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# **Injection locking of a semiconductor laser to a multi-frequency reference beam**

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## **Abstract**

Injection locking is a well known and commonly used method for coherent light amplification. Usually injection locking is done with a single-frequency seeding beam. In this work we show that injection locking may also be achieved in the case of multi-frequency seeding beam when slave laser provides sufficient frequency filtering. One relevant parameter turns out to be the frequency detuning between the free running slave laser and each injected frequency component. Stable selective locking to a set of three components separated of 1.2 GHz is obtained for (positive) detuning values between zero and 1.5 GHz depending on seeding power (ranging from 10 to 150 microwatt). This result suggests that, using distinct slave lasers for each line, a set of mutually coherent narrow-linewidth high-power radiation modes can be obtained

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## I. INTRODUCTION

Laser optical injection consists in seeding a free running slave laser with a master laser beam [1]. Since the laser is nonlinear oscillator, this seeding leads a rich variety of dynamical behaviors, including laser instabilities [2], route to chaos [3], excitability [4], extreme events [5], and injection locking [6]. Injection locking improves significantly the performances of slave lasers and, in the case of semiconductor lasers [7], it leads to several benefits for many applications including optical communications, microwave signal generation, all-optical signal processing, as illustrated in a recent tutorial publication [8]. In this paper we are concerned by the transfer of the coherence properties of the master oscillator toward an high-power slave laser, thus leading to strong optical amplification of the reference oscillator output [9]. In particular, we address the problem of injection locking with a multi-frequency reference beam. Our aim is to use each one of these frequency lines to injection lock distinct power lasers, thus obtaining a set of mutually coherent narrow-linewidth high-power radiation modes. This set of coherent modes is very attractive for generating Raman laser [10, 11] and for coherently controlling multiphotons absorption processes [12] but also for dense-wavelength-division multiplexing [13] and millimeters wave generation [14]. In our case, we intend to use this injection locking scheme to address the hyperfine levels of the  $^{87}\text{Sr } ^3P_1$  state in the 1 GHz frequency domain (Fig. 1a).

Injection locking using multi-frequency master laser has been analyzed recently using optical frequency combs as master radiation [15–17]. The frequency comb is generated with a femtosecond mode-locked Ti:sapphire laser or fiber laser, while a single-mode distributed feedback semiconductor laser is used as slave laser. The large number of modes and the small mode-spacing (100 MHz) emitted by the mode-locked laser needs to be filtered before seeding the slave laser, otherwise it may prevent the single-mode stability of injection locking [15, 18].

Our approach is based instead on a external cavity mounted tunable single-mode semiconductor laser as master oscillator, sidebands are obtained from the emitted radiation line by using an Electro-Optic Modulator (EOM) [19, 20]. Under specific conditions explained throughout the paper, we show that a slave multi-quantum-well laser can be injection locked to a well defined radiation line without being affected by the other sidebands. Our scheme features several advantages with respect to the mode-locked laser scheme discussed in [15, 16]: i) the frequency separation of the lines can be varied simply adjusting the RF frequency of the EOM, ii) the phase and the amplitude of each radiation line can be independently controlled, iii) the carrier frequency can be

