Single-shot Spectroscopy of OPO Dynamics

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Abstract

Many ultrafast optical systems exhibit complicated dynamics on extremely short time scales due to many coupled effects. These dynamics are difficult to study experimentally due to the data acquisition time limits of optical instrument. We intent to study the spectral output characteristic of doubly resonant OPO (Optical Parameter Oscillator), its steady stable state and what happen during the transition from non-degenerate to degenerate operation, using the TS-DFT (Time Stretch Dispersive Fourier Transform) technique to overcome the data acquisition limits of current spectrometers limitation.

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1 Introduction

An OPOs (Optical Parameter Oscillator) is an optical resonator, where a pump wave at frequency ν_p pumps in a non-linear crystal to generate two waves, called signal and idler at frequency ν_s and ν_i , so that the total photon energy and momentum are conserved. Mirrors of this parametric oscillator exhibit high reflectivity at both ν_s and ν_i , leading to the so called doubly resonant design where the particular characteristic of the oscillation is sensitive to the cavity length [4].

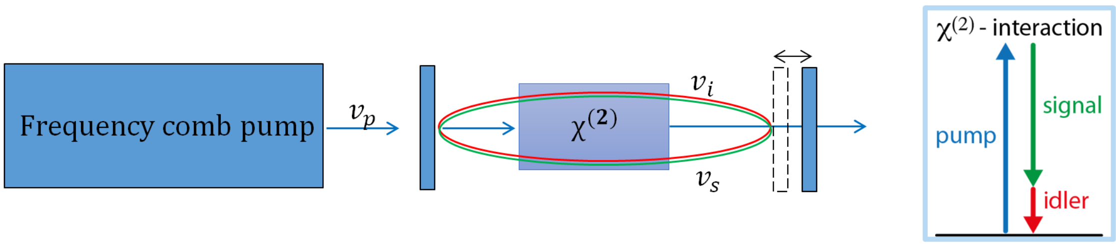

Figure 1: (a) Schematic of a doubly-resonant OPO as used for the experiments here. (b) Energy diagram of a difference frequency generation scheme

In the general case, the OPO operates either in a non-degenerate state, where signal and idler waves are spectrally well separated from each other, or in a degenerate state, the two oscillating fields are indistinguishable. The later case, the OPO can be used as a frequency comb as the OPO field in automatically locked to the driving laser pulse.

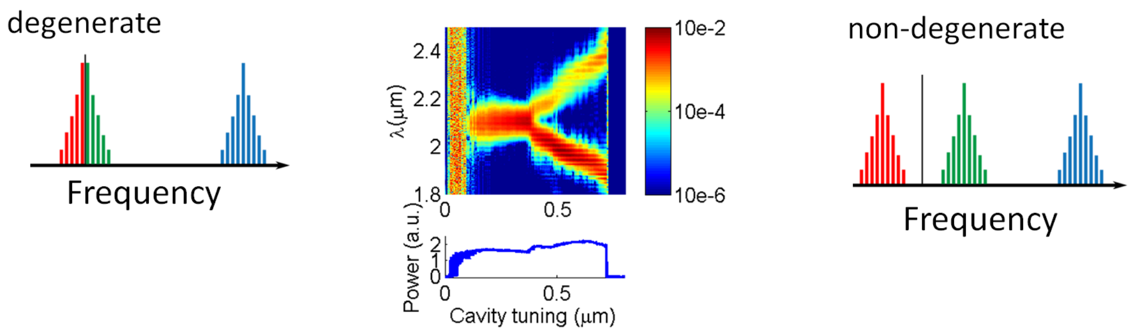

Figure 2: (a) Schematic of a degenerate state. (b) Optical spectrum of OPO vs cavity length exhibiting the transition from degenerate (left) non degenerate (right) state.Transition from degenerate state to non-denerate state. (c) Non-degenerate state

