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Generation of phase-coherent laser beams for Raman spectroscopy and cooling by direct current modulation of a diode laser

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Abstract. A setup for generation of GHz side-bands by direct current modulation of a diode laser is described. The first order side-bands are used to inject two slave power diode lasers, in order to produce phase coherent, controllable frequency shifted, light beams, the mutual phase coherence of which has been verified (beat-note FWHM of 1 Hz, instrumentally limited). Some possible applications in the context of laser Raman cooling of cesium atoms are briefly discussed.

PACS. 42.55.Px Semiconductor lasers; laser diodes – 32.80.Pj Optical cooling of atoms; trapping

1 Introduction

Stimulated Raman spectroscopy between two hyperfine sublevels of an atomic ground state is a very powerful tool in the field of laser cooling. It provides a technique for very precise atomic velocity measurement, for laser cooling below the photon recoil energy [1,2], for cooling in a far detuned dipole trap [3], and was used in a $\hbar/M$ measurement [4]. This technique has also played a major role in the observation of Bloch oscillations with colds atoms in a stationary wave [5]. However, if stimulated Raman spectroscopy/cooling is such a powerful tool, the experimental setup it requires is still relatively complicated. The main difficulty of this technique is the generation of two powerful phase-coherent laser beams with a precise and tunable frequency difference in the GHz range. Up to now, three principal methods have been used to achieve these requirements: electro-optic modulation [1,6], optical phase locking of two diode lasers [7,8] and high frequency acousto-optic modulation [9]. In this article we describe a simple and inexpensive way to generate two powerful mutually coherent laser beams with a given frequency difference in the GHz range.

Cesium-atom stimulated Raman transitions between hyperfine ground state sub-levels $6S_{1/2}(F = 3)$ and $6S_{1/2}(F = 4)$ (hyperfine splitting $\omega_{\rm HF}/2\pi \approx 9.2$ GHz – this splitting corresponds to the cesium clock transition) provide the basis of a powerful method for sub-recoil cooling [1,2] owing to the narrowness of transitions between ground state sublevels, which afford a very high sensitivity to the Doppler effect. Stimulated Raman transitions are obtained by applying to the atom two laser beams whose frequency difference is close to the hyperfine frequency interval of the ground state sublevels. These lasers are detuned with respect to the excited level $6P_{3/2}(F = 4)$ at the wavelength of $\lambda = 852$ nm by a value that should be much greater than the natural width Γ of the excited level, so that the spontaneous emission rate is negligible. The mutual coherence between the laser beams (that can be easily determined by measuring the width of the beat note between the two lasers) will be a key limitation to the atomic velocity sensitivity of the Raman spectroscopy. In the case of the cesium, the recoil frequency is about 2 kHz, and a beat note narrower than this value will be necessary to achieve sub-recoil Raman cooling, or sub-recoil velocity-sensitive Raman spectroscopy of cesium atoms.

The principle of our method is to direct modulate the current of a diode laser at a GHz rate, producing frequency side-bands that are used to inject two slave diodes. A natural idea is to modulate the laser at 9.2 GHz and inject the two slave lasers with the carrier and one of the first order side-bands. However, in practice the diode laser modulation response decreases as the modulation frequency increases. We thus chose a modulation frequency of half the hyperfine structure frequency, $\Omega_{\rm m}/2\pi \approx 4.6$ GHz, and we use the symmetric first modulation orders (-1 and $+1$) to inject the slave lasers.

High speed modulation of semiconductor lasers is widely used in optical communication systems. For instance a field effect transistor monolithically integrated with a buried heterostructure GaAs/GaAlAs laser has been used to perform modulation at frequencies greater than 10 GHz in the early 80's [10]. Yet, in the field

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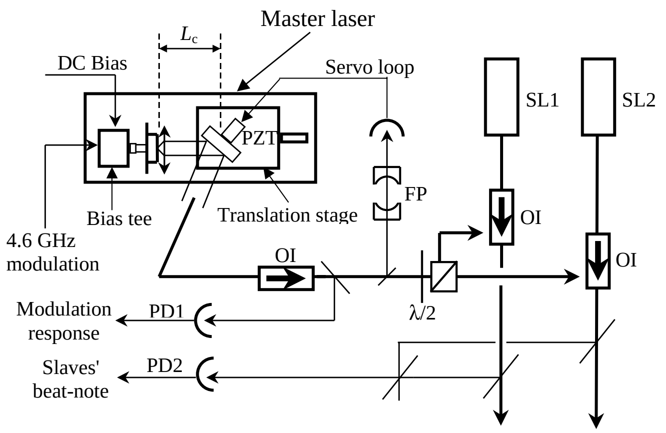

Fig. 1. Experimental setup. Symbols: L_c = extended cavity length, OI = optical insulator, SL = slave diode laser, FP = Fabry-Perot cavity, PD = photodiode, PZT = piezoelectric crystal.

