarized supercontinuum [10] was used as an input probe, ranging from 1520 nm to 1700 nm. A calibrated set of tap couplers and power meters and an optical spectrum analyzer (OSA) were used to non-intrusively measure pump power and optical spectra at the input and output of the HNLF. The pump polarisation could be tuned using a polarisation controller placed at the input to the HNLF.

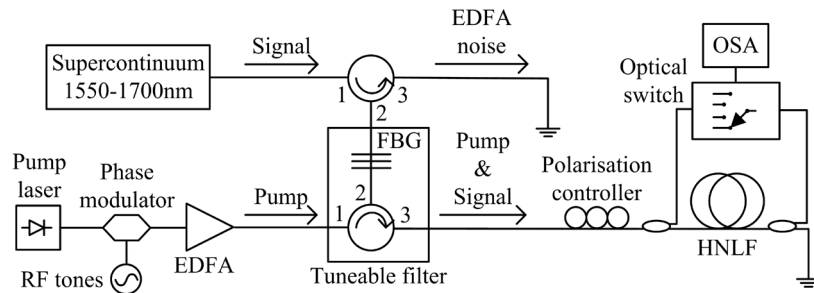


Figure 2. Experimental setup for FOPA gain spectrum analysis.

## 2.2 Experimental results and discussion

The blue curve in Fig. 3 shows a gain of  $9.6 \pm 0.5$  dB over 12.9 THz obtained using the approach discussed above in a 25 m long fibre, and using a pump power of 9 W [11]. Gain achieved beyond 10.5 THz is attributed mainly to Raman gain induced by the parametric pump. The orange curve in Fig. 3 shows even flatter gain of  $8.5 \pm 0.3$  dB obtained in the same 25 m long fibre at pump power of 8 W. In this case, the pump polarization was controlled to obtain the flattest gain possible. Using pump polarization to optimize the gain spectrum shape is a novel technique and will be discussed further at conference [12]. These two gain spectra are extremely flat and broad, but possess relatively low gain magnitude, even while using high pump power. We therefore aim to study

techniques for increasing the FOPA gain magnitude, while keeping GV low and preferably with improved energy efficiency.

The simplest way to increase the gain magnitude is to increase the HNLF length as demonstrated by the purple curve in Fig. 3. This corresponds to the gain spectrum obtained using a 100 m long HNLF with pump power of 5 W. The pump power is decreased compared to the previous two cases due to SBS threshold decrease with fibre length. A gain increase takes place at the cost of GV increase and BW decrease, providing a gain of  $17.5 \pm 2$  dB over 10.7 THz. Note that the Raman gain is substantially larger than the parametric gain in this case.

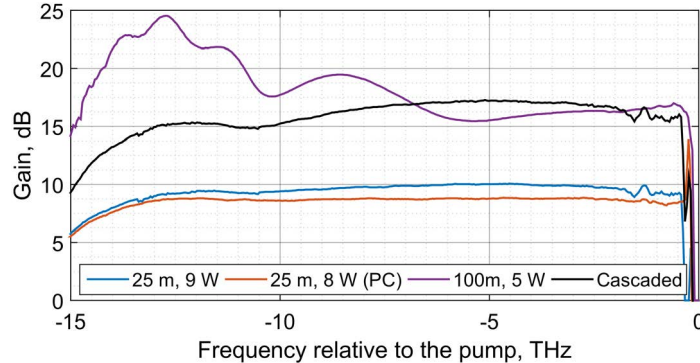


Figure 3. Experimental spectra for different HNLF length/pump power combinations: (a) 100 m/5 W (purple trace), (b) 25m/9 W (blue trace), (c) 25 m/8 W polarisation-tuned pump (red trace), (d) cascaded (black trace).

It can be seen that the GV increase in the 100 m fibre is much larger than the increase in gain magnitude. We therefore propose that the gain magnitude be increased by cascading multiple flat gain spectra. For example, two 25 m fibres could be placed sequentially with a filter between them to remove idlers of the first stage. This would lead to two independent FOPA stages, where the pump from the first stage can be reused in the second stage, thus improving energy efficiency. Assuming a filter loss of 1 dB and pump power in the first stage of 9 W, the pump power in the second stage would therefore be  $\sim 7$  W. The total gain in such a cascaded amplifier can be predicted by summing the gain spectra obtained in the 25 m fibre with pump powers of 9 W and 7 W and subtracting 1 dB to account for mid-stage loss. The resulting predicted cascaded gain spectrum is shown by the black curve in Fig. 3. Cascading suggests a gain of  $16 \pm 1.2$  dB over 13 THz, which is substantially flatter and broader than 100 m gain spectrum with similar gain magnitude. Therefore, the cascading of ultra-flat low gain spectra is viewed as a practical approach to reach high net gain over BW  $> 100$  nm with low GV. It also should be noted that in case of quadratic gain and neglecting mid-stage loss, the cascading of two identical FOPA stages provides more gain than a single stage FOPA with the same total fibre length as long as nonlinear phase shift per stage  $\gamma PL > \sqrt{2}$ .

