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# Soliton self-injection locking to a fiber Fabry-Perot resonator with sub-100 mW pump power

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## ABSTRACT

We report the observation of soliton self-injection locking (SIL) to fiber Fabry-Perot (FFP) resonator with a laser pump power of less than 100 mW. The locking process is studied analytically with a model of a Fabry-Perot laser interacting with an external FFP and the modelling results are compared to the experimental ones. The model is then extended to the case of a nonlinear FFP modifying, due to the tilt of the resonance with self-phase modulation, the frequency response of the laser. Experimentally, we obtain a large locking range with direct access to primary combs, chaotic combs and soliton while keeping a stable laser lock.

**Keywords:** Fiber Fabry-Perot resonator, Self-injection locking, soliton, frequency comb.

## 1. INTRODUCTION

The fiber Fabry-Perot (FFP) resonator is an innovative platform, as evidenced by the recent enthusiasm surrounding its use, particularly for frequency comb generation or stabilization through feedback injection. It offers a compact and robust alternative to microresonators and long fiber rings, achieving high quality factors (up to  $10^9$ ) [1] and GHz-scale repetition rates, with combs spans up to 28 THz [2][1]. The FFP consists of a short length of optical fiber with FC-PC connectors onto which high reflectivity (>99.8%) mirrors are deposited, with a bandwidth of 80 nm centered at 1.55  $\mu\text{m}$ . The centimetric dimensions of the FFP confer a free spectral range (FSR) in the microwave domain. The low losses associated with propagation in the optical fiber enable achieving high quality factors and taking advantage of fiber nonlinearity. While solitons have traditionally been observed when pumping the FFP up to 1 W with detuning scan up to the soliton step, we report here the observation of soliton self-injection locking (SIL) in a highly nonlinear FFP resonator with only 100 mW CW pump power. The laser used in this study is a commercial device from Gooch & Housego without isolator, delivering up to 100 mW power near 1550 nm. We have chosen to present the results obtained with a resonator approximately 7 cm long, corresponding to a free spectral range of around 1.28 GHz. A finesse of 721 is obtained when characterizing the resonator through Spectro-RF method [3], corresponding to a quality factor of  $10^8$ . Laser SIL to FFP has been studied both experimentally with a fully fibered system and theoretically using Lang-Kobayashi type equations [4] integrating the feedback of the non-linear transfer function of the FFP.

## 2. SETUP AND EXPERIMENTAL RESULTS

The setup is presented in Figure 1. It consists of a relatively long fibered loop compared to the resonator length, whose role is to feedback the power filtered by the resonator to the laser. To achieve this, a circulator is used. This component directs the electromagnetic field emitted by the laser towards the resonator while isolating the reflection occurring on the input mirror of the FFP. The transmission of the FFP is linked to the last port of the circulator, enabling the reinjection of the transmitted field into the laser. To control the amount of light reinjected into the laser, a variable optical attenuator (VOA) is used. The interference between the intra-cavity field of the laser and the reinjected field is a critical consideration. It is therefore necessary to control the phase of the reinjected field, which is directly linked to the fiber length comprising the feedback loop. To control this phase, a voltage-controlled phase shifter was added. However, the

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significant fiber length presents a drawback, as it makes the system highly sensitive to environmental factors, causing irregular evolution of the SIL due to random phase disturbances. Installing the setup inside a thermal foam box significantly mitigates these disturbances by isolating the system from environmental noise, particularly acoustic vibrations affecting the fibers, and by creating a thermally stable environment. The effectiveness of this setup was demonstrated in a previous study [5] where we achieved narrow-linewidth lasers using SIL to high-Q FFP.

