Determining the locking state of a Fabry–Pérot laser

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Abstract. *In this paper we experimentally examine the phenomenon of optical injection locking and its stability using a Fabry–Perot (FP) semiconductor laser with a wavelength of 1550 nm, which is widely used for the transmission in optical access networks due to its simplicity and low cost. Injection locking makes it possible to overcome the fundamental limits of the multi-longitudinal-mode behavior of the FP laser. Under injection-locking conditions, the linewidth characteristics of the master laser are transferred to the slave laser, which leads to a drastic improvement in the performance of the slave laser. However, the system dynamics of injection locking is very complex, which makes it very difficult to determine the locking state of the laser. Therefore, we propose a method whereby observing the laser's spectral coherence using self-homodyne detection we are able to determine the stable locking condition of the laser.*

Keywords. Fabry–Pérot laser diodes, injection locking, locking range, linewidth, self-homodyne

1 Introduction

In today's telecommunications networks the fiber-optic access network is wieldy accepted among academia and industry as being a future-proof solution. [1] There are several fiber-optic access solutions that enable high-data-rate capacities, but not many of them come without economic implications. One of the solutions that could be acceptable from the technological and economic points of view is the injection-locking technique. Using this technique a multi-longitudinal-mode Fabry–Pérot (FP) laser can operate in a single-longitudinal-mode regime, giving it greatly improved characteristics. [2] In a wavelength division multiplexing passive optical network (WDM-PON) the source laser in the optical network units is an optical injection-locked laser. [3]

Injection locking greatly enhances the parameters of a laser such as a multimode FP laser. This defines most of the fundamental limits of the laser, such as the mode partition noise, relaxation oscillation frequency, non-linear electron-photon coupling, relative intensity noise etc., to be improved. However, due to its rich dynamic behavior, determining the stable locking conditions is a particularly difficult task [4].

For the case of a multimode FP laser in the injection-locked state, the longitudinal modes that are not locked experience suppression. Usually, in the literature we find that for a side-mode suppression ratio (SMSR) between 30 and 35 dB the slave laser is considered to be in the injection-locking mode [4]. However, due to the complex behavior of a slave laser, the stability locking map is not only single-valued and correlated to the frequency detuning $\Delta\omega$ (between the master-laser and slave-laser frequencies) and r (ratio of the injected photon density S_i from the master laser and the photon density of the injected locked mode of slave laser S), but the stability map is a multi-valued stability function.

Under the conditions of optical injection locking, the master laser imposes its spectral distribution on the slave laser. Due to the fact that we have the complex behavior of the injection-locked slave laser, we will experimentally observe the process of transferring the linewidth of the master laser to the slave laser using self-homodyne detection, which to the best of our knowledge has not yet been done.

This paper is organized as follows. A short description of the injection-locking phenomenon is followed by different experimental measurements. First, the linewidth of a single-longitudinal-mode laser and a multi-longitudinal-mode laser (FP laser) is measured using the self-homodyne technique. Then, we present the difference between the locking and the unlocking range of the FP laser in the injection-locking map. At the end of the experimental part we present the difference in the locked laser's linewidth on the negative and positive frequency detunings. In the conclusion we propose a novel, self-restorable, injection-locking feedback loop that can contribute to a self-organized optical access network based on a WDM-PON.

2 Injection-locking phenomenon

Injection locking is a nonlinear phenomenon of synchronization that exists when coupling two or more self-sustained oscillators. The optical injection offers many dynamic regimes, such as locking, wave-mixing, relaxation and chaos. [4]

In the injection-locking process the light of the master laser is injected into the cavity of the slave laser, where the injected light coherently combines with the slave laser's internal light. If the injection power is high enough and the frequency difference between the master laser and the slave laser is not large, the slave laser is "dragged" towards the master laser's frequency, locking both the frequency and the phase [3]. The injection locking is affected by the fact that the presence of the out-of-phase component will introduce a phase shift and by the fact that to maintain the steady state of the slave laser, the gain of the injection field is changed.