The frequencies of the signal and the idler must satisfy two criteria: the energy conservation and the resonance condition. In an OPO, the photon energy conservation can be written in this way:

$$\nu_p = \nu_s + \nu_i \tag{1}$$

and, also, there is fixed phase relationship between the pump, signal and idler waves

$$\phi_p = \phi_s + \phi_i + \frac{\pi}{2} \tag{2}$$

For a non degenerate OPO the signal and the idler phases are free to adopt any values as long as Eq(2) is satisfied. When they become indistinguishable at degeneracy, we have $\phi_s = \phi_i$ and the Eq(2) becomes:

$$\phi_p = 2\phi_s, i + \frac{\pi}{2} \tag{3}$$

2 Experimental Setup

2.1 Simulation

From the simulation done by the group of M. Fejer at Standford University who collaborate on this project, we expect such OPO to exhibit a dynamic energy exchange between degenerate and non-degenerate state. Such a behaviour was not observed experimentally before. We want to see the coexisting degenerate and non degenerate states with the beating of roundtrip to roundtrip evolution. In the Fig. 3 on the right, we can observe the coexistence of degenerate state (in the middle at the carrier frequency) and non-degenerate (on the right side the Signal and on the left the Idler,respectively). One can clearly see a dynamic with a periodicity of only several roundtrip.

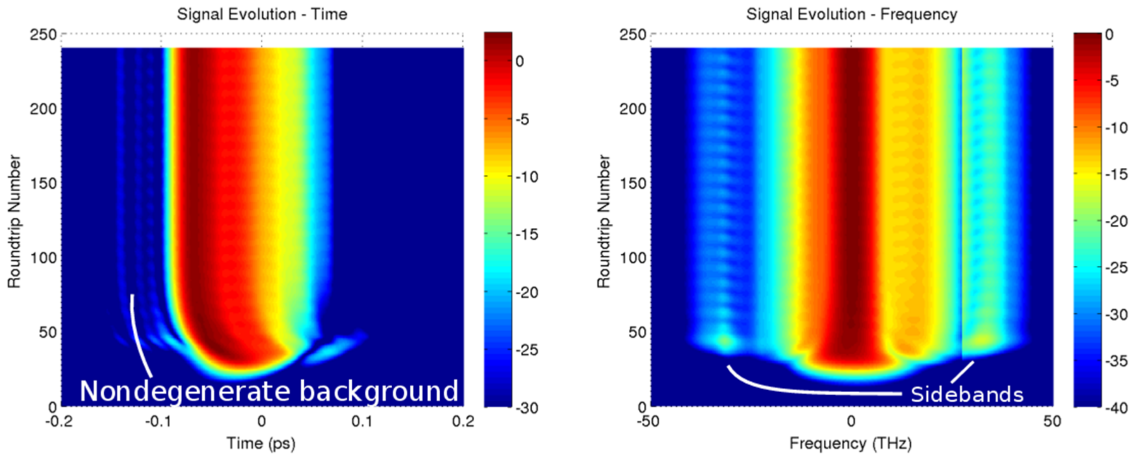

Figure 3: Round-trip resolved temporal and spectral OPO output obtained by numerical simulations.

The main problem investigating this kind of dynamics is the limit of speed of the common spectrometers, which are no so fast to capture these ultrafast pulses because they have generally an integration time of ∼ms. The solution is to use the TS-DFT (Time Stretch Dispersive Fourier Transform) [1], a technique that uses a dispersive material to strech the pulse. This method permits to investigate fast dynamics such as birth of mode-locking [2], OPOs, and so on.

2.2 TS-DFT technique

DFT consists of a dispersive element with a large GVD (Group Velocity Dispersion) and a photodetector. When a train of optical pulses accomulate a large amount of dispersion, the spectrum of each pulse is mapped into a temporal waveform, that is stretched in time, so in this way it can be captured by a photodiode in real time. Because the time stretched waveform is sufficiently slow, DFT allows the optical spectrum to be measured directly in the time domain. Without the time stretch, the single shot waveforms will be too fast to be digitalized by the convertor.

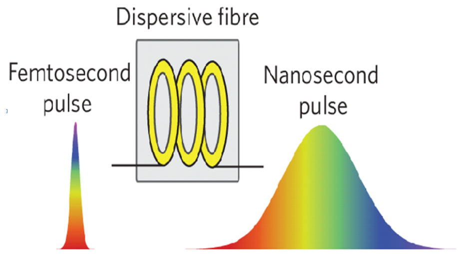

Figure 4: scetch of a fs-laser pulse which is stretched inside a dispersive fiber. After propagation the different wavelengths are distributed over time.

