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Narrowband frequency control of an injection-locked diode-laser battery

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Abstract. — We report the generalization of the optical injection locking procedure to a battery of high power diode lasers. To illustrate the principle, two 50 mW cw single-mode GaAlAs multiple quantum well structure diode lasers have been injection-locked to a low power cw single-mode diode laser. In the presence of a large number of slave lasers, the isolation of the master one becomes more critical, but the injection conditions are not changed dramatically. A typical locking bandwidth of 3 GHz is obtained for an injection power of 20 μW. Significant locking is still observed for 0.5 μW injection. Injection-locked high power laser beams can be obtained with RF range frequency offsets by injection through acousto-optical modulators, offering a large number of potential applications.

Recent developments in diode lasers have already a significant impact in atomic and molecular laser spectroscopy [1, 2]. The narrow single-mode spectrum and the tunability make their use particularly attractive. Future progresses in the visible range are very promising, and already their characteristics and their relative low cost allow experiments with a large number of commercially available diode lasers. Compared to pumped dye lasers, diode lasers offer also the facility to perform any particular temporal sequence, for instance, frequency chirping or frequency modulation by acting on the drive current of the diodes. Nevertheless, the drawbacks related to their spectral width and frequency unstability still impose limits.

Recently, important improvements have been obtained in spectral narrowing and frequency stabilization techniques by optical feedback [3, 4] or by external-cavity lasers [5, 6]. The narrowed laser frequency can be scanned, modulated or locked to a reference. The desire to produce spectrally pure high power laser beams has led to the development of injection

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locking techniques for diode lasers [7, 8]. First demonstrated in 1966 [9], the concept of injection locking involves the use of the beam of a low power stable single-mode laser, referred as the master laser, which is injected into the cavity of a high power laser, called slave laser. The result is to extinguish all free-running modes of the slave laser and to amplify the master laser mode. High single-path gain and low cavity $Q$ in diode lasers allow wide frequency locking range with low injection power. Commercial development of cw high power (up to 1 W) multimode diode lasers makes this technique especially interesting. Injection locking has also been performed with diode-laser arrays [10, 11].

The injection locking mechanism is described within the framework of the semiclassical laser theory by the van der Pol equation [7, 12, 13]. In this formulation, the electric field of the injection wave, regarded as an external driving force, is added to the rate equation which governs the time evolution of the electric field in the slave laser cavity. A locking state is a state where the oscillation frequency of the slave laser wave is equal to that of the injection wave, and where the phase difference between these two waves is constant. The steady-state solutions of the van der Pol equation for the locking states determine the injection wave frequencies for which the locking can occur for a given phase difference between injection and locked waves. The locking bandwidth $\Delta f$ is defined as the locking frequency range for which the phase difference between these two waves varies from $-\pi/2$ to $\pi/2$. It is given in reference [7] as follows:

$$\Delta f = \frac{1}{2} \pi \tau_p (P_{in} / P_{\ell})^{1/2},$$

where $\tau_p$ is the photon lifetime in the slave laser cavity, $P_{in}$ and $P_{\ell}$ represent the powers of injection and locked waves respectively. The output power of the locked slave laser is also given by the steady-state solutions. It can be demonstrated that the ratio between the powers of locked state and free-running state of the slave laser approaches unity at a large drive current of the diode, especially for low injection power [7].

Simultaneous injection to a battery of diode lasers offers the possibility of several high power phase-locked laser beams which can be at same given frequency or with frequency offsets. Furthermore, the stabilization of the different slave lasers is achieved by the stabilization of the master laser, and the frequency offsets required can be obtained by injection through different acousto-optical modulators. To study these possibilities in detail, we have locked two high power cw diode lasers to a single low power cw diode laser by injection. The experimental results reported here can be generalized to the case of a larger number of slave lasers. We have experimentally studied the optical coupling between the different lasers, which determines the required injection power and also the optical isolation necessary for the master laser. We have also focused our attention on the locking bandwidth and the coherence between injection-locked beams.