The slave laser's dynamics can be analyzed through a system of rate equations, with additional terms describing the locking phenomenon [4].
Two adjustable parameters through which we control the injection locking are the injected power ratio r (the ratio of the photon density S_i injected into the slave laser's cavity and the photon density S of the injection-locked mode of the laser) and the frequency detuning ($\Delta\omega = \omega_i - \omega_0$), where ω_i is the master laser's frequency and ω_0 is the cavity resonance frequency of the slave laser. The locking bandwidth obtained from the rate equation is:

$$\Delta\omega_{min} = -(c/2n_c L)\sqrt{(S_i/S)(1+\alpha^2)} < \Delta\omega < (c/2n_c L)\sqrt{(S_i/S)} \qquad (1)$$

where n_c is the refractive index, L is the laser-cavity length, c is the speed of light and α is the linewidth-enhancement factor. [5], [6]

3 Experimental measurements

3.1 Linewidth measurements

The laser's linewidth represents the width of the optical spectrum, or more precisely, the width of the power spectral density of the emitted electrical field in terms of the frequency, wavelength or wavenumber. [7] The width of the laser can be seen as a consequence of the fluctuations in the phase of the optical field. The laser's linewidth broadening is attributed to the change of the phase and the intensity change due to the spontaneous-emission event. [8]
To be able to analyze the interrelation between the linewidths of the master laser and the slave laser during the injection locking we need to measure the linewidth of both the lasers used in this experiment before engaging them in the injection locking.
For the linewidth measurement we deployed a technique known as the delayed self-homodyne (Fig. 1). With this technique the optical light of the laser is divided into two branches, where in one branch of the Mach-Zehner interferometer a 20-km-long single-mode fiber is introduced to add around 100 microseconds of time delay. With this time delay we are able to measure the linewidth down to the range of 10 kHz. For the detection of the optical signal after the recombination of the two branches of the interferometer, a PIN-FET photodiode is used. From the photodiode the signal is sent to a radio-frequency spectrum analyzer for further analysis. Below is a schematic drawing of the delayed self-homodyne technique.
We measured the linewidths of two laser sources. The single-longitudinal-mode laser is a HP 8153A tunable laser source (TLS). The measurement result for its linewidth is presented in Figure 2. When the optical output power was set to 6 dBm, the linewidth of 100 MHz is measured at -3 dB threshold.

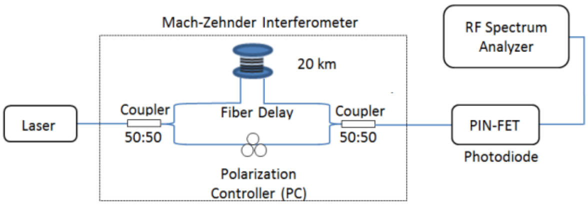

Figure 1. Delayed self-homodyne technique

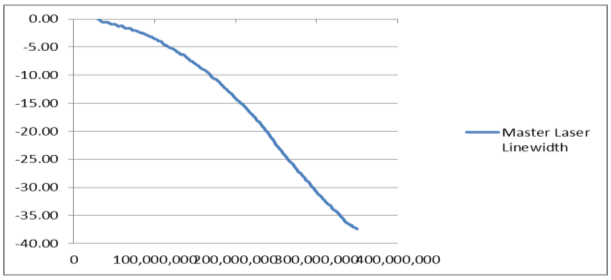

Figure 2. Linewidth measurements for a single-longitudinal-mode laser.

