Multi-scale fibre-based optical frequency combs: science, technology and applications (MEFISTA)

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Gain through loss mechanism observation in passive fibre ring cavity

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EXECUTIVE SUMMARY

The main objective of this work will be to comprehensively study the non-linear effect called “Gain Through Filtering” (GTF) in fiber optical cavities. This phenomenon consists of the formation of Modulation Instability (MI) whose spectral position depends on the position of a filter inside the cavity. It can be physically explained by the action of the filter: in addition to applying a localized spectral loss, the filter imposes a phase variation to the signal that is traveling through it.

The study of this topic will be both theoretical and experimental: firstly the student needs to become familiar with the typical theoretical and numerical tool linked to the study of intra-cavity nonlinear process. After that, an experimental setup will be required for the verification of the result predicted by the theory.

CONTENT

The first year of the project has been dedicated to the study of the GTF process and the realization of a working experimental setup.
The theoretical and numerical study consisted first in the mathematical analysis and then in the simulation of GTF with Matlab© scripts, edited to this purpose. This first step allowed the identification of two parameters to be investigated: the evolution of the signal in function of the spectral distance between the filter and the pump, and the evolution of the spectrum with the power of the pump.
In the following section, a description of the experimental setup and the main result of this first part of study will be provided.

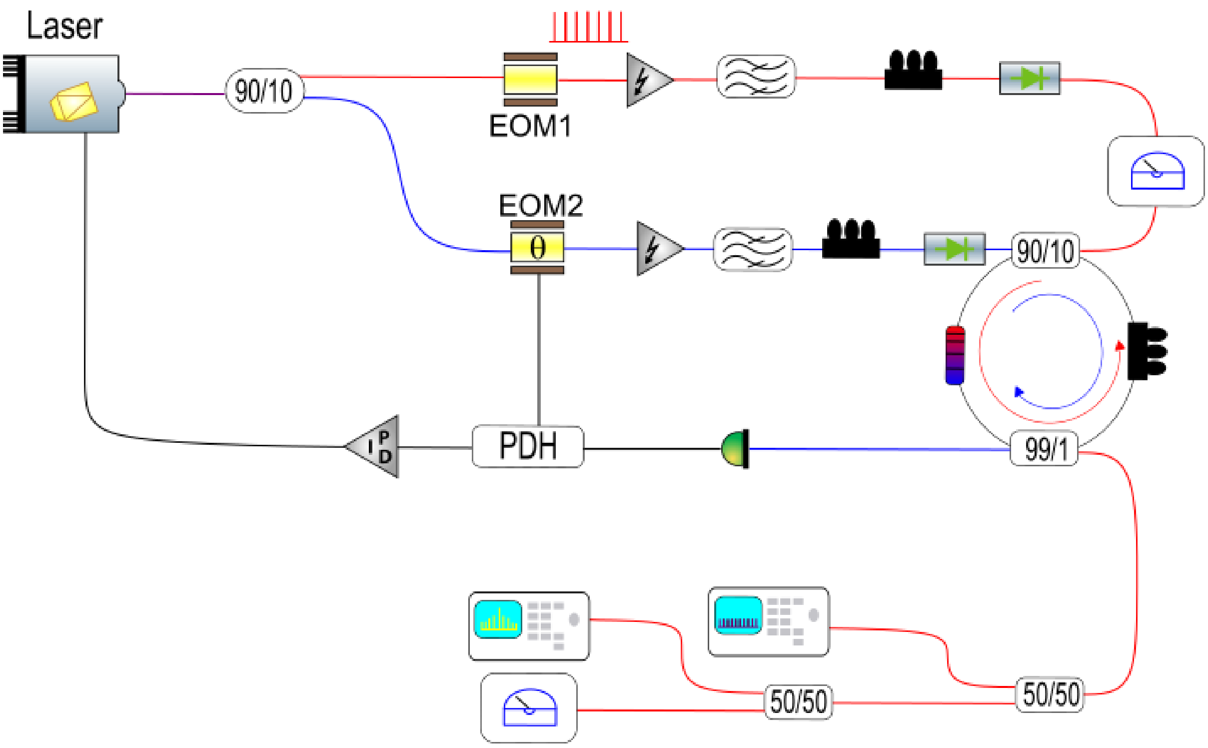

Figure 1: Experimental setup realized for the main characterization of GTF process in a fiber cavity. All the main elements of the setup are not polarization maintaining.

