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# Coexistence of Gain through Filtering and Parametric Instability in a Fiber Ring Cavity

Stefano Negrini<sup>[1]</sup>, Jean Baptiste Cepepe<sup>[1]</sup>, Matteo Conforti<sup>[1]</sup>, Alexandre Kudlinski<sup>[1]</sup>, Auro Perego<sup>[2]</sup> and Arnaud Mussot<sup>[1]</sup>

<sup>[1]</sup>Univ. Lille, CNRS, UMR 8523-PhLAM-Physique des Lasers Atomes et Molécules, F-59000 Lille, France

<sup>[2]</sup>Aston Institute of Photonic Technologies, Aston University, Birmingham, B4 7ET, United Kingdom

Author e-mail address: stefano.negrini@univ-lille.fr

**Abstract:** We experimentally and numerical investigate the coexistence of Gain through Filtering and parametric instability in a fiber ring cavity, and their dependency from input power and cavity phase detuning.  
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Modulation instability is a well-known phenomenon in nonlinear optics, deeply studied in both fiber optics and resonators. Optical resonators have application such as Optical Frequency Comb (OFC) [1] generations and is demonstrated that MI can be a trigger mechanism in such phenomena.

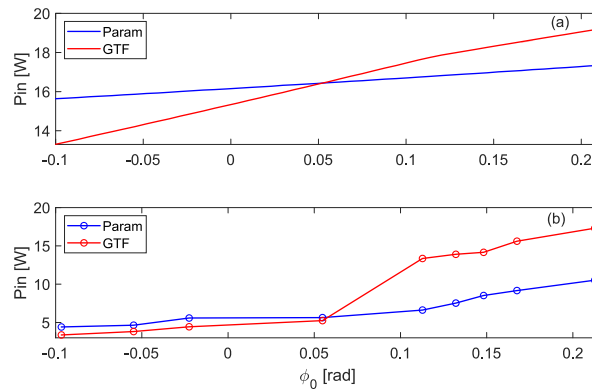
Recently, loss-induced modulation instability [2] has been proposed: the authors demonstrated that inducing a loss asymmetrically respect to the pump, can lead to a net gain at the same frequency.

In 2019, Bessin *et al.* proposed a method for generating tunable OFC in a fiber cavity [3], exploiting a fiber Bragg grating as loss source. In this context, we can name the process Gain though Filtering (GTF). In this study, the authors limit the analysis on tunability obtainable by changing the frequency shift between the pump and the filter, not considering all the other cavity parameters.

Aiming to a deeper characterization of GTF in fiber cavities, we conducted a numerical and experimental study of the evolution of the parametric gain as a function of input power and phase detuning of the cavity  $\Phi_0$ .

Unexpectedly, the analysis showed that alongside GTF, is actually possible to stimulate another family of cavity resonances, called parametric instabilities. Interestingly, the analysis that we performed show that the power threshold of the two instability is influenced by the cavity detuning, as reported in Fig. 1.

Fig. 1 (a) represents the theoretical evolution of the input power threshold of the two phenomena, calculated by analyzing the parametric gain obtained from the linear stability analysis of the cavity. Red curves correspond to GTF and blue curves to parametric instability; Fig. 1(b) depict the experimental verification, conducted by recording the threshold power at different value of cavity detuning. First, it is interesting to note the inversion mechanism which takes place at  $\Phi_0 = 0.05$  rad: for lower detuning, GTF threshold is lower than the parametric instabilities threshold, while for higher detuning is the opposite.



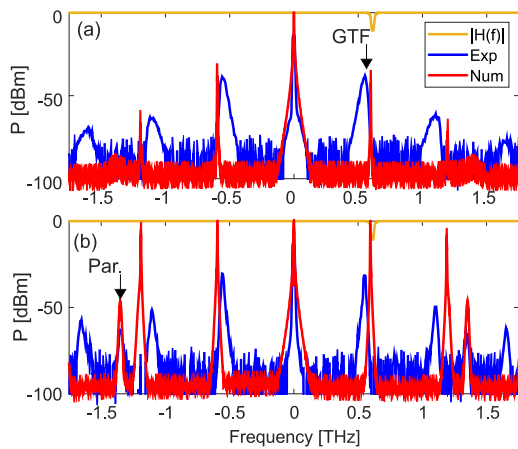
**Fig. 1** Evolution of the input power thresholds of the two instabilities as function of the detuning  $\Phi_0$ . Fig 1 (a) is the plot of the theoretical power threshold evolution, red line for GTF and blue line for boundary conditions. Fig 1 (b) is the plot of the experimental result.

