# Theoretical Study of High Repetition Rate Short Pulse Generation With Fiber Optical Parametric Amplification

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***Abstract*—In this paper, we study theoretically the generation of high repetition rate short pulses using fiber optical parametric amplification. We show that the pulse shape and duration depend on the signal location relatively to the pump frequency. We demonstrate that in order to get the shortest pulse width, the signal must be located at one of the extremities of the gain spectrum associated with the pump peak power. We derive the analytical expression of the pulse shape in this case and compare it to the exponential gain regime case. Using numerical simulations, we also analyze the impact of walk-off and pump phase modulation that is required to suppress Stimulated Brillouin Scattering and derive guidelines to design stable train of short and high repetition rate pulses.**

***Index Terms*—Nonlinear optics, optical communications, ultrafast optics.**

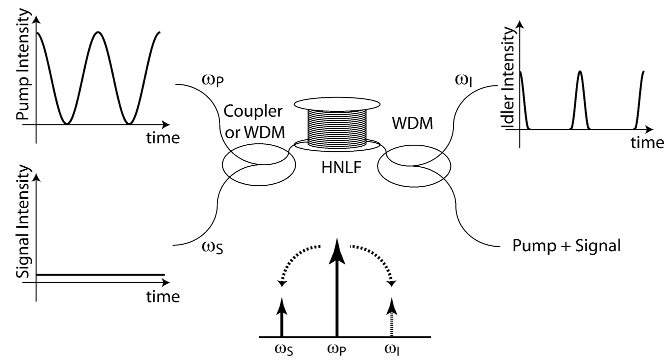


Fig. 1. Schematic of short pulse generation principle using single-pump OPA. WDM: wavelength demultiplexer/multiplexer; HNLF: highly nonlinear fiber.

## I. Introduction

WITH growing demand for capacity, optical telecommunications networks need to operate at ever increasing bitrates. At the same time, the economical viability of future optical networks will depend on their flexibility and ability to adapt to different bitrates, formats of coding and access techniques: while backbone networks are emigrating towards wideband dense wavelength division multiplexing (WDM) of 100 Gb/s channels using multiple level differential phase shift keying (n-DPSK) [1], the development of FTTx has also sparked renewed interest for flexible access techniques such as optical code division multiple access (OCDMA) [2]. For all of these, a reliable and flexible high repetition source delivering short pulses in the 1550 nm telecommunications window and easily compatible with fiber applications appears to be a key device. In backbone networks, low duty-cycle (DC) pulsed sources can be used to mitigate the effects of dispersion. In OCDMA-PON, short pulses allow for coherent spectral coding, which leads to reduced multiple user interference and better quality of service networks [3]. Moreover, high repetition rate short pulses can also find applications in time domain demultiplexing or sampling applications [4]–[8]. Using high nonlinearity and highly birefringent fiber together with a short pulse can also be used to demultiplex signals in time and wavelength simultaneously [9].

Many techniques allow for the realization of high repetition rate short pulses. Although intensity modulators can generate pulses shorter than 10 ps, the limitation of the electronic bandwidth makes it difficult to go much below. Mode-locked lasers (MLL) are another source of short pulses. Using phase or amplitude modulators, it is possible to operate at repetition rate higher than the laser cavity fundamental mode. Fiber MLL providing subpicosecond pulses at 10 GHz are commercially available. Using adjusted multiplexers, these sources can also provide repetition rates well above 100 GHz. However, they require an electrical phase-locked loop for stability. Moreover, when changing the repetition rate, the cavity length must be adjusted to recover mode-locking [10].

An alternative for short pulse generation is to use fiber optical parametric amplification (OPA). The schematic of the principle for pulse generation using a single pump OPA is depicted in Fig. 1. A sinusoidal high intensity pump is coupled with a continuous (cw) small intensity signal into a highly nonlinear fiber (HNLF). Along the HNLF, the pump wave transfers its energy to the signal wave and generates an idler wave through a phase-matched four-wave mixing (FWM) process [11].