Experimental Setup

In Figure 1, it is possible to see a schematization of the setup realized for the characterization of GTF process in a fiber cavity. In the realization of this setup, two main principles have been followed: 1) the setup must be able to fix and measure the linear detuning between the laser pump and the optical cavity; 2) the setup must be stable enough to respect environmental perturbation (random noises and vibration, temperature changing) to allow for the frequency tuneable laser pump (labelled as 'Laser' on the top left of figure 1) to be divided into two beams: the red beam or non linear beam, and the blue beam, also called the control beam.
The non linear beam is modulated into pulses, for reaching a higher peak power, amplified and filtered. After that, a polarization controller is used to match the polarization state of the beam with the one of the cavity and a power meter is inserted for measuring the input power. Thereafter, the non linear beam is injected into the cavity through a 90/10 optical coupler.

By following the blue line in the scheme, it is possible to spot a phase modulator, governed by the PDH controller, followed by amplification, filtering and polarization adjustment as in the non linear beam. After those steps, the control beam is injected into the cavity in the opposite direction of the non linear beam from the other input of the same 90/10 optical coupler. The signals are propagated in the opposite direction to facilitate their separation at the output of the cavity.

Inside the cavity there is the fiber Bragg grating which acts as spectral filter, and another polarization controller which allows us to change the linear detuning of the cavity by imposing a physical deformation to the fiber.

Since the signals are counter propagating inside the cavity, a tap coupler is sufficient to separate and collect them outside of the cavity. The non linear beam is then sent into the recording section (spectrum analyser, oscilloscope, power meter), and the control beam is sent into the control section after being converted into an electronic signal with an optical diode. As anticipated, the control section is composed by a PDH system, which controls a PID controller. The exit of the PID is sent to an appropriate input in the laser pump, which controls a piezo crystal used for fine-tuning the frequency of the laser.

The PDH system is the most important variation that has been made in this scheme, which usually for the stabilization only uses a PID controller. The result is a very stable system, almost completely independent from any kind of noise, able to perform measurements.

Investigations

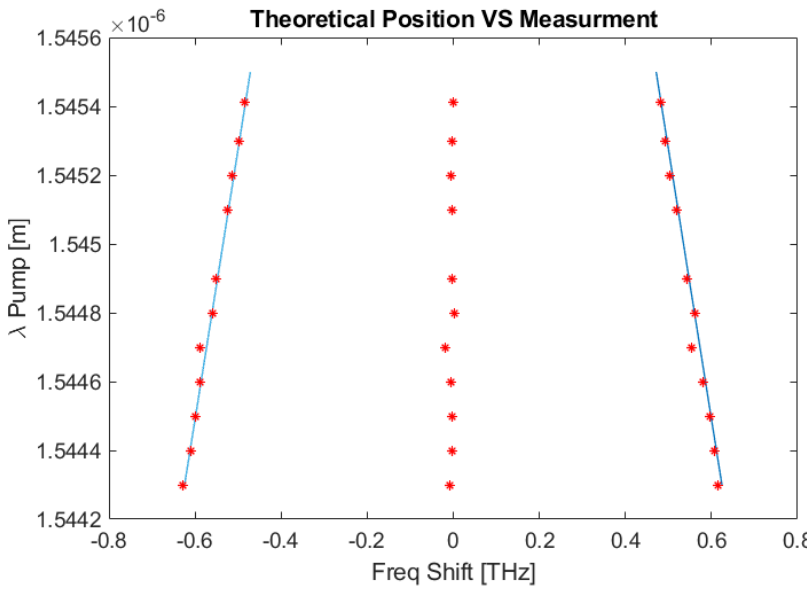

Figure 2: Demonstration of the tunable capability of the GTF process, with the pump positioned at 1545 nm.