The second laser is a multi-longitudinal-mode laser with attached external cavity. We measured the linewidth of a 240-micrometer-long InGaAsP (indium gallium arsenide phosphide) FP laser. The external cavity is made up of 1-m long single-mode optical fiber and physical contact (FC) optical connector of 0.5% reflectivity. This FP laser has a threshold current of 10 mA. When the FP laser is stabilized at 20°C, with a bias current of $I=3I_{th}$, we find the dominant mode at 1546.244 nm. The free spectral range of external cavity is 100 MHz. For the linewidth of the FP laser with attached external cavity, due to its multi-longitudinal spectrum, in the RF spectra we have the corresponding mixing products of the optical longitudinal modes and the total linewidth is quite broad (Figure 3).

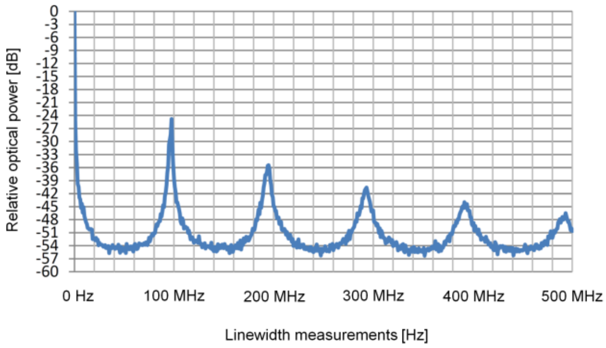

Figure 3. Linewidth measurements for the multi-longitudinal-mode laser

3.2 Injection-Locking Measurement

For the measurement of the injection-locked FP laser the reflection style set-up presented in Figure 4 is used [3]. For the master laser the single-longitudinal-mode laser is employed, while for the slave laser the multi-longitudinal-mode laser is employed. We used two optical spectrum analyzers: the OSA1 is used to control the power of the output signal from the master laser, and the OSA2 is used to observe the injection-locking phenomenon.

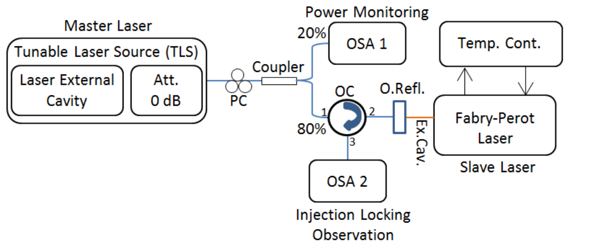

Figure 4. Experimental set-up for injection locking

The mode chosen to be locked was the first mode on the right of the central mode with a wavelength of 1457.660 nm. The FP laser was forward biased with a current of 30 mA, and was stabilized at 20°C. For this experiment we considered the FP laser to be in the injection-locked state when we measured the SMSR to be higher than 30 dB. Above this value the FP laser is operating as a single-longitudinal-mode laser. The optical spectrum of the FP laser in the injection-locked state and the free-running state is presented in Figure 5 and the locking map of the FP laser achieved from our experiment is presented Figure 6.

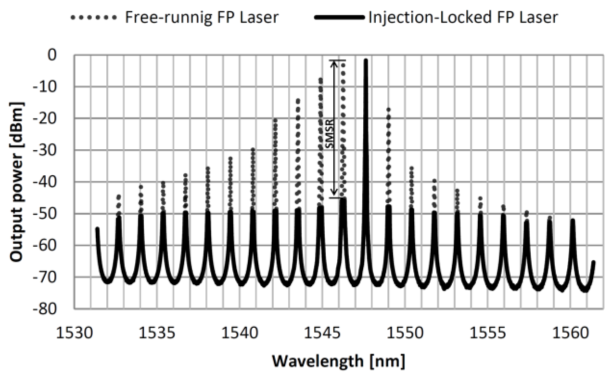

Figure 5. Optical spectrum of the FP laser

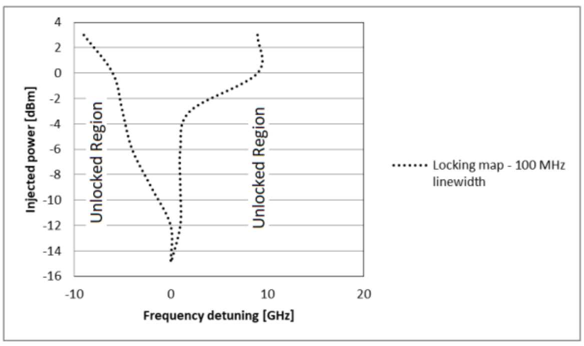

Figure 6. Injection locking map of the FP laser

As expected, with a higher injected power we could achieve a higher frequency detuning and a broader locking region.