The experimental set-up is schematically presented in figure 1. The diode lasers are centered at a wavelength of 852 nm, which corresponds to the D$_2$ line of the cesium atom. This study had been developed, at the beginning, for experiments on both the observation of the atomic clock transition on a slowed cesium beam [14] and the study of 1-D sub-Doppler molasses [15]. The master laser (ML) is a single-mode (~ 20 MHz FWHM) 15 mW cw Hitachi HPL 1400 GaAlAs double-heterostructure diode. The slave lasers (SL) are 50 mW cw STC LT50A-03U GaAlAs multiple quantum well diodes with a single-mode spectrum of about 20 MHz FWHM. All the three diodes operate at the room temperature with a drive current about twice the threshold value (~ 100 mA). Electronic servoloops ensure a short term stability of 4 μA on the drive current and 10$^{-4}$ °C on the diode temperature. The master laser can be spectrally narrowed by optical feedback from an external confocal Fabry-Perot cavity with a finesse of 20. By analyzing the beat-note signal between the beams of two
individually stabilized lasers, a resulting linewidth of about 50 kHz is measured. The injection is performed with either a free-running or a stabilized master beam. The master laser is optically isolated by using a home-made optical isolator (ISO) with an attenuation of 45 dB and an acousto-optical modulator (AOM) driven by a radio frequency (RF) wave of 100 MHz. Only the first order shifted beam from the AOM is used for injection. These two elements of the set-up are necessary to totally suppress the retro-injection of the slaves into the master. By changing the RF power the injection intensity can be varied. Typically a beam of 0.5 mW is reflected by a mirror and used for injection. In our experimental configuration, the output beams of the slave lasers are collimated by microscope objectives to be parallel with a cross section of 4 × 8 mm². In order to get optimum focusing at the slave diodes, the injection beam is collimated by a lens to be parallel with a cross section of 4 × 4 mm². The overlap between the injection beam and the slave beams is not critical as long as the cross section sizes are of the same order of magnitude. About 5% of the injection beam (∼ 20 μW) is taken by two beam splitters and focused at the slave diodes through their own objectives. The spectrum of an injection-locked diode laser is analyzed by observing the transmission signal through a confocal Fabry-Perot cavity (FP) with a free spectral range of 0.75 GHz and a finesse of 20.

Experimentally, the injection beams are aligned to the slave laser beams using of micrometric mirror supports. The frequencies of the slave lasers are matched to that of the master laser by adjusting their drive currents. Once they are within the locking range, injection locking occurs. This is identified by observing the Fabry-Perot transmission signals of the slave beams. As shown in figure 2, transmission fringes are observed when the drive currents of the slave diodes are swept and the injection beams are cut off (Fig. 2a). When the injection beams are switched on, the transmission signals show a constant level with the disappearance of several fringes (Fig. 2b and Fig. 2c). The length of each Fabry-Perot cavity is adjusted to get a high constant transmission level. The difference between figure 2b and figure 2c is that in the former case the master is free-running and in the latter case the master is stabilized. The constant level in the transmission signals indicates that the slave lasers are

![Schematic representation of the experimental set-up.](image-url)
Fig. 2. — Transmission signals through the Fabry-Perot cavities (FP1 and FP2) when the drive currents of the slave diodes are swept. The free spectral range and the finesse of the cavities are respectively of 0.75 GHz and 20. (a) The injection beams are cut off. (b) The slave diodes are injected by a free-running master laser. (c) The slave diodes are injected by a feedback stabilized master laser.

locked to the master laser. The locking bandwidth is measured in this case by the width of the constant level. In figure 3, the measured locking bandwidth $\Delta f$ is given as function of the ratio between the injection power and the locked power, $P_\mathrm{in}/P_\ell$. As predicted by equation (1), the locking bandwidth varies as the square root of the injection power for a fixed locked power. A numerical value of $\tau_p$ of $1.1 \times 10^{-12}$ s is obtained for the used STC GaAlAs multiple quantum well diode, which is about half of the value of $2.3 \times 10^{-12}$ s given in reference [7] for a GaAlAs double-heterostructure diode. For a locked power of 50 mW, a typical locking bandwidth of 3 GHz is obtained for an injection power of 20 $\mu$W. A significant locking is still observed for an injection of 0.5 $\mu$W. The measured short photon lifetime of the used STC diodes is essentially due to the transparent and the high reflectivity coatings on the facets of the chip. According to the manufacturer, the nominal reflection coefficients of the output and the back facets are 0.05 and 0.90 respectively. Such a structure is generally used in high power diode-laser devices. With these given reflection coefficients, a cavity-finesse of 1.34 can be calculated instead of 2.77 for a facet-cleaved chip ($R_1 = R_2 = 0.32$ as in Ref. [7]).