In our case, we used Corning's SMF28 optical fiber, which is often employed for fiber-optic communication. This optical fiber is designed for operation in the spectral band 1200-1600 nm.and imposed hence certain limitation for 2 μm pulses as emitted by the OPO because of bending loss, unknown dispersion and soon not fast enough.

2.3 Setup

In Fig. 1 is shown schematically the setup used for the measurement [3]. It consists of an oscillator that produces a pump pulse at 1 μm, that is amplified by fiber laser frequency comb up to 2W, generating a pulse of $\sim$100 fs and $\sim$150 MHz of repetition rate. The AOM (acoust-optic modulator) is used to modulate the pump frequency. This pump comb enters in the optical parameter oscillator (OPO), where a non-linear crystal (PPMgO:LN) is placed to generate a second harmonic, verifying the quasi-phase-matching condition. The cavity consists in four mirrors, on of these is a dicroic mirror that have high reflectivity at the frequency of signal and idler. One of the cavity mirrors is mounted on a piezo (PZT) stage enabling cavity length tuning. The output beam is focused in a Corning's SMF28 Optical Fiber, that is $\sim$ 200 m. It is respooled on a bicycle wheel of 1.75 m of circumference to reduce the bend losses. The output of fiber is detected with a fast photodiode (12.5 GHz), linked to a fast Tektronix oscilloscope (16 GHz), that permits to record the spectra-temporal dynamics of the OPO.

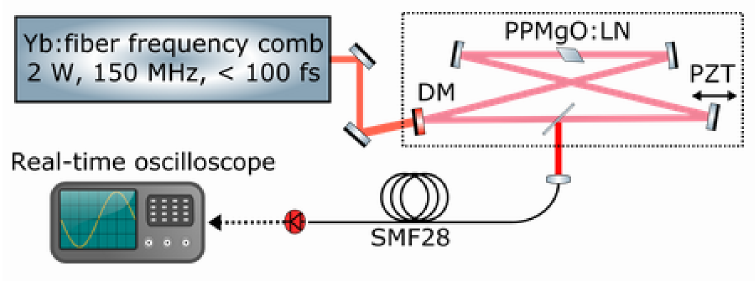

Figure 5: Experimental Setup

2.4 Implementation

The fiber that we use is a Corning's SMF28 optical fiber with high bend losses for wavelength ≥ 2 μm. The bend losses depend on the radius of wheel, where we respool the fiber, and the lenth of the fiber. They decrease with the increasing of radius and with shorter fiber. Without the fiber we have a pulse duration of $\sim$100 fs. We respooled $\sim$200 m on a bicycle wheel of 1.75 m of circumference to reduce the bend losses and to have a FWHM pulse duration of $\sim$ 3 ns, with central wavelength of 2050 nm and spectral FWHM of 100 nm.
The output of fiber is detected with a fast photodiode EOT of InGaAs ($\sim$12.5 GHz) capable to measure optical fields at wavelength below 2.1 μm.
It is linked to a fast Tektronix oscilloscope with a bandwidth of 16 GHz and a sample rate of 25 GS/s and a maximum of record length of 100 ms at given sample rate, reducing in a point spacing of 10 ps which allows to use an approximation 10 times higher sampling rate compared to the resolution of the diode.
The recorded data were segmented into intervals of length corresponding to the round-trip time, obtaining a two-dimensional representation, where the vertical axis corresponds to optical spectrum of a single round-trip and the horizontal axis to the round-trips. Due to the limited sampling rate, the data set couldn't be cut into exactly the roundtrip time so events occurring at the same time within successive roundtrips do not lie on a horizontal line but are slightly tilted. To resolve this problem the sample rate of oscilloscope should be match to the repetition rate of the OPO.

