

# Wideband Uniform Generation of Shape-Adjustable Pulses in Two-Pump Fiber Optic Parametric Amplifier

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**Abstract** *A tunable, stable pulse generation technique based on two-pump fiber optic parametric amplification is theoretically analyzed and experimentally demonstrated to generate uniform near-Gaussian pulses over 32 nm. It is shown that pulse shape can also be tuned and that a specific phase matching case enables Nyquist pulse generation over a wide bandwidth.*

## Introduction

Optical pulse generation in an all-fibered environment has been a very active area of research over the past three decades. Efforts were driven by the need for compact, flexible and high bandwidth pulse sources for sensing and telecommunications applications. Indeed, being able to generate short pulses in the optical domain offers the possibility to sample at resolutions much higher than those of electronics. Furthermore, in optical communication networks where demand for bandwidth is on steady rise, all-fibered solutions offer the potential of easy integration. Moreover, by using different carrier wavelengths simultaneously, one can readily multiply the available bandwidth<sup>1</sup>.

Numerous architectures based on either mode-locked operation or pulse compression have been suggested in order to generate short pulses at optical communication bit-rates. All fibered mode-locked lasers can provide short pulses at repetition rates of more than 40 GHz but require fine tuning of the cavity, which impedes flexibility for repetition rate and wavelength tuning<sup>1</sup>. Techniques based on pulse compression offer more simplicity and flexibility<sup>2</sup>, but also require some adjustments to the electro-optical modulators depending on the operation wavelength. Pulses generated this way usually exhibit a Gaussian shape that may induce inter symbol interference (ISI) in OTDM systems and crosstalk in WDM systems.

Recently, a few techniques to generate Nyquist pulses in order to avoid ISI have been demonstrated<sup>3-5</sup>. In particular, using one pump fiber optic parametric amplifier (FOPA), it was shown that according to the seed position, different pulse shapes can be generated, notably Gaussian and sinc-like temporal pulse shapes.

In this work, it is shown theoretically that using two-pump FOPA, it is possible to generate an identical temporal window over a wide bandwidth. In addition, the temporal shape can

be adjusted, for example to Gaussian or Nyquist shape. As a proof of concept, we experimentally generate identical pulses of 37.6 ps width at repetition rate of 10 GHz over 32 nm in a single modulated pump two-pump FOPA.

## Theory

Two-pump FOPA operates based on four-wave mixing processes in which energy is transferred from the pumps to the signal and generated idlers. The efficiency of the energy transfer is governed on the phase matching between the interacting waves  $\kappa(t) = \Delta\beta_L + \gamma(P_1(t) + P_2(t))$ , where  $P_1(t)$  and  $P_2(t)$  are the instantaneous powers of the pumps at angular frequencies  $\omega_1$  et  $\omega_2$ , and  $\Delta\beta_L$  is the linear phase mismatch between the interacting waves.  $\Delta\beta_L$  can be expanded in highly nonlinear fibers (HNLf) as  $\Delta\beta_L = \beta_2(\Delta\omega^2 - \Delta\omega_p^2) + \beta_3/12(\Delta\omega^4 - \Delta\omega_p^4)$ , with  $\beta_2$  and  $\beta_4$  the dispersion and dispersion curvature of the HNLf at  $\omega_c = (\omega_{p1} + \omega_{p2})/2$ ,  $\Delta\omega$  and  $\Delta\omega_p$  the signal and pumps detuning from  $\omega_c$ . Using the four-wave model and neglecting pump depletion, stimulated Raman scattering, absorption and walk-off, the generated idler amplitude is given by Eq. (1)<sup>6</sup>.

$$A_i(L, t) = jA_S^*(0, t) \frac{2\gamma\sqrt{P_1(t)P_2(t)}}{g(t)} \times \sinh(g(t)L) e^{j\left(\gamma(P_1(t)+P_2(t)) + \frac{\beta_3}{6}(\Delta\omega^3 - \Delta\omega_p^3)\right)L} \quad (1)$$

where  $g(t)^2 = 4\gamma^2 P_1(t)P_2(t) - [\kappa(t)/2]^2$ ,  $\gamma$  is the fiber nonlinearity coefficient and  $A_S(0, t)$  is the signal amplitude at the fiber input. Eq. (1) shows that when the pumps are intensity modulated (IM), a temporal window is generated on the idler side, which can be used either for sampling  $A_S(0, t)$  or pulse generation if  $A_S(0, t)$  is a continuous wave (CW) seed. Depending on the pumps IM, a wide variety of temporal windows can be generated. In the following, we consider that the pumps IM are pulse shapes of repetition frequency  $f_R$  and total peak power  $P_0 = P_1(0) + P_2(0)$ .