Tunability

The first interesting results, obtained starting from a similar result of Bessin in [1], are the confirmation of the possibility to tune the position of the sidebands of a MI spectrum by modifying the relative position of the filter in respect to the pump.
The concept is simple in its versatility: if the band's position is related to the position of the filter, by changing the latter, it is possible to change the spectral distances of the MI spectrum.
Figure 2 represents the position of the first 3 peaks of the MI spectrum, the pump in the zero, and the lateral band at the sides. On the X axis of the plot we have the frequency position of the bands in

respect to the pump, and on the Y axis we have the wavelength of the pump. Red dots are the measurement performed on the setup, while the blue lines are the theoretical position predicted by the theory. It is clearly visible that by changing the wavelength of the laser, and thus the distance between the laser and the pump, the two sidebands grow at different positions. Figure 2 also verifies the validity of the theoretical model used, as the position of the measured spectra superimpose almost perfectly with the one predicted by the theory.

Competition between two phenomena : GTF and Boundary conditions lead MI

The initial studies of GTF have been focused mostly on the property of tunability. The investigation of different wavelengths, on the other side of the filter with respect to the one analysed in the part described above, showed that the dynamics can be much more complex.

Figure 3 represents the evolution of the parametric gain as function of the distance between the pump and the filter.

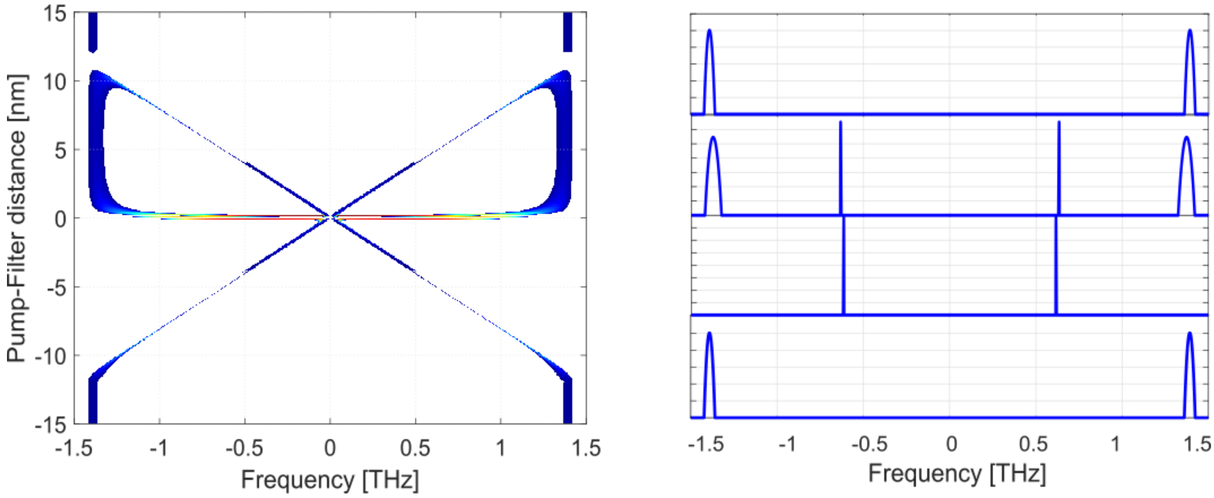

Figure 3: Evolution of the parametric gain as function of pump-filter distance

The X axis represents the position of the bands and the Y axis represents the distance. By studying the evolution of the gain in this manner, we can isolate four different behaviours: at the two extremities we only have two sidebands, due to the boundary conditions of the cavity. Then one can distinguish two other areas: from a distance between -13nm and 0nm only the GTF gain is present; from 0nm up to about 10nm of distance, by the way, it is possible see the coexistence of four bands. The most internal ones are due to the GTF process, and the most external ones are due the boundary conditions of the cavity.