3 Results

We recorded 10 million samples with 10 ps step size. The data has signal to noise ratio of 35. We could measure the spectral range of about 1900 to 2100 nm, corresponding to the blue part of the non-degenerate state.
In Fig. 6, the OPO cavity length is adjusted such that the OPO is in non-degenerate state so the output shows stable pulse to pulse evolution. The figure shows the raw recorded data and the corresponding wrapped 2D map of the spectral evolution over time. In Fig. 7 the OPO cavity length is tuned close to the transition point between degenerate and non-degenerate states and the output spectral show periodic pulse to pulse evolution with periodicity about 100 roundtrips. The reason for the periodic evolution could be that both degenerate and non-degenerate states exist inside the OPO and they exchange energy periodically like predicted in the simulation as in Fig. 3. Even more complicated dynamcis were observed as can be seen from fig. 8. Their interpretation and analysis will be done with future numerical simulations which will hopefully lead to a more complete understanding of the complicated dynamics involved.

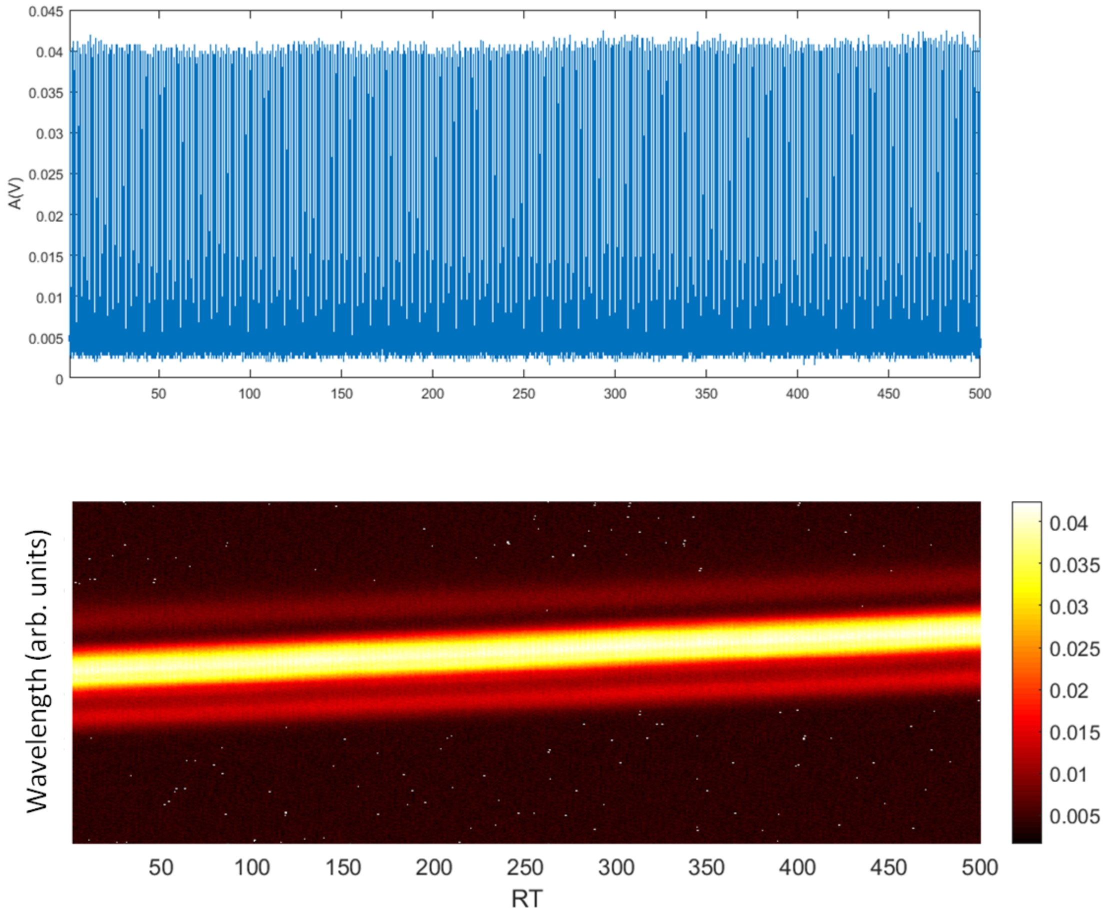

Figure 6: Stable state

3.1 Conclusion

The aim of the project was establish a measurement technique capable to record optical spectra of ultrafast optical systems in a round trip resolved fashion typically occuring at several ns roundtrip time. This was setup on the basis of Time Stretch Dispersive Fourier Transform spectroscopy. The setup was successfully tested at a doubly-resonant OPO where the dynamics between and coexistence of two modes of operation were measured for the first time. The system is capable to measure up to 10 us of consecutive data corresponding to 1500 roundtrips of the OPO under test. Although not capable to measure the full wavelength range of the OPO, the set-up measurement system is a powerful and simple experimental tool to measure complicated ultrafast dynamics.