4 Difference with respect to the negative and positive frequency detunings

It is well known that a FP laser under injection locking inherits most of the characteristics of the master laser. [4] The linewidth is one of the characteristics that is passed to the slave laser, and in our experiment we expected to observe a radical linewidth transformation, because we will transform the linewidth of a multi-longitudinal-mode laser such as a FP laser into a single-longitudinal-mode linewidth source.

The set-up for this experiment is a combination of the two previously presented set-ups. We preserved the same set-up values as in the previous section for both lasers. With the combined set-up we were able to engage the laser in the injection-locking process and also observe the process of transforming the FP laser linewidth from its free-running mode into the injection-locked state linewidth.

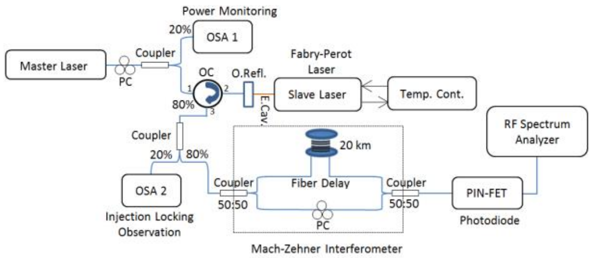

Figure 7. Experimental set-up for injection locking and linewidth observation using the delayed self-homodyne technique.

The output power of the master laser is fixed for all the conducted experiments presented in this section. In first experiment we analyzed the transformation of the linewidth of the FP laser in three different stages, related to the SMSR, as shown in Figure 8. It is worth underlining that we performed this experiment for negative $\Delta\omega$, which means that we had a lower master-laser frequency in comparison to the slave-laser frequency.

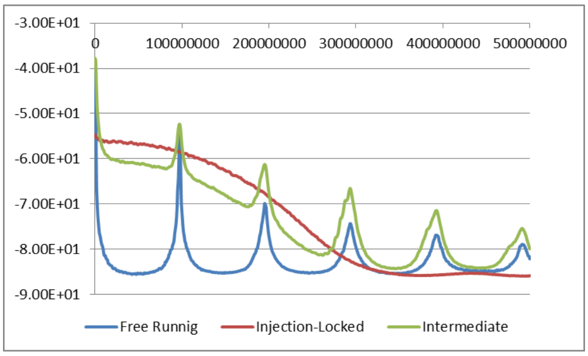

Figure 8. Experimental results for negative frequency detuning

The blue line represents the spectrum of the FP laser in the free-running state when no optical injection is applied to the FP laser. As expected, we have a similar curve as in Figure 2. For the spectrum of the FP laser when fully injection locked we have the same linewidth as for the case when we measure the linewidth of the master laser. Therefore, we have a complete transformation of the FP laser. At this stage the SMRS was higher than 35 dB. We also measured an intermediate stage, where we see that we have an in-between curve. At this point the measured SMSR was around 15 dB.

The second part of our measurement was to analyze the spectrum of the FP laser during the process of injection locking for the positive $\Delta\omega$.

