Near-Nyquist sinc shaped optical pulse generation in fiber optical parametric amplifier

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Abstract *Using optical fiber amplification and phase modulation, we demonstrate experimentally the generation of pulses with characteristics that are close to Nyquist limited sinc pulses. Bandwidth limited pulses of full width half maximum less than 17 ps at 10 GHz repetition rate are achieved.*

Introduction

With the growing need for end user bandwidth, the demand for higher capacity optical fiber networks remains steady. Limitations of viable alternatives to expand the bandwidth of optical telecommunications beyond the limitations imposed by erbium doped fiber amplifiers (EDFAs) has funneled recent research efforts towards increasing the spectral efficiency of transmitted signals. Besides multiplying the number of transmitted bits per symbol with multi-level phase and/or amplitude modulation schemes in coherent transmission systems, efforts are underway to contain the transmitted signal spectrum within a bandwidth that is as close as possible to the symbol rate, which is the lower bound dictated by Nyquist theorem.

Such trend is observed in recent demonstrations of Nyquist-WDM transmissions[1]. In these schemes, the symbol pulse is fabricated so that its spectrum has a near rectangular shape. This can be done by optical filtering techniques, with limitations due to achievable fiber steepness or by digital signal processing techniques that are limited by the electronic bandwidth[1,2]. Furthermore, for applications such as all-optical sampling or optical analog-to-digital convertion (ADC), being able to use optical Nyquist-limited pulses for sampling of the data could ease constraints on bandwidth[3] and improve performances

In recent works[4,5], it was shown theoretically and experimentally that it is possible to achieve close to sinc shapes optical pulses using fiber optical parametric amplifiers (FOPAs). However, the pump-induced chirp provokes a spreading of the generated spectrum. In this work, we compensate that chirp using a phase modulator and demonstrate a bandwidth-contained pulse that nears the characteristics of a Nyquist pulse.

Theory and numerical simulation

Suppose that the pump wave amplitude is modulated such that $A_P\left(0,t\right)=\sqrt{P_0}\cos\left(\pi f_R t\right)$, where P_0 is the pump peak power and f_R is the repetition rate, and the signal is detuned from the pump angular frequency by $\Delta\omega_S$ such that:

$$\beta_2\Delta\omega_S^2+\frac{\beta_4}{12}\Delta\omega_S^4=-4\gamma P_0 \qquad (1)$$

where β_2 and β_4 are the amplifying fiber second and fourth order parameters. The generated idler at the FOPA output will have the following wave amplitude[4]:

$$A_i(\tau)\approx\left(\sqrt{P_s}\,\gamma P_0 L\right)\mathrm{sinc}(2\pi\gamma P_0 L f_R\tau)\times e^{i\left(\gamma P_0\cos^2(\pi f_R t)+2\gamma P_0\right)L} \qquad (2)$$

where γ is the nonlinear coefficient of the amplifying fiber. Eq. (2) shows that the combination of quasi-phase matching and cross-phase modulation from the pump induces a chirp on the generated idler that prevents the spectrum from being Nyquist limited. Unlike Gaussian pulses, this chirp cannot be straightforwardly compensated by a passive dispersive medium. Rather, an active chirp compensating module is required. Here, we used a phase modulator to compensate for the chirp. The principle is shown in Fig. 1. Before the phase modulator, the generated idler at the FOPA output is chirped and hence its spectrum is spread. Driving the phase modulator with a sinusoid pattern that oscillates between $\pm\gamma P_0 L$, it is possible to suppress the FOPA induced chirp on the idler by aligning the peak of the