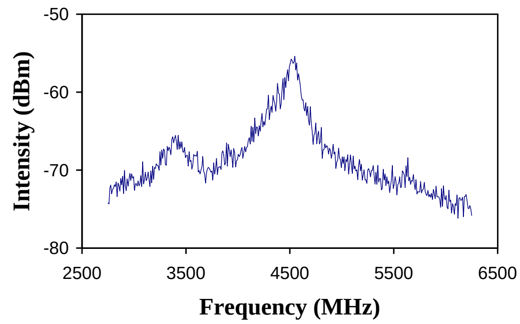

Fig. 2. Multimode behavior of the laser observed by slightly scanning the extended cavity length L_c (microwave off, signal detected by PD1).

of atomic physics this method is still underused. Generation of a 6.6 GHz sideband has been demonstrated on a 785 nm diode laser [11], and was used to yield simultaneously trap and repumping frequencies in a Rb magneto-optical trap. Here we develop another kind of application, where cross-band phase coherence is also requested. Microwave modulation of a master diode laser used to inject slave lasers has also been previously studied [12,13], but not with the application to Raman cooling/spectroscopy in mind.

2 Modulation setup

The experimental set up is shown in Figure 1. We use a commercial 100 mW SDL 5412-H diode laser with a 852 nm central wavelength, close to the D2 cesium optical transition. This laser is mounted in a TO3 package including a Peltier cooler and a temperature sensor. The microwave source is a 1 GHz range synthesizer (HP ESG1000A) whose output at 0.92 GHz is frequency-multiplied by five by saturation of an RF amplifier with subsequent filtering of the idle harmonics. The diode laser bias current and the microwave power (200 mW) are mixed in a 6 GHz bandwidth, SMA plugged, bias-tee. The bias-tee is connected to the diode through a SMA socket whose ground is directly connected to the diode laser anode and the central plug to its cathode. We take care in making the connections as short as possible, but do not attempt to insure a 50 Ω impedance matching. No special microwave skills are demanded for these connections. The impedance mismatch might induce coupling losses greater than 10 dB, but we can easily compensate for them by increasing the incoming microwave power. Thus, the real microwave power coupled in the laser diode is unknown.

In order to insure single-mode behavior and narrow line-width, the diode laser is mounted in an extended cavity configuration with a diffraction grating used as the cavity output mirror. The cavity length L_c can be scanned on the micrometer range through a piezoelectric ceramic, and on the millimeter range by a translation stage. In order to insure the stability of the extended cavity, its length can be locked on an external stable Fabry-Perot cavity through a servo-loop. The outgoing beam travels through an optical insulator, and a fraction of it is focused on a high speed Hamamatsu G4176 AsGa detector (PD1 in Fig. 1). The beat-note among the different frequency components is then monitored by a spectrum analyzer.

3 Optimization of the modulation depth

The modulation signal for frequencies up to 3 GHz is easily obtained, but the amplitude of the side-bands rapidly decreases for higher frequencies. Our interpretation of this fact is that the free (*i.e.*, without extended cavity) laser response to a GHz modulation is maximum around 2–3 GHz, which corresponds to well-known relaxation oscillation frequencies for this kind of device. One expects the spectral response to be modified by the extended cavity. This is verified by slightly scanning the cavity length in the absence of the microwave power until the laser becomes multimode. One then observes some broad lines (FWHM ≈ 100 MHz) in the spectrum of the laser (see Fig. 2), corresponding to beat-notes among transient modes (the width of these lines is due to the low sweeping time of the spectrum analyzer). We found empirically that the appearance of the broad line spectrum is a signature of the ability of the laser to accept additional oscillation modes and thus to respond to an external modulation (this behavior is probably related to the phenomenon known as *coherence collapse* [14], but we have not performed any characterization of it). Furthermore, the spectrum can be frequency-shifted by adjusting the cavity length L_c. This fact allows the optimization of modulation amplitude by scanning the L_c value. Figure 3 shows for each value of L_c the frequency corresponding to the maximum modulation depth. For $\Omega_m/2\pi = 4.6$ GHz, three optimum lengths are available.

We also observed that, as well as the optimal modulation at a given frequency corresponds to more than one cavity length, a given cavity length optimizes more than one frequency. For example, for $L_c = 22.6$ mm, the laser can respond also around 8.3 GHz.

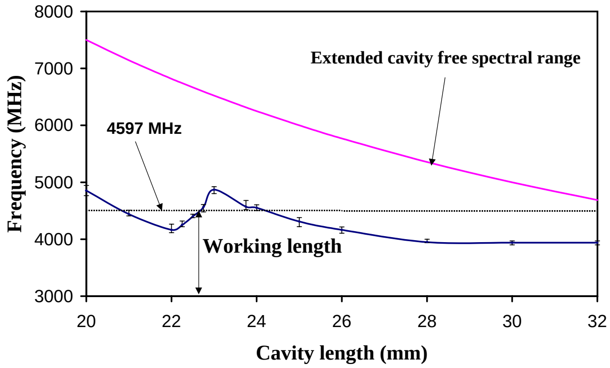

Fig. 3. Frequency corresponding to the maximum modulation depth as a function of the extended cavity length L_c (signal detected by PD1).