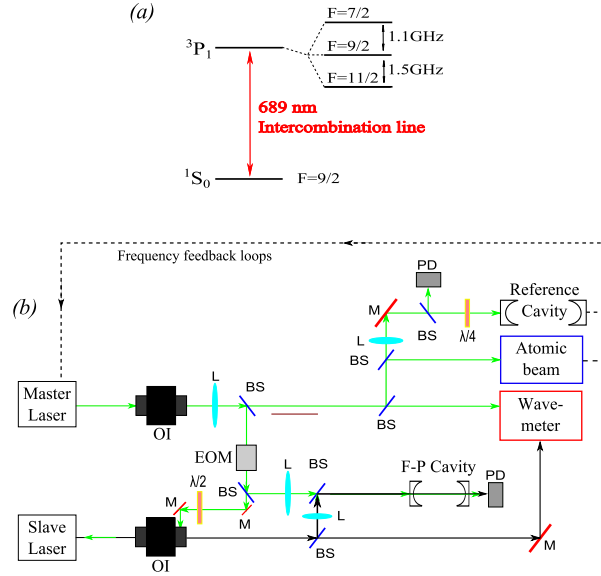


Figure 1: (a) Energy levels of the  $^1S_0 \rightarrow ^3P_1$  intercombination line of  $^{87}\text{Sr}$ . The laser system address the Hyperfine structure of the  $^3P_1$  state. (b) Schematic of the experimental set-up. The master laser is frequency locked on a reference cavity and on an atomic beam. The multi-frequency lines are generated in an EOM. The frequency spectra of the master laser and the slave laser are analyzed trough a wavemeter and a Fabry-Perot cavity. We use the following notation, L: Lens, M: Mirror, BS: Beam splitter, OI: Optical isolator and PD: Photodetector.

shifted quasi-continuously acting on the tunable diode laser, iv) filtering is simply obtained by relying on the coupling with the slave laser resonator without additional external filters and v) diode laser master oscillator is more compact, flexible and cheaper than Ti:sapphire laser.

The paper is organized as follow: We first describe the experimental set-up and the detection scheme of the lasers frequency and power spectrum. Then we present and discuss in detail our experimental results. In particular, we show that injection locking only occurs when the frequency of the free running slave laser is close to the frequency of the master oscillator. Finally we draw our conclusion.

## II. EXPERIMENTAL SET-UP

Master oscillator radiation is provided by a tunable external cavity diode laser (Fig. 1b). This system is electronically locked on an ultrastable reference external cavity using the Pound-Drever-

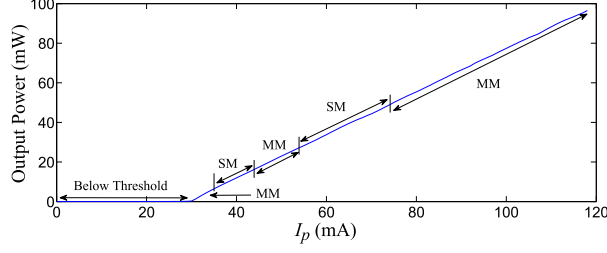


Figure 2: L/I curve of the free running slave laser. Above the threshold, SM means Single-mode laser emission, MM means Multi-mode laser emission.

Hall technic [21]. Under this condition, the frequency linewidth is below 1 kHz over one second. The long term absolute frequency drift of the cavity is below 30 Hz/s. It is corrected thanks to a saturated spectroscopy set-up on Strontium atomic beam. The master laser is maintained constant at an absolute frequency  $\nu_0=434848.50(5)$  GHz.

Before seeding, the master laser beam is sent through an EOM which generates lateral bands at  $\Omega = 1.2$  GHz. The phase modulation index of the EOM is adjusted at 1.43 such as the central band and the  $\pm 1$  lateral bands have the same amplitude. In this case 90% of the optical power is equally distributed among the three sidebands, and we ignore the contribution of the higher order sidebands.

After EOM, the master laser beam is sent into the slave laser using a lateral port of an optical isolator (Fig. 1b). We control the seeding power adjusting a  $\lambda/2$  retardation wave plate in front of the optical isolator port. The slave laser is a AlGaInP multi-quantum-well semiconductor laser from Opnext lasing at  $0.69 \mu\text{m}$  (Model: HL6738MG). Its cavity has a free spectral range of roughly 47 GHz. The absolute frequencies of master and slave lasers are monitored continuously by a lamdbameter with an accuracy of 60 MHz. The frequency spectra of the lasers are monitored through the transmission of a scanning Fabry-Perot interferometer with a free spectral range of 1.5 GHz.

The L/I curve of the free running slave laser is shown in Fig. 2. The lasing threshold is at  $I_p = 30$  mA. Increasing the pumping current  $I_p$  further, we observe an alternation of single-mode and multi-mode emission. This alternation can be explained considering that, the temperature of the active region increases with the pumping current. It induces a frequency shift of the gain curve together with a variation of the refraction index, leading to a frequency shift of the cavity resonances [22, 23]. Because the cavity resonances shift at a smaller rate with respect to the gain peak, an increase of the pumping current induces longitudinal mode jumping towards higher wavelength.

