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# Chirped Pulsed Four-Wave Mixing Spectrogram retrieval from single shot spectrum measurement

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**Abstract:** Four Wave Mixing band spectrogram has been retrieved from single shot spectra when a chirped pulse is injected in a fiber. This method leads to the seed chirp required for a large gain bandwidth.

## 1. Introduction

Ultra-fast four wave mixing (FWM) in an optical fiber is a promising method to parametrically amplify ultra-short pulses at high gain in a compact and rugged geometry [1]. As the process usually involves high power pulses, the pump and signal pulses are initially stretched before being injected in the fiber. For a chirped pump pulse, the instantaneous frequencies are temporally dispersed and therefore the gain has a temporal and spectral distributions which strongly depend on the fiber and pump properties according to the phased-matched FWM relation [2,3]. Thus, the chirp of the injected signal needs to be optimized to achieve the best gain bandwidth [1]. Therefore, the temporal and spectral distributions should be characterized to design a broadband amplifier. In this presentation, we present a method to retrieve the spectrogram from the measurement of an ensemble of single shot FWM spectra using the dispersive Fourier transformation (DFT) method [4] without injecting the signal.

## 2. Method and numerical demonstration

We firstly illustrate the principle of this method using numerical simulations by integrating the nonlinear Schrödinger equation with the split step method. The parameters used were as follows. The input pump pulse has a chirp of 83.3 ps/nm with a spectral bandwidth of 6 nm (full width at half maximum-FWHM) centered at 1024 nm. This corresponds to a pulse duration of 500 ps (FWHM). The pulse is injected in a 5-meter-long photonic crystal fiber (PCF) which has a nonlinear coefficient of  $11 \text{ W}^{-1} \cdot \text{km}^{-1}$  and a zero-dispersion wavelength (ZDW) at 1028 nm. It means the pump spectrum lies in the normal dispersion regime. 1000 simulations have been performed with random noise initial condition by adding half photon per temporal mode. Figure 1.a shows the ensemble of spectra and the average (red line) for an input peak power 250 W. Two FWM lobes are clearly observed at 900 and 1200 nm. These two bands are numerically filtered and the two spectrum maxima have been selected for each single shot (Fig. 1.b). This measurement represents the simultaneous occurrence of the signal and idler photons [5] and a well identified denser zone can be observed along a diagonal. As the two axes represent the wavelength of the signal and idler, the theoretical relationship of the FWM from the photon energy conservation law can be also plotted. The three lines represent cases for a selection of pump wavelengths. Then, it is possible to infer the particular pump part, which generates the FWM bands. In our case, the known linear chirp of the pump is used to get the relative delay as the function of the pump instantaneous wavelength. Therefore, from Figure 1.b and the pump chirp, the spectrogram of each FWM band be reconstructed.

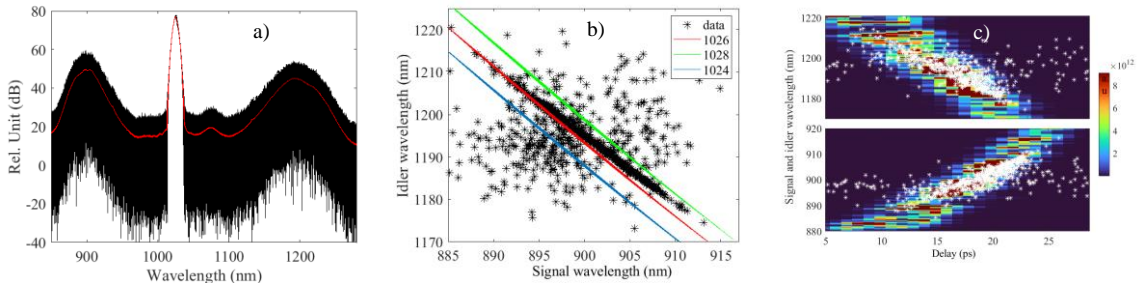


Fig. 1. a) 1000 single shots (black line) and averaged spectrum (red line) of the simulated fluorescence spectrum. b) Signal/Idler wavelength corresponding to the spectrum maxima of each FWM band. The lines are plotted from the photon energy conservation law for several pump wavelengths. c) Simulated spectrogram and spectro-temporal distribution from the spectrum maxima (white crosses).