The efficiency of this process is based on the quasi-instantaneous Kerr effect and depends on the phase-matching between the pump, signal and idler waves. The phase matching depends on the dispersion parameters of the amplifying fiber, but also on the pump instantaneous power through self phase modulation

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(SPM), also due to the Kerr effect. Hence, the amplification of a signal and the generation of an idler depend on their locations relatively to the pump frequency, but also on the pump instantaneous intensity. Through its impact on phase-matching, small decrease of the pump power can lead to an abrupt shrinking of the gain. Therefore, using a sinusoidal intensity modulated pump, parametric gain is generated on the idler side only when the pump power is close to its peak, which leads to the generation of short pulses. In recent years, these sources have been experimentally demonstrated and used for sampling and demultiplexing applications [12]–[15]. These sources have the advantage of being all-fibered. Moreover, they offer more stability and flexibility over MLL as there is no need to adjust and maintain the cavity length. Theoretical studies of pulse generation with OPA have focused on the case of perfect phase-matching [13], [16].

In the following, we revisit the theory of pulse generation with OPA, taking into account the impact of phase matching on the pulse shape and duration. Using numerical simulations, we study the detrimental impact of walk-off and pump phase modulation, which is required to avoid stimulated Brillouin scattering (SBS)-induced pump depletion, on the generated pulses and give guidelines to design stable short pulses at ultrahigh repetition rates.

## II. Theory

### A. Gain Sensitivity to Pump Power

We consider the propagation along a HNLF of the pump, signal and generated idler waves at angular frequencies $\omega_P, \omega_S$ and $\omega_I$, respectively. Parametric amplification being an energy conserving process, we have: $|\omega_I - \omega_P| = |\omega_S - \omega_P| = \Delta\omega_S$.

The slowly varying envelope (SVE) of the sinusoidal pump field at the amplifying fiber input is of the form: $A_P(0,t) = \sqrt{P_0}e^{j\varphi_P}\cos(\pi f_R t)$. $f_R$ is the repetition rate of the intensity-modulated pump, which also determines the repetition rate of the generated pulse. $\varphi_P$ is the arbitrary pump SVE phase, which can be set to zero without loss of generality in phase-insensitive fiber OPAs. Assuming non-depletion and neglecting fiber loss, one can derive the output pump SVE from the nonlinear Schrödinger equation (NLSE) [11], [17]

$$A_P(L,\tau) = A_P(0,\tau)e^{j\gamma|A_P(0,\tau)|^2 L} = \sqrt{P_0}\cos(\pi f_R \tau)e^{j\gamma P_0 \cos^2(\pi f_R \tau)L} \quad (1)$$

where $L$ is the amplifying fiber length and $\gamma$ is the fiber nonlinearity coefficient. $\tau = t - z/v_g$ is the time in a reference frame moving at the pump carrier frequency group velocity. Note that the above expression holds as long as self-phase modulation (SPM) dominates over dispersion along the fiber [18].

Using (1), one can also derive the generated idler gain from the NLSE [11], [13]

$$G(L,\tau) = \left[\frac{\gamma P(\tau)}{g(\tau)}\sinh(g(\tau)\times L)\right]^2 \quad (2)$$

where $P(\tau) = P_0\cos^2(\pi f_R \tau)$ is the time varying pump intensity, $g(\tau)^2 = [\gamma P(\tau)]^2 - (\kappa(\tau)^2)/(4)$ and $\kappa(\tau) = 2\gamma P(\tau) + \Delta\beta_L$ is the phase matching term between the pump, the signal and the idler. $\Delta\beta_L = \beta_2\Delta\omega_S^2 + (\beta_4)/(12)\Delta\omega_S^4$ is the linear phase mismatch with $\beta_2$ and $\beta_4$ the dispersion and the dispersion curvature at $\omega_P$ respectively. Note that $\Delta\beta_L$ is not time varying and depends on the fiber dispersion parameters and the interacting waves locations ($\Delta\omega_S$).