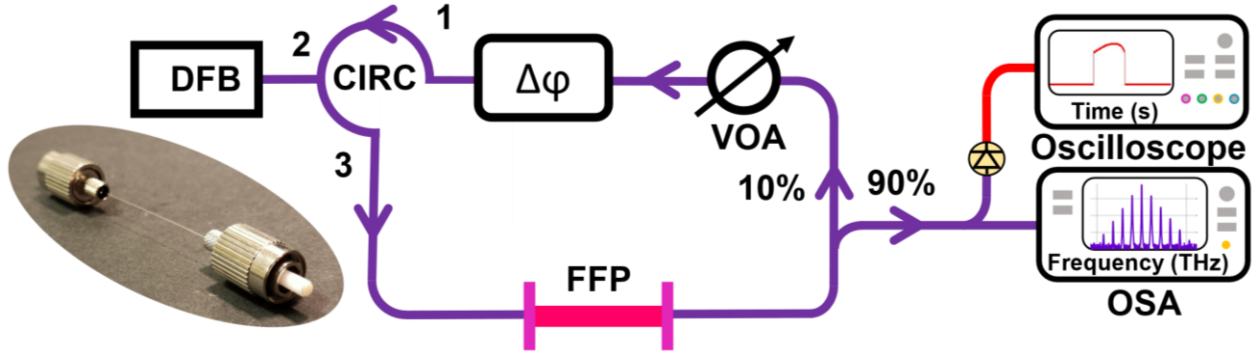


Figure 1. Schematic representation of the SIL setup, comprising a distributed feedback laser (DFB), a circulator (CIRC), a variable attenuator (VOA), a 90/10 coupler and a phase shifter. Measurements are performed using an oscilloscope and an optical spectrum analyzer (OSA). The inset show a photography of the FFP used in this setup.

The same setup is utilized with our nonlinear FFP. The self-injection locking process has been extensively described in previous works [5-8]. It is observed that the emission frequency of the laser, which typically evolves linearly (see black dashed line in Figure 3) with the laser current in the absence of feedback to the laser, becomes dependent on the feedback field (see grey locking curve in Figure 3). The feedback amplitude broadens the locking bandwidth to the resonance, while the phase modifies the locking dynamics [6]. This allows the laser to go through the resonance with large current variations, enhancing both stability and detuning precision.

A laser current scan from 300 mA to 400 mA, accompanied by a frequency decrease and a linear power increase from 80 mW to 120 mW, enabled locking with sufficient power to generate frequency combs. Figure 2 illustrates the spectra obtained on the OSA during a resonance scan. Initially, primary combs associated with the onset of modulation instabilities were observed (Figure 2(a)). Increasing the current led to the filling of all resonances, resulting in a chaotic comb (Figure 2(b-e)). Subsequently, beyond this chaotic comb stage, we observed the emergence of soliton crystals (Figure 2(f-h)) followed by multiple solitons (Figure 2(i)) and eventually, a single soliton (not shown here). Each stage was achieved with excellent stability.

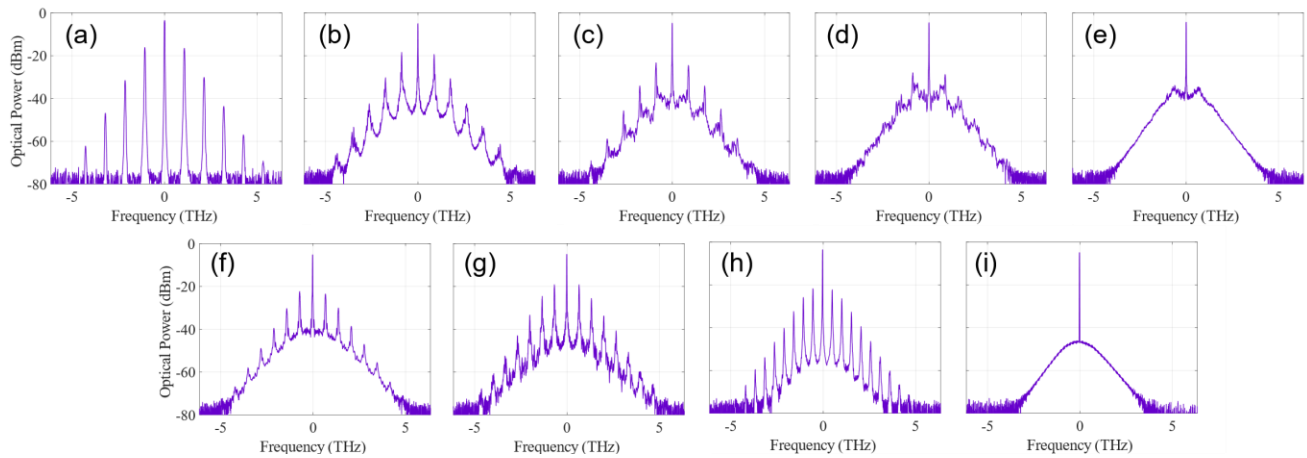


Figure 2. Experimental optical spectra of comb states for varying detuning frequencies, with an input power of approximately 100 mW.

### 3. SYSTEM MODELING

The generation of optical Kerr effect is associated with self-phase modulation, which tilts the resonance (purple curve in Figure 3). This phase effect has significant implications for the self-injection locking process, prompting us to analytically study the locking behavior on the tilted resonance.