Figure 1.c shows the spectrogram directly calculated from the frequency resolved correlation between the average electric field and a ps pulsed-gate. The retrieved spectrogram from the single shot spectra is also displayed in Figure 1.c (white points) and the very good agreement between the two distributions confirms the great potentiality of the method.

### 3. Experimental implementation

The pump pulse is generated from a regenerative amplifier (S-pulse, Amplitude Systèmes) delivering a train of pulses at 85 kHz with a duration of  $\sim 300$  fs and a spectrum centered at 1024 nm. The output beam is injected in a volume Bragg grating (VBG) that stretches the pulses to a duration of  $\sim 500$  ps with a linear chirp. The pump pulse is then injected in a 5-meter-long PCF with the same properties used for the simulation. The injected peak power is 940 W. Two FWM lobes are observed with an optical spectrum analyzer (OSA) and they are located around 900 and 1220 nm (Fig. 2.a, blue line). At the PCF output, single shot spectra are also recorded by a dispersive Fourier transform set-up with a 6.3 km long fiber (SMF28) [4], a fast photodiode and an oscilloscope with a maximum bandwidth of 8 GHz. Figure 1.b shows a superposition of 1000 single shot spectra (black curves) and the averaged curve (red curve). From their comparison with the spectrum recorded with the OSA, we can confirm that the DFT method provides a good representation of single-shot spectrum.

For each single shot, the two FWM bands are numerically filtered and the wavelength of maxima on each side are recorded and plotted in Figure 2.b. As previously, the theoretical relationship of the FWM from the photon energy conservation law are added for 3 instantaneous pump wavelengths. It confirms that the FWM maximum are generated from the center of the pump spectrum. In addition, the signal and idler photons are uniformly spread and no clear dense zone are observed due to some experimental constraints as the inhomogeneous dispersion profile or the structured pump pulse. From the energy conservation, the scatter points can also be plotted as the function of the pump wavelength or the delay since the pump chirp is known from the VBG (Figure 2.c). The signal is linearly spread in time while the full idler spectrum is generated at any delay. This information is very interesting and cannot be obtained from the average spectrum recorded with the OSA. It means the signal should be injected with a specific chirp of  $\sim 60$  ps/nm.

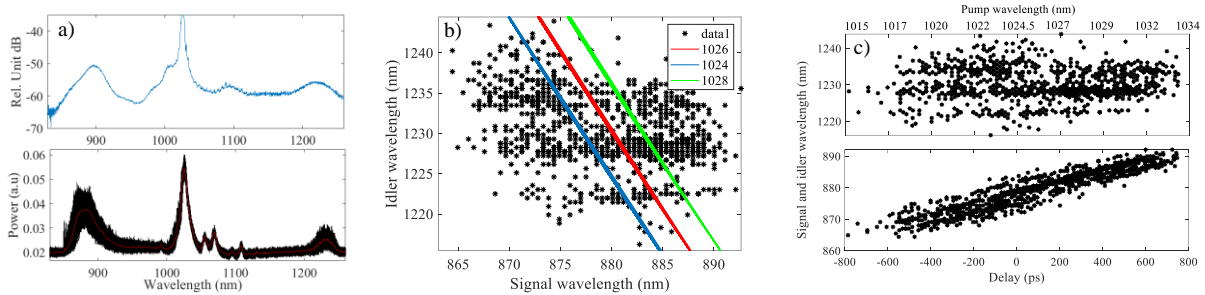


Fig. 2. a) Fluorescence spectrum (blue line) recorded with an OSA, 1000 single shots (black line) and averaged spectrum (red line) using the DFT method. b) Signal/Idler wavelength corresponding to the spectrum maxima of each FWM band. The lines are plotted from the photon energy conservation law for several pump wavelengths. c) Retrieved spectrogram from the spectrum maxima.

### 4. Conclusion

We have shown that the temporal and spectral distributions of the FWM bands can be retrieved from an ensemble of single shot spectra using the DFT method. This technique will be very important to design ultrafast parametric amplifier since it leads to the expected seed chirp required for large gain bandwidth.

### 5. Acknowledgments

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