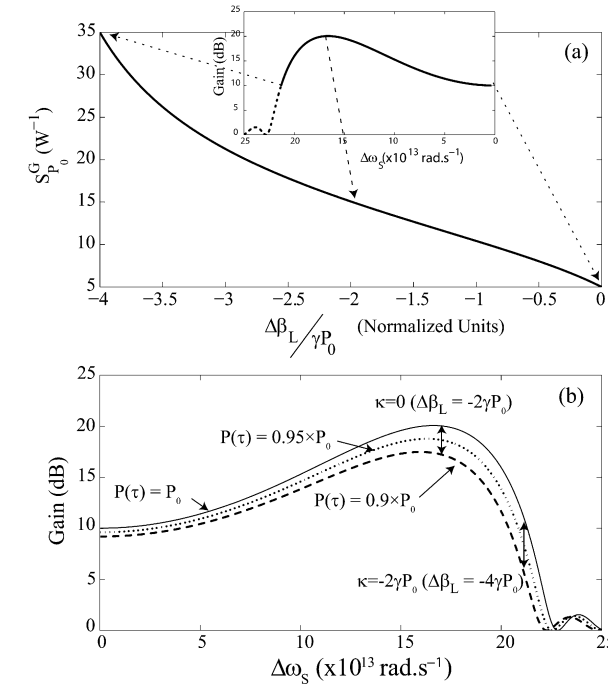


Fig. 2. (a) Sensitiviy as a function of $\Delta\beta_L$ normalized by $\gamma P_0$. The inset represents the corresponding gain spectrum for a typical HNLF with dispersion parameters $\beta_2 = 2.9\times10^{-29}$ s$^2$.m$^{-1}$ and $\beta_4 = -6.4\times10^{-55}$ s$^4$.m$^{-1}$. (b) Parametric gain spectrum for different pump powers.

From (2), it can be readily shown that the parametric gain drops when the pump power is decreased. However; the rate at which the gain drops depends on the signal position. In order to locate the signal position relatively to the pump position where the gain drops the most abruptly, we introduce the sensitivity of the gain relative to the pump power as

$$S^G_{P_0} = \frac{\partial \ln G}{\partial P_0} = \frac{\frac{\partial G}{\partial P_0}}{G} \quad (3)$$

$S^G_{P_0}$ can be viewed as a measure of how sharp the generated idler normalized power drops with decreasing pump power. It is plotted on Fig. 2(a) as a function of $\Delta\beta_L$. It shows that the sensitivity reaches its maximum when $\Delta\beta_L = -4\gamma P_0$. It decreases with increasing $\Delta\beta_L$. Note that this location corresponds to the edges of the gain spectrum when $P(\tau) = P_0$. This can be explained graphically by looking at Fig. 2(b). A reduction in pump power induces a shrinking of the gain level and bandwidth simultaneously [11]. When the pump power is decreased, a signal located at one of the edge of the gain spectrum will therefore fall outside the gain bandwidth sooner than signals located closer to the pump. As a consequence, $S^G_{P_0}$ will be highest at the corresponding idler location and will hence allow for the generation of the shortest pulse duration at this location. Note also that this location corresponds to the minimum idler gain one can obtain when $P(\tau) = P_0$. There will therefore be a trade-off between the generated pulse duration and its peak power.

### B. Pulse Duration and Shape

Because of the $1/f_R$-periodicity of the pump, we can restrain ourselves to the time interval $[-1/(2f_R), 1/(2f_R)]$ without loss of generality. Following the above discussion, it is clear that the gain shrinks abruptly with a slight pump power decrease. Hence, we may assume that over most part of the generated pulse, the pump can be replaced with its development to the second order in $\tau$:

$$P(z,\tau) \approx P_0\left[1-(\pi f_R\tau)^2\right]. \quad (4)$$

Inserting (4) into (2) and keeping only the second order terms in $\tau$, the amplitude of the generated pulse at the HNLF output is found to be

$$P_{\rm out}(\tau) = \left[P_s(\gamma P_0 L)^2\right]\,{\rm sinc}^2(2\pi\gamma P_0 L f_R \tau) \quad (5)$$

where ${\rm sinc}(x) = \sin(x)/x$. Equation (5) shows that the generated pulse cannot be assumed to be Gaussian for any $\Delta\beta_L$, as in [13]. The pulse duration, defined as the full width at half maximum is then given by

$$T_{\rm FWHM} = \frac{\alpha}{\gamma P_0 \pi f_R L} \quad (6)$$

where $\alpha \approx 1.3916$ is solution to the equation ${\rm sinc}(\alpha) = 1/\sqrt{2}$. The duty cycle, defined as ${\rm DC} = f_R T_{\rm FWHM}$ is then found to be

$${\rm DC} = \frac{\alpha}{\pi\gamma P_0 L} \approx \frac{0.443}{\gamma P_0 L}. \quad (7)$$