### 3. RAMAN ENHANCEMENT OF FOPA

Raman gain in the FOPA can arise from the parametric pump itself, or from an intentional extra pump. The use of the latter can provide extra gain, BW or improved signal performance [13]. However, the single-pump FOPA gain BW is typically much larger than that of a single-pump Raman. Therefore, multiple Raman pumps would be needed to provide impact over the whole parametric gain range. On the other hand, parametric pump generated Raman has to be considered whenever the parametric gain is wide enough to overlap with areas with notable Raman susceptibility. It has been shown that the amplitude of parametric gain starts to be notably affected by both imaginary and real parts of Raman susceptibility at offset of just over 5 THz from the parametric pump [14]. Obviously, significant Raman gain will arise in the usual range (10-15 THz away from the pump in silica), where there is a high imaginary part of Raman susceptibility. It should be noted that Raman gain coefficient is typically 3-4 times smaller than phase-matched parametric gain coefficient [15], therefore Raman gain induced by the parametric pump often invokes localized peak on the Stokes side and dip on the anti-Stokes side, which increase GV across gain spectrum, but does not add much useable gain. Consequently, one reasonable way of exploiting the parametric pump induced Raman gain is to suppress parametric gain peak or to fill a parametric gain dip. However, this has never been experimentally demonstrated. Another way is to extend parametric gain rolling off at  $\sim 10$  THz away from the pump by Raman gain as was demonstrated in Fig. 3. However, this requires a similar amplitude of Raman and parametric gain. Given the difference between Raman and FOPA gain coefficients, we found that it is possible to keep Raman and quadratic parametric gain on the same level up to  $\sim 10$  dB in a fibre with a measured Raman fractional strength  $f_R = 0.29$ . Figure 4a demonstrates how Raman gain with various  $f_R$  compares with phase-matched (blue curve) and quadratic (black curve) parametric gain plotted versus nonlinear phase shift  $\gamma PL$ . Raman gain was calculated as  $G_R = \exp(2 \cdot f_R \gamma PL)$ , quadratic gain as  $G_q = (\gamma PL)^2 + 1$  and phase-matched gain as  $G_m = [\cosh(\gamma PL)]^2$ . It can be seen that the gain magnitude where quadratic parametric gain is equal to Raman gain (black dots) depends on  $f_R$ . Figure 3 demonstrates higher Raman gain than the one calculated and shown in Fig. 4, because in practice there is an overlapping and

a complex interaction between parametric and Raman gains [14]. However, it is important that gain value where parametric and Raman gains are equal increases with decrease of  $f_R$  (Fig. 4b). Therefore, it is expected that in fibres with low  $f_R$  it is possible to match magnitudes of the Raman gain and the quadratic parametric gain up to  $\sim 15 - 20$  dB.

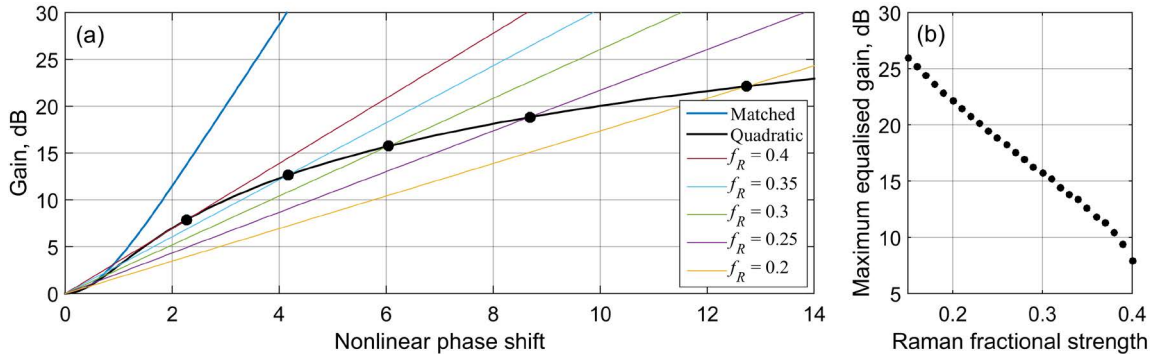


Figure 4. Analytical comparison of Raman and parametric gain:

- (a) Raman gain with varied fractional strength and parametric gain (phase-matched and quadratic) are shown as a function of nonlinear phase shift. Black dots show where parametric and Raman gains are equal;  
 (b) Equal parametric and Raman gains as a function of the Raman fractional strength.

#### 4. CONCLUSIONS

We have shown that cascading of two independent FOPA stages with broad and flat gain spectrum suggests lower GV comparing to single stage. We demonstrated that cascaded FOPA may have gain BW up to 13 THz (110 nm), gain magnitude over 15 dB and GV of 2.4 dB. Gain BW over 10 THz in the suggested approach is attributed to Raman gain induced by the parametric pump.

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