The analysis made before only focused on the first area, where GTF bands were present. So, a new analysis, focused on the area of coexistence has been done, and the results are very interesting.

For this investigation the distance between the pump and filter is fixed at a value where both bands are visible (at about 5nm). The relationship between the two different gain bands is then studied as function of the power, since by changing the power the relative height of those bands changes. The results of that can be seen in Figure 4 below. On the left side we see the evolution of the spectrum as a function of the power, and on the right side we have three inserts at three different power levels. For each insert we have the measured spectrum in blue, and the simulated one in red.

The unexpected result is that in those conditions, the first spectrum to appear is the one which depends on the boundary condition of the cavity. Then, by rising the power, the GTF spectrum starts to rise from the noise background and, when the power is high enough, some beatings are also visible in the measurement. The limitation in this case was the EDFA used, which reached its peak of amplification, but in theory more complex phenomenon can happen at even higher powers.

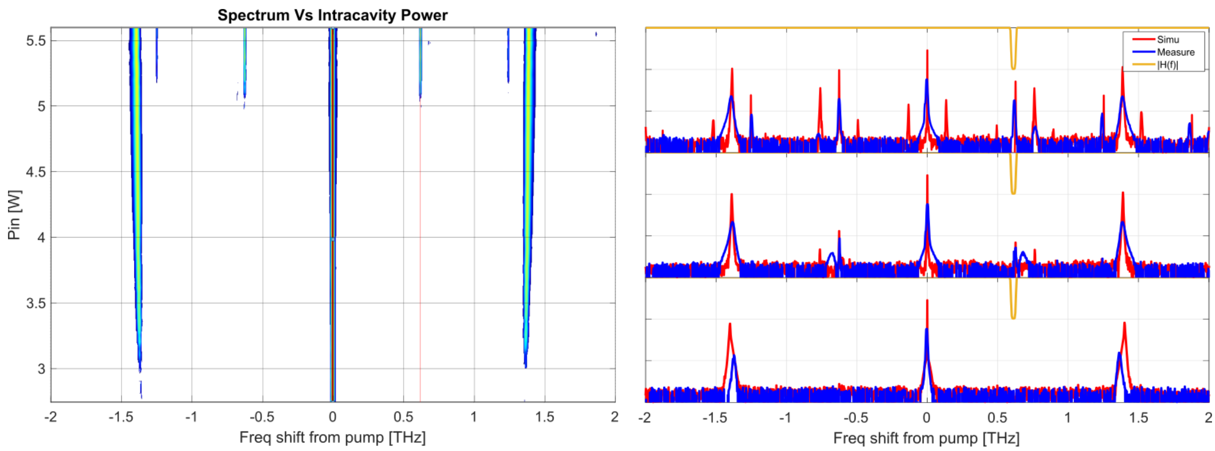

Figure 4: Analysis of the competition between two typologies of gain in the cavity at a pump-filter distance of 5nm.

This result is totally new and shows how thanks to GTF, it is possible to reach very complex dynamics like the coexistence of two different kinds of gain at the same time.

Conclusion

The first year of project led to the following results:

- The construction of a stable and reliable experimental setup
- The verification of the property of tunability of the GTF process
- The analysis of a totally new behaviour: competition of two kinds of gain at the same time.

Next steps in the projects are:

- Writing and publishing an article with the latest results
- Further new experimentation: the study of the cavity dynamics by changing linear detuning (bistability)
- Building and testing a totally PM cavity with the goal of stimulating a spectrum for each polarization state

Reference

[1] Bessin, F. *et al.* Gain-through-filtering enables tunable frequency comb generation in passive optical resonators. *Nature Communications* **10**, 4489 (2019).

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