This expression shows that the duty cycle is inversely proportional to $\gamma P_0 L$. For comparison, we have derived the expression of the generated pulse when the maximum parametric gain is achieved at the pump peak power. In this case the signal, idler and pump waves verify the perfect phase matching condition ($\kappa(0) = 0$ or $\Delta\beta_L = -2\gamma P_0$):

$$P_{\rm out}(\tau) = P_s\frac{e^{2\gamma P_0 L}}{4}e^{-2\gamma P_0 L(2\pi f_R\tau)^2}. \quad (8)$$

This latter expression is similar to [13], and shows that the generated pulse shape can be assumed Gaussian only when $\kappa(0) = 0$. The DC is then found to be

$${\rm DC} = \frac{1}{\pi}\sqrt{\frac{2\ln 2}{\gamma P_0 L}} \approx \frac{0.375}{\sqrt{\gamma P_0 L}}. \quad (9)$$

Equation (9) shows that in the case of perfect phase matching at the pump peak power ($\kappa(0) = 0$ or $\Delta\beta_L = -2\gamma P_0$), DC is inversely proportional to $\sqrt{\gamma P_0 L}$ and greater than in the case where $\Delta\beta_L = -4\gamma P_0$. Using (7) and (9), we have depicted in Fig. 3(a) the DC of the generated pulses as a function of $\gamma P_0 L$ for $\Delta\beta_L = -4\gamma P_0$ and $\Delta\beta_L = -2\gamma P_0$. We have also plotted the DC as calculated using (2). There is a very good agreement between the analytical and the calculated DC. Therefore, Fig. 3(a) shows that one can obtain shorter pulses by increasing the pump power, the fiber length or both. Fig. 3(b) also depicts the normalized generated pulses for $\Delta\beta_L = -4\gamma P_0$ (using (5))

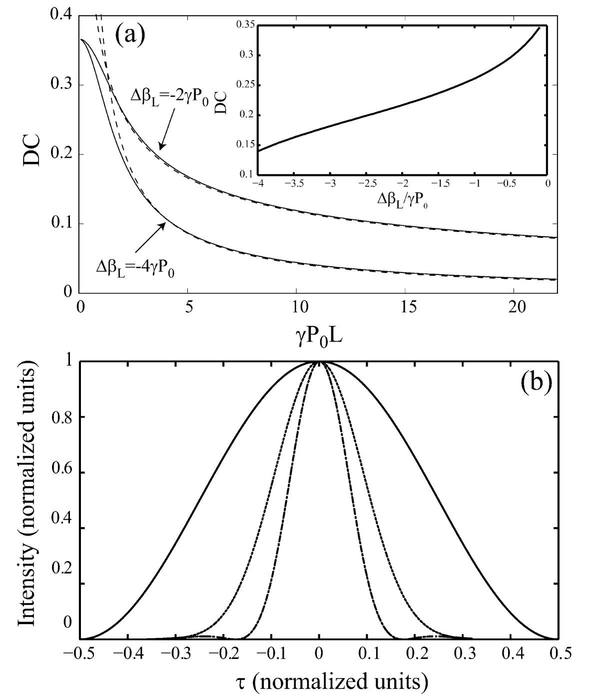


Fig. 3. (a) Duty cycle as a function of $\gamma P_0 L$ for $\Delta\beta_L = -4\gamma P_0$ and $\Delta\beta_L = -2\gamma P_0$, using the derived analytical expressions of (7) and (9) (solid line), and using the gain expression of (2) (dashed line). (b) Normalized temporal traces of pump (solid line) and generated idler for $\Delta\beta_L = -2\gamma P_0$ (dotted line) and $\Delta\beta_L = -4\gamma P_0$ (dashed-dotted line).

and $\Delta\beta_L = -2\gamma P_0$ (using (8)) for a typical fiber optical parametric amplifier in an HNLF with $P_0 = 400$ mW, $\gamma = 0.015$ W$^{-1}$m$^{-1}$ and $L = 500$ m. This gives a minimum peak gain of 9.5 dB when $\Delta\beta_L = -4\gamma P_0$ and a maximum peak gain of 20 dB when $\Delta\beta_L = -2\gamma P_0$. It clearly shows that the generated pulse for $\Delta\beta_L = -4\gamma P_0$ is shorter than the one for $\Delta\beta_L = -2\gamma P_0$. This also points out the trade-off that exists between the highest achievable pulse peak power and the shortest achievable pulse duration.