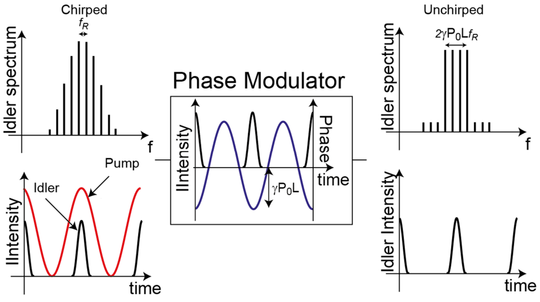

Fig. 1: Principle of near Nyquist pulse generation

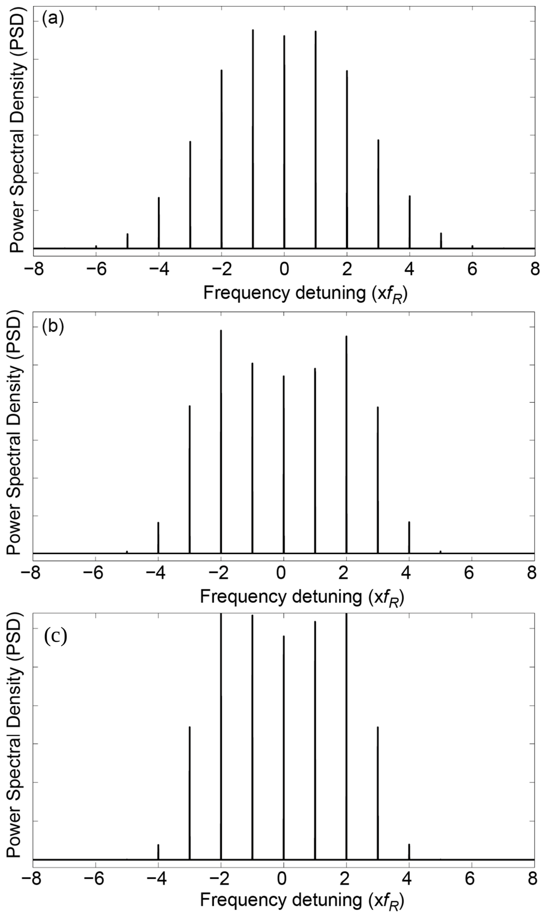

Fig. 2: Numerical simulations of the proposed scheme. (a) FOPA output idler spectrum. (b) Idler spectrum after phase modulation. (c) Idler spectrum after phase modulation with parabolic pulse FOPA pumping.

generated pulse with the trough of the driving sinusoid. In the ideal case, the pulse spectrum becomes rectangle shaped of width $2\gamma P_0 L$.

We have performed numerical simulations of this scheme by solving the nonlinear Schrodinger equation (NLSE) and applying the phase modulation to the output idler. The FOPA was designed so that $\gamma P_0 L$ = 4. This corresponds to a peak gain of 12.3 dB at the signal location. Fig. 2(a) and (b) show the spectrum of the generated pulse on the idler side at the FOPA output before and after phase modulation, respectively. After the FOPA, the spectrum is spread. After phase modulation, we note that the distant sidebands power spectral density (PSD) is decreased, hence containing the spreading of the pulse spectrum. We note that the spectrum is not rectangular. The reason is that in obtaining Eq. (1), we made the assumption that the pump sinusoidal shape is close to a parabola, which is valid only close to the pump peak power. However in recent years, optical parabolic pulses have been developed[6]. Fig. 2(c) shows that using parabolic pulses for pumping the FOPA and driving the phase modulator, it is possible to achieve Nyquist limited pulse.

Experimental Setup

The experimental setup is sketched in Fig. 3. For the pump, a continuous wave (CW) laser was intensity modulated by a sinusoid at 10 GHz, then phase modulated by a 5 GHz 2^{15}-1 PRBS to eliminate stimulated Brillouin scaterring (SBS). Two subsequent stages of amplification and filtering were used to reach the required pump peak power. Pump and signal were mixed into a 500 m long highly nonlinear fiber (HNLF) through a wavelength division multiplexer (WDM). At the output of the FOPA, a 10% tap was used to monitor the parametric conversion. The idler was isolated from the pump and signal by going through two WDMs and subsequently phase modulated by the same sinusoid used to drive the pump intensity modulator (IM). RF attenuators and drivers were used to adjust the peak-to-peak voltages of the driving signals to ensure that the pump IM is in the linear regime and the idler phase is modulated between $\pm\gamma P_0 L$. A variable optical delay line (VODL) was inserted to align the idler pulses with the trough of the sinusoid. The idler wave was then observed on an optical spectrum analyzer (OSA) with a resolution of 0.02 nm,