Multi-mode regimes occur when the gain peak is not close enough to any longitudinal modes to impose single-mode behavior, thus leading to multi-mode instability.

We set the pumping current of the slave laser in the range of  $I_p = 55\text{-}75$  mA where the laser is single-mode and mode hop free. The frequency of the free running laser  $\nu_{\text{free}}$  is continuously and linearly tuned by changing  $I_p$  with a slope:

$$\partial\nu_{\text{free}}/\partial I_p = -3.85, \text{ GHz/mA.} \quad (1)$$

So in the current range explored, the laser output frequency has shifted of more than 1.5 times its cavity free spectral range, though maintaining single-mode behavior. At the injection current value of 73 mA, the slave laser emission power is about 50 mW and its frequency coincides with the master laser frequency.

### III. SINGLE-FREQUENCY INJECTION

Semiconductor laser injection of a single-frequency has been largely explored in semiconductor lasers both theoretically and experimentally. Our observations do not differ from what have been reported so far (see for example: [24–28]). However it worths to analyze the behavior of our slave laser in this regime so we can pinpoint similarities and differences of the multi-frequency injection discussed in the next section.

We did a systematic search of the injection locking domains as a function of the seeding power and frequency detuning,  $\Delta\nu = \nu_{\text{free}} - \nu_0$ , between the free running slave laser and the master laser.  $\Delta\nu$  is scanned changing the pumping current of the slave laser. We limit our search in the interval  $I_p$  above defined, where  $\Delta\nu$  can be clearly defined.

The results are summarized in Fig. 3. In the graph, the dots materialize the boundary between the injection locked domains and regions where the slave laser is not interacting with the seeding beam or where injection leads to a non single-frequency emission. Injection locking is observed for a minimum seeding power of about  $10 \mu\text{W}$  corresponding to an amplification ratio of the laser radiation of 50 dB.

For the lowest seeding power values, injection locking occurs when the free running slave frequency  $\nu_{\text{free}}$  and the master laser frequency  $\nu_0$  almost coincide (Fig. 3a). More precisely, the lower limit of frequency difference for injection locking is  $\Delta\nu \simeq +0.2$  GHz. This red/blue asymmetry of the injection frequency with respect to the free running frequency is well known [25, 26]. It

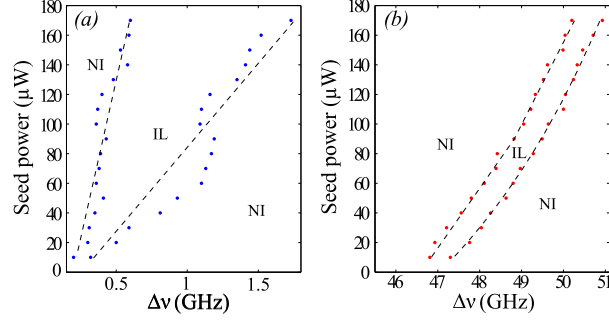


Figure 3: Single-frequency injection locking domain of slave laser in the frequency detuning-seeding power plane. The dots are the measured values whereas the dash lines are not fits, but guide the reader eyes. (a): injection locking domain when the free running laser frequency is close to the seeding laser frequency  $\Delta\nu \approx 0$ . (b): injection locking domain when the free running laser frequency is detuned by a free spectral range of the seeding laser frequency  $\Delta\nu \approx 47$  GHz IL (NI) means (no) injection locking on the master oscillator. The detuning values refer to the master frequency of  $\nu_0 = 434848.50(5)$ , GHz

can be easily understood considering that light injection inside the slave laser decreases the carrier number in the active region, thus affecting the refraction index and shifting the cavity resonances of the slave laser towards lower frequencies. In order to compensate this effect it is necessary to place the slave laser emission line (which coincide with one cavity resonance) on the blue side with respect the master frequency. The required positive detuning value increases with the injected power and it results in a progressive shift towards higher detuning values of the injection locking region. We note as well that the injection locking region get broader when the seeding power is increased. The maximum seeding power used in this work is  $180 \mu\text{W}$ , however we observed that injection locking persists at even higher seeding power.