## III. Numerical Simulations

### A. Impact of Walk-Off

In order to validate our analytical results, we have conducted numerical simulations of the nonlinear Schrodinger equation (NLSE) using the split-step Fourier method. The parameters of the fiber OPA are the same as in Fig. 2(b). The dispersion properties $\beta_2, \beta_3$ and $\beta_4$ are $-2.9\times10^{-29}$ s$^2$.m$^{-1}$, $5.3\times10^{-41}$ s$^3$.m$^{-1}$ and $-6.4\times10^{-55}$ s$^4$.m$^{-1}$, respectively. These parameters lead to a half gain bandwidth of 3.38 THz (or 27 nm in the C and L-band Telecom window) at pump peak power, similar to the gain spectrum depicted in the inset of Fig. 2(a). The cw-signal is located at the edge of the gain spectrum ($\Delta\omega_S = 21.26\times10^{13}$ rad.s$^{-1}$) where $\Delta\beta_L = -4\gamma P_0$. The repetition rates range from $f_R = 1$ GHz to $f_R = 100$ GHz.

In Fig. 4(a), the pulse shapes are depicted for increasing repetition rate. For $f_R = 1$ GHz, the pulse shape is in good agreement with theory. As the repetition rate increases, we can see that the generated pulses are shifted to later times. This behavior

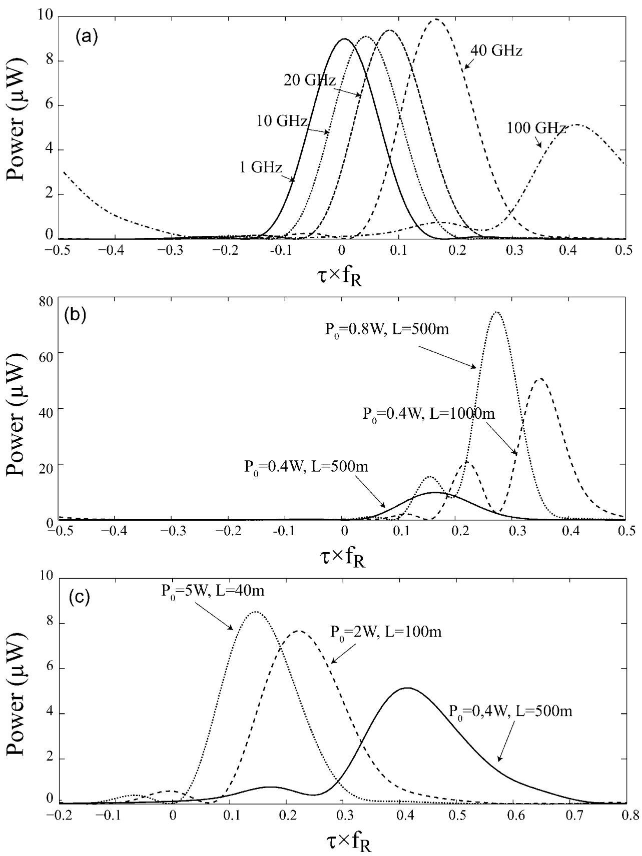


Fig. 4. (a) Generated pulse shapes for different repetition rates $f_R$. In all cases, we have $\gamma P_0 L = 3$. (b) Generated pulse at $f_R = 20$ GHz for $\gamma P_0 L = 3$ (solid line) and for $\gamma P_0 L = 6$ with a doubled pump power (dotted line) or a doubled HNLF length (dashed line). (c) Generated pulse at $f_R = 100$ GHz for different sets of $P_0$ and $L$ leading to $\gamma P_0 L = 3$.

suggests that the walk-off between the pump and the generated pulse is playing an important role. We also observe that for $f_R \leq 40$ GHz the pulse shape is not deteriorated, however its peak power increases with higher repetition rate. At $f_R = 100$ GHz the pulse is clearly deteriorated. These observations can also be accounted for by the walk-off effect [16]. Indeed the walk-off induced delay between the pump and the generated idler at the HNLF output is 6 ps. At low repetition rate, the impact of walk-off is therefore negligible and the pulses are not deteriorated. As $f_R$ increases, the generated pulse spectrum becomes wider. The pulse spectral components that are closer to the pump experience less walk-off and more parametric gain. This leads to higher pulse peak power as long as the overlap between the pump and the generated pulse remains. At $f_R = 100$ GHz, the overlap between the pump and the idler is lost and hence the generated idler is deteriorated.