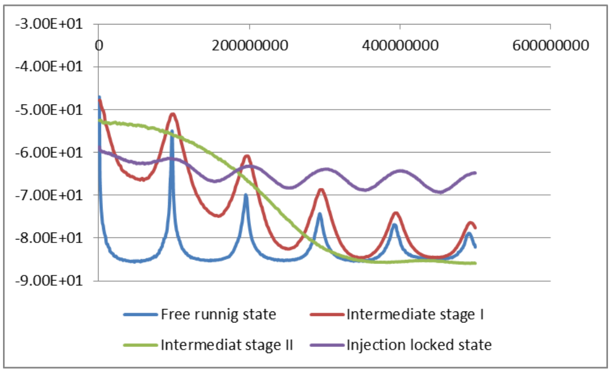

Figure 9. Experimental results for positive frequency detuning

It is worth noting that for this set of measurements, even though for the intermediate stage II we had a SMSR higher than 35 dB, we can see that the transformation of the linewidth is not complete, which could pose a problem when using an injection-locked FP laser.

For the free-running state and the injection-locked states, the optical spectra of the FP laser that correspond to the self-homodyne spectra presented in Figures 7 and 8 are clearly depicted in Figure 6, where the longitudinal free-running modes are presented with a dotted line and with a solid line we have the injection-locking spectra, where we see the injection-locked mode and the other suppressed modes. In addition to the explanation for the results in Figure 8, for the intermediate stage II in Figure 9 we present the corresponding optical spectrum, where we can clearly see that even though we have a SMSR higher than 30 dB, the linewidth transfer is not completed.

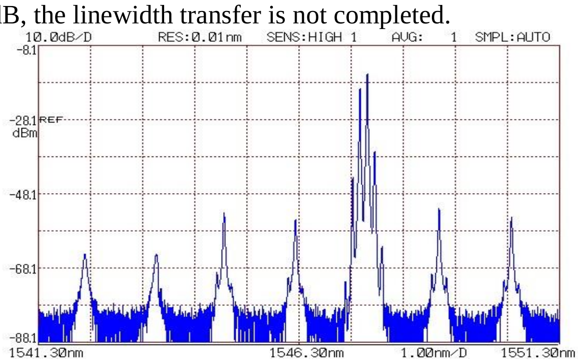

Figure 9. Optical spectrum for the intermediate stage II.

5 Conclusion

In this paper we determined the stable locking range for an injection-locked FP laser by observing the linewidth transformation of the injection-locked FP laser. By using a delayed self-homodyne technique we were able to measure the linewidths of the master laser and the FP laser in the free-running mode and then observe the transfer phenomenon of the linewidth during the injection-locking process. After performing the linewidth analysis, for the positive and negative frequency detunings, we came to the conclusion that for the stable injection locking of the FP laser the widely used condition of an SMSR higher than 30 dB is a necessary but not sufficient condition. As we have shown from the results for positive frequency detuning, even when we had a 30-dBm SMSR, the linewidth was not completely transferred for certain values of the frequency detuning.

In this paper we show that the injection-locking condition can be observed from the radio-frequency spectrum using the delayed self-homodyne technique and FP laser with attached external cavity. Based on the achieved results we propose a self-restorable architecture for the stable injection-locking behavior, as presented in Figure 9. The proposed system makes it possible to observe the linewidth change of the injection-locked FP laser, and through the temperature changes, the feedback loop keeps the injection-locked laser in a stable operational state.

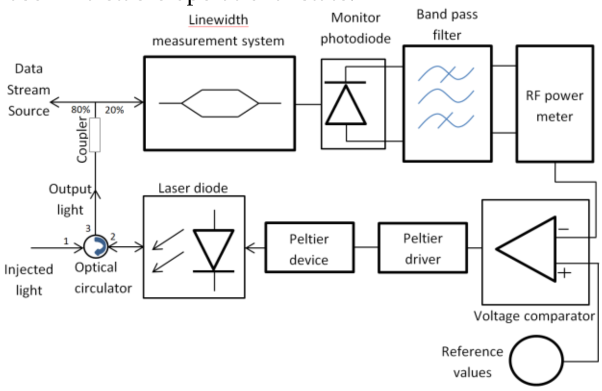

Figure 9. Self-restorable architecture for stable injection locking of a FP laser

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