The coherence between injection and locked beams is demonstrated by observing the beat-note signal between a slave laser beam and the zero-order master laser beam. The frequency of the beat-note signal corresponds to the RF drive frequency (here 100 MHz). In figure 4a
the injection beam is cut off, the observed beat-note signal at a frequency close to 100 MHz vanishes over a time scale of 45 ns, which corresponds to a linewidth of the free-running slave diode of about 20 MHz. In figure 4b, the injection beam is switched on, the beat-note signal of a frequency equal to 100 MHz is observed over a very large time scale. The beat-note signal between the two injection-locked slave lasers has also been observed. Two acousto-optical modulators are used to independently shift the frequencies of the injection beams. Beat-note signals at lower frequencies can be observed. In figure 5, a 50 kHz beat-note signal is presented over a time scale of 1 ms. The coherence between the two beams is only limited by the stability of the used RF generators. In this way, we are able to obtain two phase-locked laser beams with adjustable frequency offset. The use of a such «laser-tandem» is very interesting in high resolution stimulated Raman spectroscopy. In this case, two coherent laser beams with a frequency offset in the RF range induce absorption-stimulated emission cycles and transfer atomic population from one ground-state sub-level to another. It has been recently pointed out that by performing such transitions on an atomic beam in the presence of a magnetic field gradient, micron spatial resolution can be attained in atomic beam profile measurements [16].

Before concluding, different points of the experimental set-up should be discussed. The polarizations of the master beam and the slave beams are set to be identical. Rotating the linear polarization of the master beam with respect to that of the slave beams results in an attenuation of the injection power. Only the component with a polarization parallel to that of the slave lasers plays a role in the injection procedure. The isolation of the master is the most critical point in the set-up. A power of 0.1 μW retro-injected into the master diode is enough to perturb it. When the number of slaves increases this retro-injection increases too. For our two slave experiment the use of a 45 dB isolator alone is not sufficient. The use of an acousto-optical modulator is necessary for a complete isolation of the master. Since the slaves are injected by the first order shifted master beam, the retro-injection beams are frequency-shifted by twice the acousto-optical drive frequency and then coupled less with the master

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**Fig. 3. — Locking bandwidth \( \Delta f \) versus the ratio between injection power and locked power \( P_{in}/P_l \) (10^{-4} \( \text{corresponds to an injection of 5 } \mu \text{W for 50 mW locked power} \). The fit is given by equation (1) with a numerical value of \( \tau_p \) equal to 1.1 \( \times 10^{-12} \) s.**
Fig. 4. — Beat-note signals between master and slave laser beams, in (a), the injection beam is cut off; in (b), a feed-back stabilized master beam is injected into the slave diode, the beat frequency is exactly 100 MHz equal to the AOM drive frequency. The signals are recorded by a digital oscilloscope triggered by the beat-note signal at time zero. An average over 1024 traces is taken, which corresponds to a recording time of 205 ms for each signal.

laser. The mechanical stability of the experimental set-up is not very critical. The alignment is conserved from one day to another.

To conclude, by using injection into a battery of diode lasers by a single master diode laser, several high power coherent laser beams can be available at the same frequency or with frequency offsets. This allows us to control and to stabilize only one diode laser. For injection locking, the free-running slave diodes should operate within the same frequency range as the master diode. The low required injection power allows injection into a large number of slave diodes by a single master diode.

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Fig. 5. — Beat-note signals at 50 kHz between two injection-locked slave laser beams. The signals are recorded in real time over a scale of 100 μs in (a) and 1 ms in (b).

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