In Fig. 4(b) & (c), we verify the impact of walk-off on the generated pulse. Fig. 4(b) shows that in order to decrease the pulsewidth by a factor of two at $f_R = 20$ GHz, it is preferable to double the pump power rather than the HNLF length. Indeed, when the HNLF length is doubled, the walk-off induced delay is also doubled and leads to deteriorated pulses, whereas when the pump power is doubled, $\Delta\omega_S$ must be tuned to $27.8 \times 10^{13}$ rad.s$^{-1}$ in order to keep $\Delta\beta_L = -4\gamma P_0$, which increases the walk-off induced delay to 9.5 ps. Fig. 4(c) shows

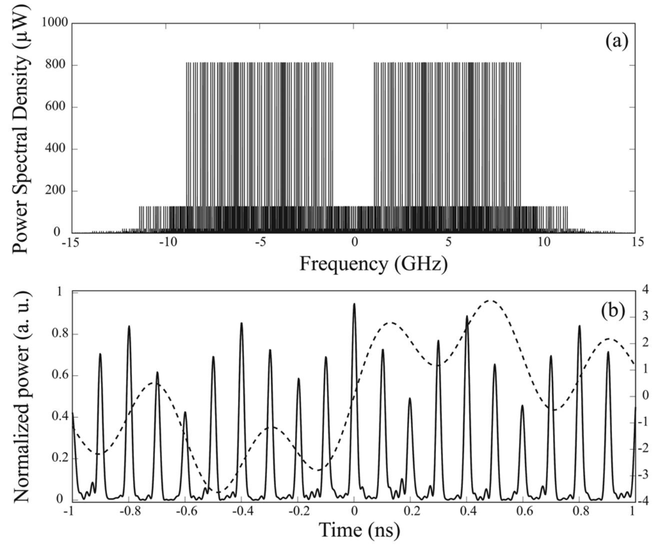


Fig. 5. (a) Spectrum of multitone phase modulated sinusoidal pump. (b) Train of generated pulses at the idler location (solid line, left axis) showing how it fluctuates because of pump phase fluctuations in time (dashed line, right axis).

that we can obtain shorter pulses even at $f_R = 100$ GHz by increasing pump power and decreasing the HNLF length. For an HNLF length of 40 meters and pump peak power of 5 W, the pulse shape becomes close to the theoretically predicted pulse shape with $T_{\mathrm{FWHM}} = 1.6$ ps. Note that a similar OPA with cw pumping was experimentally demonstrated in [19], suggesting that such scheme is feasible. It should be noted that at such high repetition rate, one of the main experimental challenge would be to generate a high peak power and broad spectrum pump without adding too much noise. One way could be to separately amplify and filter the sinusoid components and recombine them through a WDM.

### B. *Impact of Pump Phase Modulation*

In practical experimental OPA setups, the parametric pump also generates stimulated Brillouin scattering (SBS) that can lead to pump depletion. Modulating the intensity of the pump by a sinusoid only increases the Brillouin power threshold by 3 dB, which is still not sufficient to avoid SBS [20]. The most commonly used technique to avoid SBS is phase modulation (PM) of the pump either by a pseudo-random bit sequence (PRBS) or a set of RF tones at different frequencies (multitone) [21]–[23]. In particular, a multitone modulation scheme is known to broaden the pump spectrum evenly and leads to more efficient SBS suppression than PRBS. However, it has been shown that in cw OPA, pump phase modulation induces signal and idler distortions [24].

We have performed numerical simulations of the NLSE for a multitone and a PRBS pump phase modulation. The parameters are the same as in Fig. 4(a). The repetition rate was set at 10 GHz where walk-off has a negligible influence. Fig. 5(a) and (b) show the influence of a multitone driven pump phase modulation.

When the frequencies of the multitone signal are selected such that they don't have any common denominator, we verify in Fig. 5(a) that the pump spectrum is evenly spread and the components are above Brillouin threshold.