Increasing  $\Delta\nu$  (by decreasing slave pumping current) beyond the high frequency borderline of Fig. 3a, the injection locking is lost. It is recovered, when the detuning corresponds roughly to the free spectral range of the slave laser such as the neighbor longitudinal mode gets almost resonant with the seeding beam frequency. We obtain then the locking region depicted in Fig. 3b. As for the previous case, we observed a blue shift of the free running laser frequency for the injection locking condition when the seed power is increased. However the injection locking frequency range is now narrower. This narrowing is probably due to a more stringent mode competition between the injection locked mode and the free running lasing mode.

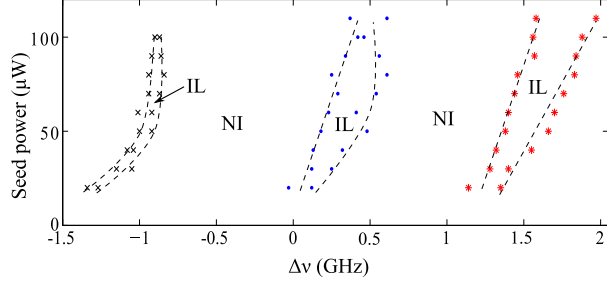


Figure 4: Multi-frequency injection locking domains of slave laser in the frequency detuning-seeding power plane. The ordinate axis gives the total seeding power. The detuning is measured with respect the central frequency of the injected beam. The slave laser is injected by three lines separated by 1.2 GHz. The dots, crosses and stars are the measured values whereas the dash lines are not fits, but guide the reader eyes. IL (NI) means (no) injection locking on the master oscillator. The detuning values refer to the master frequency of  $\nu_0 = 434848.50(5)$ , GHz

#### IV. MULTI-FREQUENCY SEEDING

It has been shown that a multi-frequency injection affects the stability of injection locking [18]. This fundamental problem can be solved by using a slave laser whose resonator is capable of selecting a single frequency component and filtering out the remaining ones. In other words, slave laser frequency selectivity is the key point for achieving stable injection locking in presence of a multi-frequency master radiation. Accordingly, slave laser selectivity determines a minimum frequency separation between the master components for which injection locking can still be achieved.

Let us analyze injection locking of our slave laser to a multi-frequency master radiation obtained by using an EOM to generate sidebands on the master beam, as described in Section II

As for the single-frequency case, we scan the free running frequency  $\nu_{\text{free}}$  around the central frequency of the seeding beam and we observe that the slave laser can be injection locked to each frequency component of the master beam. Our result are summarized in Fig. 4, showing the locking ranges and in Fig. 5, showing the optical spectrum emission of the injection-locked slave laser. Within the injection locking domains, more than 90% of the slave power is in the selected sideband. As it occurs in the single-frequency case, we observe that the detuning range where injection locking occurs is asymmetrically shifted towards positive values of  $\Delta\nu$  (Fig. 4). This (positive) detuning range remains however smaller than the separation of the frequency components of the



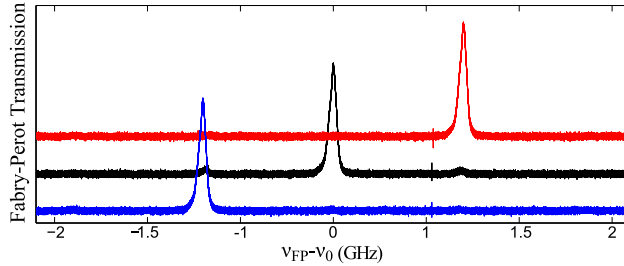


Figure 5: Fabry-Perot transmission spectra of slave laser injected by three lines separated by 1.2 GHz for a seeding power of  $50 \mu\text{W}$ . The blue, dark and red curves correspond respectively to injection locking of the red, central, and blue line. The spectra are obtained for different  $\Delta\nu$  values within the injection locking domains depicted in Fig. 4. Spectra baselines have been shifted along the ordinate axis to easily observed the presence of minor peaks.

master beam. Injection locking is achieved for seeding powers smaller than  $110 \mu\text{W}$ . Instead for seeding power larger than  $110 \mu\text{W}$  the filtering of the slave laser resonator is not anymore sufficient to avoid competition between the injected frequency lines and the system becomes unstable.