### Wideband uniform temporal window

For given pumps IM, the shape of the generated temporal window will depend on the linear phase mismatch  $\Delta\beta_L$ <sup>7</sup>. Eq. (1) imposes  $-3\gamma P_0 \leq \Delta\beta_L \leq \gamma P_0$  for  $g$  to be real. It is well known that in order to get a flat high gain over a wide bandwidth in two-pump FOPA with CW pumps, it is necessary to bound  $\Delta\beta_L$  close to  $-\gamma P_0$  using Chebyshev polynomial<sup>6</sup>. For IM pumps however, being able to bound  $\Delta\beta_L$  around any value  $m\gamma P_0$  with  $m \in [-3,1]$  offers the unique possibility to generate similar temporal dynamics over a wide bandwidth. In order to achieve such bounding, the following conditions must be satisfied:

$$\Delta\omega_p >^{1/4} \sqrt{12m\gamma P_0 / \beta_4} \quad (2)$$

$$\left( \frac{\beta_4}{12\gamma P_0} \right) (\Delta\omega_p)^4 + \left( \frac{\beta_2}{\gamma P_0} \right) (\Delta\omega_p)^2 + (\rho + m) = 0$$

$$\rho = \frac{3}{2} \frac{\beta_2^2}{\beta_4 \gamma P_0}$$

is the amplitude of the  $\Delta\beta_L / \gamma P_0$

fluctuations over a  $\Delta\omega_i = 2\sqrt{-12\beta_2 / \beta_4}$  bandwidth between the two pumps. A thorough analysis of Eq. (2) shows that for  $m \in [-3,0]$ , fibers with positive  $\beta_4$  and negative  $\beta_2$  must be used, whereas for  $m \in [0,1]$ , fibers with negative  $\beta_4$  and positive  $\beta_2$  have to be used. By choosing particular pumps IM profile and  $\Delta\beta_L$ , specific invariant pulse shapes can be generated over  $\Delta\omega_i$ . In the following, we consider that both pumps are modulated by a sinusoid at frequency  $f_R$ . By Taylor expansion in the vicinity of the pumps peak power, we have  $P_1(t) = P_2(t) \approx P_0 / 2 (1 - (\pi f_R t)^2)$ .

### Gaussian pulse generation

For large  $gL$  and  $m$  near -1, it can be shown that:

$$P_1(L,t) \approx P_s(0,t) \frac{4}{3-m(2+m)} e^{\gamma P_0 L \left[ \sqrt{\beta_3 - m(2+m)} - (\pi f_R t)^2 \right] \left( \frac{3-m}{\sqrt{\beta_3 - m(2+m)}} \right)} \quad (3)$$

We use  $m=-1$  to illustrate Gaussian pulse generation in a 500-m HNLf with  $\gamma = 15 \text{ W}^{-1}\text{km}^{-1}$  and  $\beta_4 = 8 \times 10^{-56} \text{ s}^4 \text{ m}^{-1}$ . Adjusting  $\Delta\omega_p$  and  $\beta_2$  according to Eq. (2), Fig. 1(a) shows that  $\Delta\beta_L$  is bounded with variations of less than  $0.01\gamma P_0$  over 6.2 THz and induces a flat peak gain spectrum. We verify on Fig. 1(b) that the generated pulses exhibit indeed invariant and Gaussian shapes over the whole bandwidth.

### Nyquist pulse generation

We now consider the case  $m=-3$ . In this case, it can be shown that:

$$P_1(L,t) \approx P_s(0,t) (\gamma P_0 L)^2 \text{sinc}^2(\sqrt{3}\gamma P_0 L f_R t) \quad (4)$$

Eq. (4) shows that a sinc-like pulse shape is generated. These pulses constitute a class of Nyquist pulses and allow for reduced ISI in OTDM communications systems<sup>5</sup>. Using the same HNLf, we verify on Fig. 1(c) & (d) that invariant Nyquist pulses can be generated over a bandwidth of 5.2 THz.