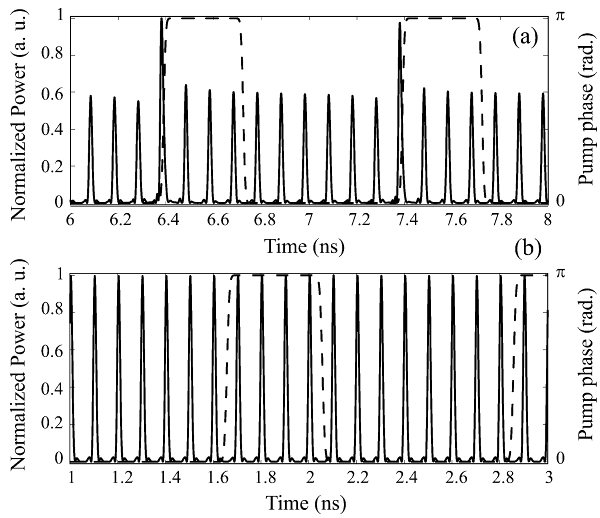


Fig. 6. (a) Train of generated pulses (solid line. left axis) and pump phase (dashed line, right axis) for a 3 Gb/s PRBS phase modulation. (b) Train of generated pulses (solid line. left axis) and pump phase (dashed line, right axis) for a 2.5 Gb/s PRBS phase modulation with an adjusted delay time.

However, Fig. 5(b) shows that the generated train of pulses is not uniform, but fluctuates due to the pump phase variations. These variations are both due to PM induced idler broadening and PM induced pump frequency shift [25], [24].

A PRBS driven phase modulation has been shown to better alleviate idler broadening provided that the pump phase jumps are equal to $\pi$ [25]. Fig. 6(a) shows a train of generated pulses with a sinusoidal pump phase modulated by a 3 Gb/s PRBS with a rising/falling time of 33 ps between each phase jump. The pulses are uniform only when the pump phase is constant. When a pulse is generated during a pump phase jump, its peak power is either reduced or increased. This is due to the pump frequency being shifted during each phase jump, inducing a variation of the phase-matching between the pump, signal and idler waves and consequently a parametric gain variation.

In order to attenuate these fluctuations, it is thus necessary that the pump phase jumps occur in between the generated pulses. The PRBS must therefore be tuned to a rate that is a fraction of the repetition rate $f_R$ and delayed by $\pm 1/(2f_R)$ from the pump peak power location. In this case, the pump phase jumps occur only during the dip of the sinusoidal pump where no idler is generated. Fig. 6(b) illustrates that a PRBS phase modulation with 2.5 Gb/s rate and 50 ps delay from the pump peak power location enables to generate a uniform pulses train at 10 Gb/s. In this case, it can be clearly seen that the pump phase jumps always occur when no pulse is generated on the idler side and hence do not interfere with the generated pulses train.

## IV. Conclusion

By revisiting the theory of pulse generation with single pump fiber OPA, this study reveals the strong influence of phase matching on the pulse duration and shape. The concept of sensitivity to pump power decrease was introduced and was shown to increase with decreasing linear phase mismatch $\Delta\beta_L$. As a consequence, the shortest pulse is obtained when $\Delta\beta_L = -4\gamma P_0$. This location corresponds to the edge of the parametric gain spectrum when the pump power is at its peak $P_0$ in a typical fiber OPA.

Using a Taylor development, we have derived analytical expressions of the generated pulse in the case where the generated pulses are the shortest, and in the case where the gain is the highest at $P_0$ (exponential gain regime) with the generated pulses having the highest peak power.

The theory was shown to be in good agreement with numerical simulations of the NLSE. The impact of walk-off was studied and shown to deteriorate the generated pulses. By using higher pump peak power and lower fiber length, it is possible to attenuate the impact of walk-off and obtain non deteriorated 1.6 ps width pulses at 100 Gb/s repetition rate.

Finally, we have shown that the unavoidable pump phase modulation may lead to fluctuations in the train of generated pulses. In order to get a uniform train of pulses, we have shown that it is preferable to use a PRBS driven phase modulation with an adjusted bit rate and time delay so that the phase jumps occur during a dip of the sinusoidal pump. Note that other sources of noise such as quantum noise, relative intensity noise (RIN) transfer from pump to signal and idler [26], [27], or Raman induced noise [28] may cause random fluctuations of the generated pulse train and need to be quantified in order to satisfactory predict the stability of high repetition rate short pulses based on fiber OPA.

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