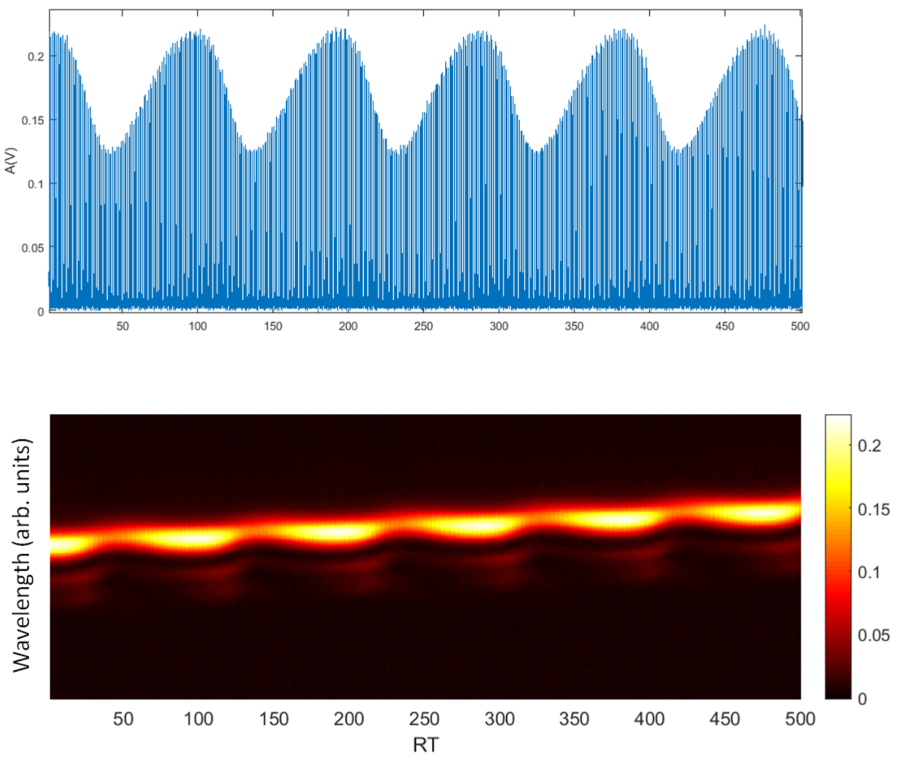

Figure 7: Unstable state

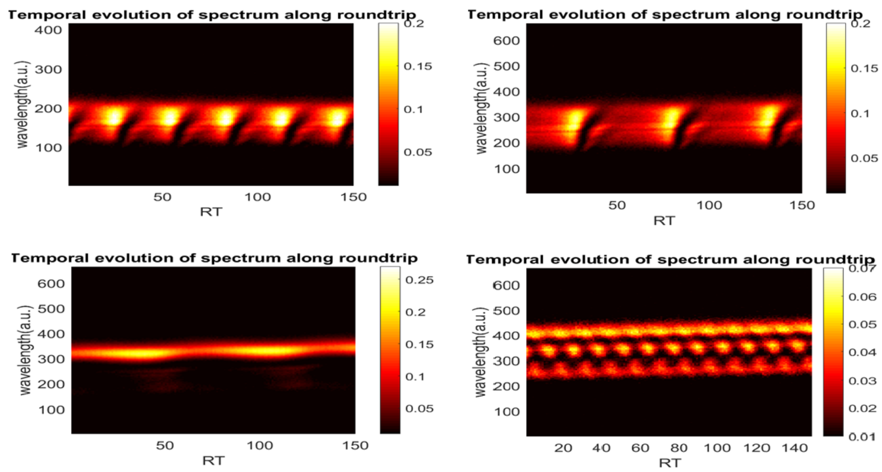

Figure 8: Other pattern observed

References

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