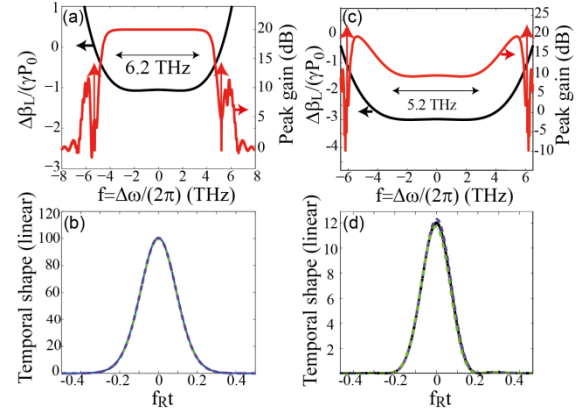


Fig. 1: (a) Linear phase mismatch and gain spectra with  $\Delta\omega_p = 33 \times 10^{12} \text{ rad/s}$  and  $P_0 = 400 \text{ mW}$ . (b) Generated Gaussian pulses at  $f = 0.5 \text{ THz}$ ,  $1.5 \text{ THz}$  and  $3 \text{ THz}$ . (c) Linear phase mismatch and gain spectra with  $\Delta\omega_p = 44.4 \times 10^{12} \text{ rad/s}$  and  $P_0 = 500 \text{ mW}$ . (d) Generated Nyquist pulses at  $f = 2.4 \text{ THz}$ ,  $1.6$ ,  $1.8 \text{ THz}$ .

### Experimental Setup

In order to validate the theory, we performed an experiment using the setup depicted in Fig.2. Two tunable high signal to noise ratio (SNR) CW external cavity lasers (TL<sub>1</sub> and TL<sub>2</sub>) were used as FOPA pumps at 1535.5 nm and 1603.7 nm, respectively. In this experiment, one of the pumps (TL<sub>1</sub>) was intensity modulated by a 10 GHz sinusoidal wave. One can show that pulses generated this way are wider by a factor  $\sqrt{2}$  compared to the two-pump IM case of Eq. (3). Both pumps were phase modulated by a pseudo random bit sequence (PRBS) in order to suppress stimulated Brillouin scattering (SBS), before being amplified and filtered to suppress amplified spontaneous emission (ASE) in order to reach  $P_0 = 480 \text{ mW}$  at the fiber input. The two pumps were coupled via a WDM and combined with a tunable CW laser (TL<sub>3</sub>), which was used as the signal seed and swept across the C and L band. The three optical waves were then launched into a 350 m long segment of HNLf with nonlinearity coefficient  $\gamma = 13 \text{ W}^{-1}\text{km}^{-1}$  and zero dispersion wavelength (ZDW)  $\lambda_0 = 1569.1 \text{ nm}$ . The third and fourth order dispersion parameters of the fiber are  $\beta_3 = 3.6 \times 10^{-34} \text{ s}^3 \text{ m}^{-1}$  and  $\beta_4 = 6 \times 10^{-56} \text{ s}^4 \text{ m}^{-1}$ , respectively. At the output of the HNLf, the parametric process was monitored through a 1% tap on an optical spectrum analyser (OSA). Finally a WDM was employed to separate the generated idler from the high power pumps and signal. The temporal and spectral characteristics of the generated

pulsed idler was monitored on an OSA and high speed oscilloscope.

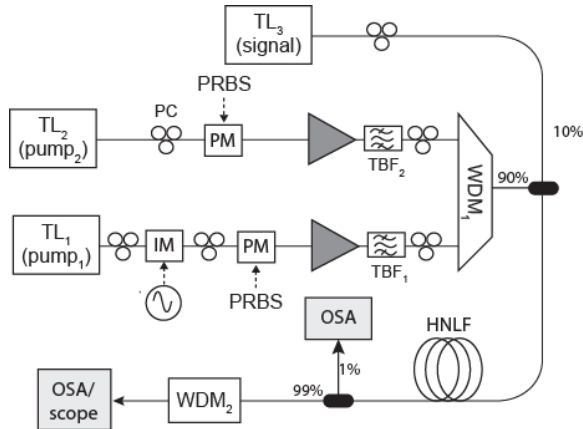


Fig. 2: Experimental setup. TL: tunable laser; IM: intensity modulator; PM: phase modulator; PC: polarization controller; TBF: tunable bandpass filter; WDM: wave-length division multiplexer; OSA: optical spectrum analyser