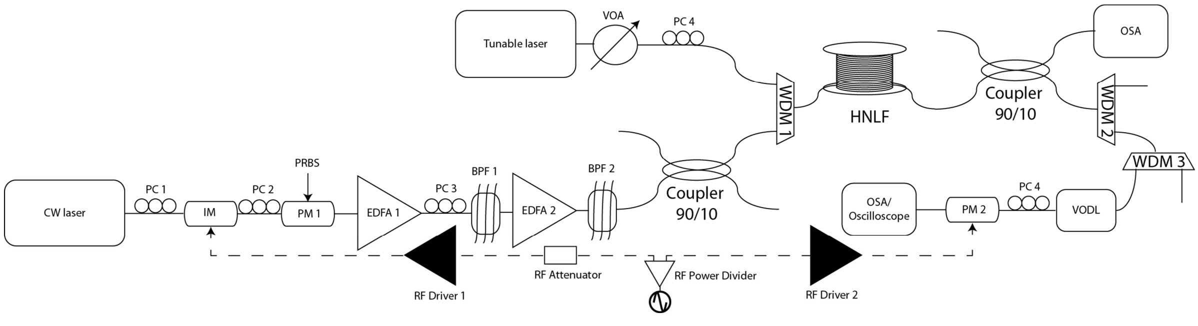

Fig. 3: Experimental Setup. PC: Polarization Controller. EDFA: Erbium Doped Fiber Amplifier. BPF: Bandpass Filter, PM: Phase Modulator, IM: Intensity Modulator, OSA: Optical Spectrum Analyzer.

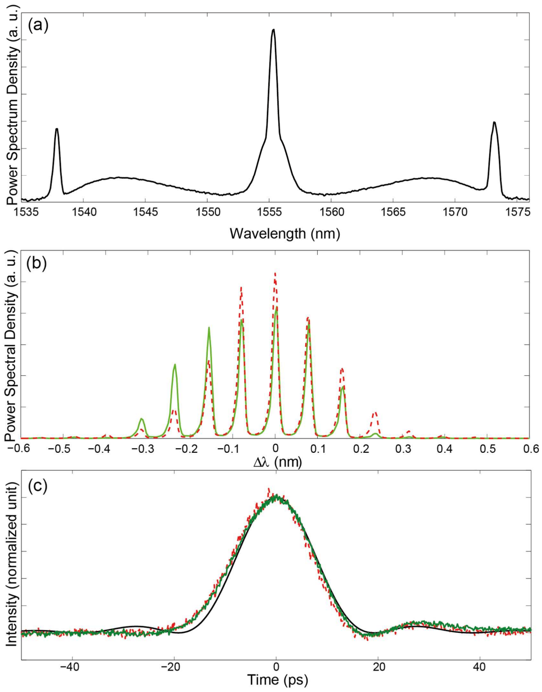

Fig. 4: Experimental results: (a) Spectrum of pump, signal and idler. (b) Idler spectrum before (dashed line) and after (solid line) phase modulation. (c) Temporal traces of sinc pulses with (solid line) and without (dashed line) phase modulation. The fitted Sinc shape is shown in black.

which corresponds to 2.5 GHz. Such resolution was sufficient to observe the 10 GHz spaced spectral components of the generated pulse. The pulse waveform was observed on an oscilloscope with electrical bandwidth of 50 GHz.

Results and Discussion

The pump wavelength was tuned on the 26th ITU grid channel (1556.56 nm). The HNLF nonlinear coefficient was 12 $W^{-1}.km^{-1}$. The maximum achievable peak to peak voltage at the output idler phase modulator (PM2) was around 7.5 V, leading to a peak to peak phase shift of 2π. Therefore, the pump peak power was tuned so that $\gamma P_0 L$ was equal to 3.2, which corresponded to P_0 = 560 mW. The signal wavelength was tuned at 1573.1 nm to satisfy Eq. (1). The corresponding idler wavelength was generated at 1537.85 nm. Fig. 4(a) shows the spectrum at the HNLF output with the pump, signal and idler waves. Fig. 4(b) shows the spectrum of the idler for the case with and without phase modulation for de-chirping. We observe that when phase modulation is applied, the energy in the central frequency component is spread to the neighboring sidebands while the higher harmonics at the spectrum edges are lowered. Hence, the spectrum is more contained and approaches the characteristics of a Nyquist pulse. We verify in Fig. 4(c), which shows the electrical waveforms retrieved from the oscilloscope, that the shape of the generated pulses are not modified by the applied phase modulation. The pulses full width half maximum (FWHM) was measured at 17 ps, which is a little wider than the theoretical value of 14 ps (black solid trace in Fig 4(c)). Note however that the measured FWHM is below the oscilloscope resolution and that our measurements were therefore limited by the available equipment. At lower repetition rate, the accordance between the experimental data and theory was been verified[5].

Conclusions

We have shown the feasibility of all-fiber all-optical near Nyquist sinc pulses using fiber optical parametric amplifiers by compensating the pump induced chirp with a phase modulator. This achievement opens up the path for new research to improve on the experimental scheme demonstrated in this work. For instance, phase conjugation technique could be used instead of phase modulation to compensate for the chirp. Furthermore, by using parabolic pulses[6] for pumping, it should be possible to generate pulses that are even closer to Nyquist pulses. Finally, this work enables new applications in sampling and transmission systems.

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