Spectral Distributions of Chirped Pulsed Four-Wave Mixing in a Photonic Crystal Fiber Measured by Dispersive Fourier Transform Method

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Abstract: Spectral correlation of four wave mixing has been investigated when a chirped pulse pump is injected in a photonic crystal fiber. The dispersive Fourier transform method was used to record single shot spectra and to measure the spectral correlation between the signal and idler components. We show that this method can determine the origin of the FWM in the pump spectrum.

1. Introduction

Four-wave mixing (FWM) in optical fibers has been extensively investigated in order to amplify ultra-short pulses since it provides large gain-bandwidth [1,2], high gain [2] and very wide tunability. When a chirped pulse pumps a fiber, the instantaneous frequencies of the pump are temporally dispersed and the spontaneous photons are generated with temporal and spectral distributions according to phase-matched FWM relation [3]. In this case, we demonstrated that this configuration allows getting a very large gain bandwidth [2] that enables ultra-short pulse amplification [1]. However, the injected signal requires chirp optimization to match the temporal distribution of the parametric gain spectrum, which depends on both the pump and fiber properties [1]. Therefore, this parametric gain distribution needs to be firstly characterized before being used in a broadband amplifier. In this work, we present a simple approach that allows the spectral and temporal distribution of the instantaneous parametric process to be retrieved using the dispersive Fourier transformation (DFT) method [4]. This powerful technique is significantly simpler to implement compared to pump-probe techniques [5] since it provides the desired information without the need to inject a suitable signal. In our case, we use DFT to measure the spectral correlation between the side bands, which allows us to determine the particular portion of the pump spectrum responsible for generating the FWM.

2. Experiment and method

The pump pulse is generated from a mode-locked oscillator (Flint, LightConversion) delivering a train of pulses at 76 MHz with a duration of 80 fs centered at 1030 nm. A part of the oscillator output (around 750 mW) seeds an amplifier composed of a volume Bragg grating (VBG) that stretches the pulses to a duration of ~50 ps, an acousto-optic modulator to decrease the repetition rate to 1 MHz and cascaded ytterbium doped fiber amplifiers to increase the average power up to 1 W. The spectral bandwidth at the output of the amplifier is ~9 nm and is modulated due to self-phase modulation (SPM). The pump pulse is then injected in a 5-meter-long PCF with a zero-dispersion wavelength at 1028 nm. Two FWM lobes are observed and located around 1001 and 1071 nm for an average power of 18 mW (Fig. 1.a). Single shot spectra are then recorded by a dispersive Fourier transform set-up with a 11.5 km long fiber (SMF28) to stretch the output with an approximate chirp value of ~-2.54 nm/ns, a fast photodiode and an oscilloscope with a maximum bandwidth of 12 GHz. Figure 1.a displays the superposition of 500 single shot spectra and the averaged curve. Good agreement is obtained with the curve recorded by the optical spectrum analyzer (OSA).

From the single shot spectra, the spectral correlation $\rho(\lambda_1, \lambda_2)$ has been calculated between any two wavelengths λ_1 and λ_2 according to

$$\rho(\lambda_1,\lambda_2)=\frac{\langle I(\lambda_1)I(\lambda_2)\rangle-\langle I(\lambda_1)\rangle\langle I(\lambda_2)\rangle}{\sqrt{\langle I^2(\lambda_1)\rangle-\langle I(\lambda_1)\rangle^2\cdot\langle I^2(\lambda_2)\rangle-\langle I(\lambda_2)\rangle^2}} \quad (1)$$

where the bracket represents the average over the ensemble. The correlation ρ varies from -1 to +1 indicating intensity fluctuations in the opposite or same directions respectively. For ρ=0, no correlation exists between the two wavelengths.

3. Results and discussion

Figure 1.b shows the spectral correlation map between 980 and 1090 nm for an average power of 24 mW together with the average spectra. The pump spectrum is positively correlated with itself. Similarly, the correlation between two identical FWM bands corresponds to a positive yellow line with ρ = 1. The signal and idler photons are degenerated with respect to the pump and therefore an anti-correlation between the pump and the two side lobes are observed (black dashed squares) [6]. A zoom view of the spectral correlations between two side bands (black square in Fig. 1.b) is also shown in Fig. 1.c. The black lines are plotted from the photon energy conservation law for several pump wavelengths λ_p; ie $2/\lambda_p=1/\lambda_1+1/\lambda_2$. A positive correlation is observed with a specific shape and is mainly between 1070-1075 nm and 995-1005 nm. From the black line, we deduce that these parts of the bands are generated from the pump spectrum at 1030-1035 nm. A negative correlation value (ρ=-0.15) at around 1082 nm is also observed. This is attributed to SPM from the pump that decreases the correlation value. According to the FWM relation, it originates from the pump spectrum at >1035 nm and correspond to the spectral hole in the pump observed at 1037 nm (Fig. 1.b-black circle).

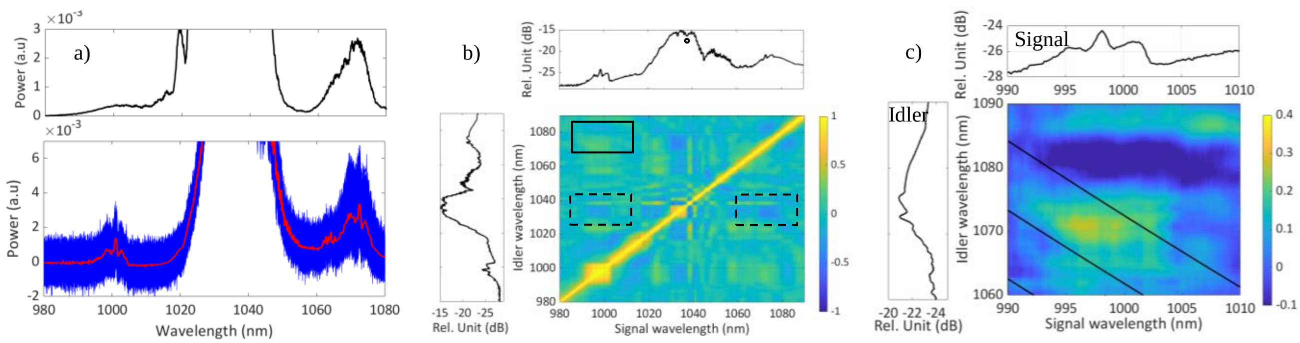

Fig. 1. a) FWM bands detected with an OSA (black line) and with the DFT method (red and blue lines). The averaged spectrum (red line) of 500 single shots (blue lines) are displayed. b) Spectral correlation map of the full spectrum. The black dashed squares correspond to the correlation between the pump and the FWM bands while the black square shows the correlation between the two bands. c) Spectral correlation between the bands. The black lines are plotted from the photon energy conservation law for several pump wavelengths.

4. Conclusion

We have shown that the DFT method can be used to infer the origin of the FWM within the pump from the spectral correlation between side bands. This technique brings significant new information such as the spectral distribution of parametric gain, which cannot be obtained from a standard spectrometer. We believe that it will be of prime interest for the development of fiber amplifiers supporting a very broad bandwidth [1].

5. Acknowledgments

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