In Fig. 2 and 3, we report the spectra as function of the power for  $\Phi_0 = -0.1$  rad and  $\Phi_0 = 0.15$  rad respectively. In Fig. 2 (a) is plotted the spectrum for  $P_{in} = 14$  W just above the threshold, while Fig. 2(b) shows the spectrum for

$P_{in}=16.3$  W. Red traces are numerical simulations, blue traces are the measurements and in yellow is the plot of the modulus of the transfer function of the filter. The evolution is clear, at  $\Phi_0 = -0.1$  rad, at lower power (Fig.1 (a)) the spectrum exhibits GTF instability bands (blue curve) shifted at 0.55 THz from the pump, as confirmed by numerical simulations (red curve). By rising the power (Fig.1 (b)), parametric instability bands appear shifted at 1.33 THz from the pump, coexisting with GTF bands.

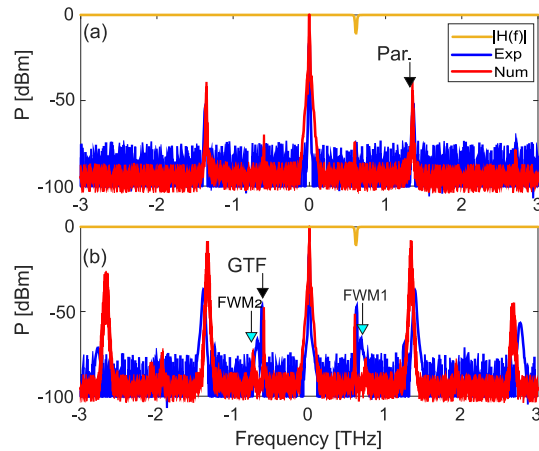
Similarly, in Fig. 3(a) is reported the spectrum for  $\Phi_0 = 0.15$  rad, with  $P_{in}=17$  W and in Fig.3 (b) the spectrum for  $P_{in}=18.5$  W. This time, the order of appearance of the bands is inverted, with parametric instability band appearing for lower power respect to GTF. Interestingly, in this case for higher power is possible to see additional components shifted  $\pm 0.73$  THz from the pump (FWM1 and FWM2), resulting from the beating of GTF and parametric instabilities via four wave mixing. Once again, the experimental results are in good agreement with the numerical simulations.

In conclusion, we numerically and experimentally explored the impact of phase detuning and power on the evolution of the spectrum and the coexistence of GTF and parametric instability in a fiber ring cavity. In particular we described the dependency of the power threshold of the two phenomena from  $\Phi_0$ , and how the evolution of the spectra as a function of the power is consequently modified. Interestingly, when the power exceeds both thresholds, a state of coexistence can be reached, where both instabilities are visible.



**Fig. 2**

**Fig. 2** Spectrum evolution as function of the power for  $\Phi_0 = -0.1$  rad. Blue traces are the experimental recording while red traces are numerical simulations. (a) Spectrum for  $P_{in}=14$  W, (b) spectrum for  $P_{in}=16.3$  W. Parameters:  $\gamma = 2.5$  /W/km,  $L=100$  m,  $\beta_2 = 0.46$  ps<sup>2</sup>/km,  $\lambda_{pump} = 1554.4$  nm. The finesse is  $F = 14$  corresponding to  $\rho = 0.7962$ . The filter has  $\lambda_{Bragg} = 1549.44$  nm and a FWHM of 0.29 nm (60 GHz)



**Fig. 3**

**Fig. 3** Spectrum evolution as function of the power for  $\Phi_0 = 0.15$  rad. Blue traces are the experimental recording while red traces are numerical simulations. (b) Spectrum for  $P_{in}=17$  W, (a) spectrum for  $P_{in}=18.5$  W.

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