We notice in Fig. 4 that the injection locking range of the blue sideband is larger than the injection locking range of the red side band. This feature is not universal and different values of the central frequency of the seeding laser leads to different shape of the injection locking domains.

If we shift the free running slave laser frequency up to one free spectral range, as we did for the single-frequency case, selective injection locking is not achieved anymore. More precisely, not more than 60% of the slave power is in one specific line and the system is usually dynamically unstable.

We can then conclude that selective injection locking occurs for a multi-frequency seeding beam with a band spacing of  $\Omega = 1.2 \text{ GHz}$ , provided that the free running slave laser is tuned close to the central injected frequency, i.e.  $\Delta\nu \simeq 0$ . Similar studies, but with a larger band spacing of  $\Omega \sim 10 \text{ GHz}$  have shown that selective injection locking is obtained without mentioning the important role  $\Delta\nu$  observed in this current work [11, 19, 20].

By slightly modifying the set-up described in Section II, we test the multi-frequencies injection with a smaller separation between the components. In this new set-up the master beam is composed by only two frequency components whose separation is of  $\Omega = 0.16 \text{ GHz}$ . In this situation we were not able to achieve injection locking, as also reported in similar experiment [15, 16]. In Fig. 6 we plot the optical spectrum of the slave laser emission when injected and it is evident that

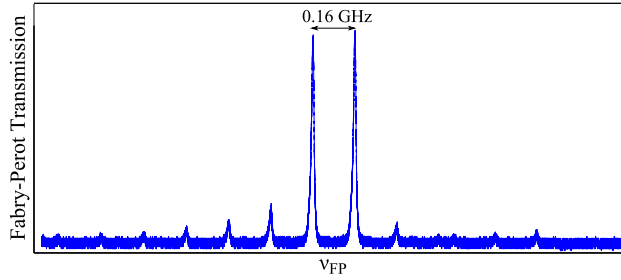


Figure 6: Example of a Fabry-Perot transmission spectrum of slave laser injected by two lines separated by 0.16 GHz for a seeding power of  $50 \mu\text{W}$ . The asymmetry in the spectrum is probably due to an imbalance of the injection power of the two lines which, in this particular case, cannot be accurately controlled.

both lines are present. Similar spectra were obtained by changing the value of  $\Delta\nu$ , suggesting that frequency selectivity of the slave resonator is not strong enough to filter a single injection band. Due to nonlinear mixing of the two lines in the gain medium, the slave laser spectrum contains also other lateral bands appearing at frequencies separated from the two main lines by an interval  $\pm n\Omega$ , where  $n$  is an integer (Fig. 6). The amplitude of these extra lateral bands depends on the seeding conditions.

## V. CONCLUSION

In this paper, we study the injection properties of a multi-quantum well semiconductor laser subject to multi-frequency seeding. In particular we address the important issue of injection locking of the laser to a single band, relying on the frequency selectivity of the slave laser only. Using a frequency spacing of the seeding sideband of 1.2 GHz, single band injection locking occurs only if the free running slave laser is close to the injected frequency. If the slave laser is detuned by one frequency spectral range, single band injection locking is lost. This result shows that the frequency selectivity to injection of the slave laser seems to crucially depend on the frequency difference between the slave laser and the seeding laser. We also observe that for a frequency spacing of the seeding sidebands of 0.16 GHz, single line injection locking is not possible. Under this condition the injected slave laser always exhibits a multi-frequency spectrum.

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