The soliton existence detuning range is shown as the light red area in Figure 3, while the locking range is represented by the dashed light red area. This locking range depends on the initial phase [7] which is chosen as  $\psi_0 = 0$  in Figure 3. Including the effects of SPM shifts the detuning according to the following relations:

$$\bar{\xi} = \xi - 6L\gamma P_{IC}/2\pi\tau \quad (1)$$

$$\bar{\zeta} = \zeta - 6L\gamma P_{IC}/2\pi\tau \quad (2)$$

where  $\xi$  is Laser-FFP detuning,  $\zeta$  is the effective detuning,  $P_{IC}$  is the intra-cavity power,  $L$  is the FFP length,  $\gamma$  is the nonlinear coefficient and  $\tau$  is the round-trip time in the FFP. With these adjustments, the nonlinear tuning curves become:

$$\bar{\xi} = \bar{\zeta} + \bar{K}|T(\bar{\zeta})| \sin \psi(\bar{\zeta}) \quad (3)$$

where  $T$  represents the resonator transmission,  $\psi$  is the total phase delay and  $\bar{K}$  is a coupling factor that depends on system attenuation, the FFP quality factor and the DFB round-trip time. Relation (3) describes the tuning curves for the nonlinear SIL, which are plotted as orange lines in Figure 3. When the laser is scanned forward (from blue to red), a specific locked state region within the locking range, as indicated with red dashed lines. For comparison, the grey solid line and dashed area represent the tuning curves and the locking range under the linear SIL.

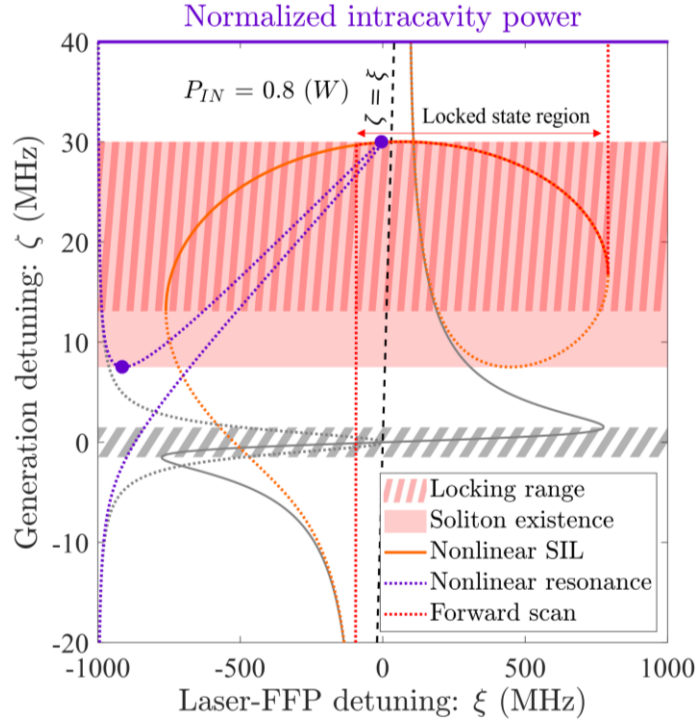


Figure 3. Simulated tuning curves incorporating self-phase modulation are shown with an input power of 0.8 W (orange lines), alongside the forward detuning path (red dashed lines) for an initial phase of  $\psi_0 = 0$ . The corresponding tilted resonance is depicted with a purple dashed line, representing the normalized intracavity power as a function of  $\zeta$ . The grey

lines illustrate the simulated tuning curves without self-phase modulation (solid line) and the normalized resonance as a function of the effective detuning (dashed line).

#### 4. CONCLUSION

Thanks to the laser linewidth narrowing when stabilized through SIL, this innovative process allowed us to get frequency combs generation with a pump power of less than 100 mW. A fine tuning of the laser current together with a selection of the initial phase made it possible to generate primary combs as well as solitons. We also demonstrate in this study that by deriving relations describing the laser's behavior when resonator transmission power is fed back to the laser, it is possible to stabilize the laser within the cavity soliton existence range. This further validates the accuracy of our observations. In conclusion, this study not only advances the understanding of nonlinear dynamics in a coupled system with laser and optical resonators but also demonstrates a robust and versatile platform for soliton-based frequency comb generation. The results pave the way for further exploration of SIL to high-Q FFP, offering exciting opportunities for both fundamental research and technological applications.

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