## Results and discussions

The experimental gain spectrum corresponding to the described setup is shown in Fig.3. The theoretical fit based on six-wave model is also plotted for comparison. A flat gain over a 50 nm interval with less than 0.25 dB ripples is observed with an excellent match between experiment and theory. Theoretically, the flat top region could be extended by several tens of nanometer. In practice we were restricted by available WDMs. The plot of the phase mismatch term shows that  $\Delta\beta_L$  is bounded around  $-0.0024 \text{ m}^{-1}$  ( $-0.38 \gamma P_0$ ) with  $\rho < 0.13$  over 32 nm bandwidth.

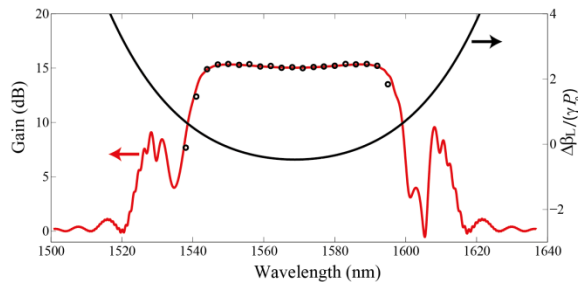


Fig. 3: Experimental gain (circles), theoretical gain and phase mismatch as a function of wavelength for the 2-pump FOPA.

The characteristics of the generated pulses in terms of peak intensity and FWHM are depicted in Fig.4 along with a typical waveform and the Gaussian fit. Pulses with more than 25 dB SNR were generated over the bounded interval of the phase mismatch term with average FWHM of 37.6 ps and average peak intensity of 15.5 mV and deviation below  $\pm 0.18 \text{ ps}$  and  $\pm 0.06 \text{ mV}$ , respectively. The pulses are fitted with a Gaussian function of FWHM 37.6 ps in good accordance with theory. The slight deviation is

attributed to the fact that in our experiment the value of  $m$  is well above -1.

In order to decrease the value of  $m$  and obtain shorter Gaussian pulses ( $m = -1$ ) or Nyquist pulses ( $m = -3$ ), it is necessary to increase the spacing between the pumps. Indeed, the low value of the HNLFF  $\beta_4$  imposes a minimum spacing of 112 nm between the two pumps in order to generate Nyquist pulses. The pumps spacing should even be more extended so as to achieve a flatter  $\Delta\beta_L$  by tuning  $\beta_2$ . Using high power wavelength conversion, the spacing between the pumps can be increased beyond limitations imposed by C and L band EDFAs. Also, HNLFFs with lower positive  $\beta_4$  could be used, but at the expense of bandwidth.

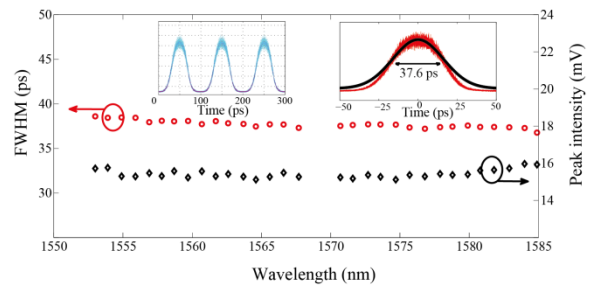


Fig. 3: FWHM and peak intensity of the generated pulses as a function of wavelength. The insets show pulse colorgrade and Gaussian fit.

## Conclusion

The theory of pulse generation with two pumps FOPA was derived for the first time to the best of the authors' knowledge. It showed that two-pumps FOPAs offer the unique possibility of generating the same temporal dynamic over a wideband spectrum. The temporal dynamic can also be adjusted to generate a wide variety of pulse shapes including Nyquist pulses. The theory was verified experimentally and uniform pulses at 10 GHz were generated over 32 nm of bandwidth. Efforts are underway to generate Nyquist pulses over a bandwidth of more than 100 nm. These concepts may be further expanded to generate Nyquist pulses for WDM systems.

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