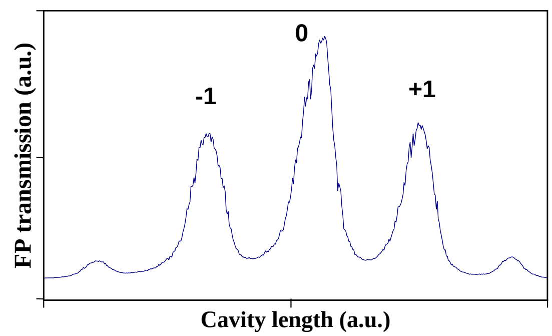

Fig. 4. Optical spectrum of the modulated diode laser analyzed by a Fabry-Perot interferometer.

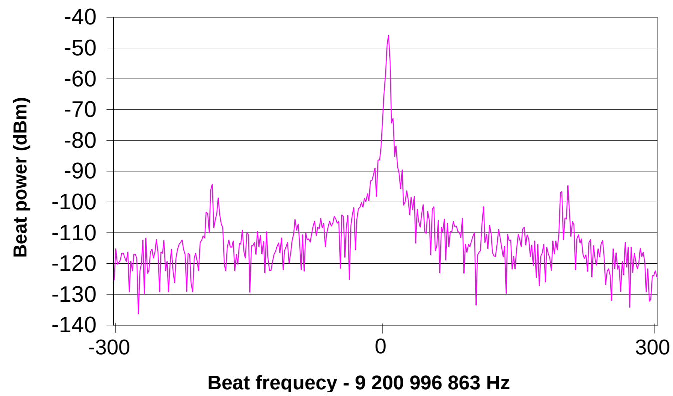

Fig. 5. Beat-note at 9.2 GHz between the two injected power lasers (detected by PD2). FWHM = 1.7 Hz.

We performed a careful experimental study of the behavior of the laser at each of the three possible values of L_c, and found that the intermediate length (L_c = 22.6 mm) corresponds to the best stability of the device. The cavity length is adjusted with an accuracy of 100 μm for maximizing the modulation depth at the frequency $\Omega_m/2\pi = 4.6$ GHz. It becomes clear from the above discussion that the external cavity length is a key parameter for high frequency modulation, even if we are unable to explain the mechanisms behind the observed effects.

Another significant parameter is the DC bias current. We work at 37 mA (2.2 times the measured diode laser threshold current) where the modulation depth is nearly optimum. For higher bias current, the modulation depth continuously decreases; at lower current it might increase, but as the total voltage is falling, the risk of applying an inverse voltage to the diode through the microwave increases (we prefer to avoid this risk, although we do not know if a reverse bias modulated at 4.6 GHz can damage the diode, as a DC one does). Since the real microwave power actually coupled into the laser is unknown, we cannot deduce the ratio between the DC bias current and the microwave current amplitude. In the current range between 35 and 50 mA we verified that turning on the microwave increases the output light power by about 1%. At our working value of 37 mA, the available light power is 8 mW, large enough to achieve slave injection-locking.

The third relevant parameter to the maximization of the modulation amplitude is the temperature, which is not surprising as it is equivalent to a cavity length shift. All experiments have been done at 20 ± 1 °C.

Let us emphasize that we do not found any simple explanation for the values of the parameters found for maximizing the modulation depth in the literature. One can intuitively expect the parameters mentioned above to play an essential role, but we have not found any way of calculating the values they should take. We thus consider that the values we found are particular to our device, and that an equivalent experimental study would be necessary for another device.

The optical spectrum of the modulated laser through a confocal Fabry Perot is shown in Figure 4. The height of the side-bands in our working conditions is half the carrier height, and it is possible to have a side-band intensity comparable to that of the carrier, simply by increasing the incoming microwave level. The efficiency of the modulation we achieve in our setup is thus more than one order of magnitude greater than what is reported with acousto-optical or electro-optical modulators [1,6,9]. Once the current value, the cavity length and the diode temperature are chosen, the device is very stable. The laser is still tunable over one free spectral range through the PZT crystal with no observable effect on the modulation amplitude (at least for low DC bias current), and the laser can work for many hours without degradation in the performance, provided the thermal drifts of the cavity are corrected by a servo. On a time scale of one year no reproductibily problems were observed.

4 Injection of the slave power lasers

A small fraction of the master beam (50 μW) is used to inject and frequency-lock two 150 mW slave power diode lasers (see Fig. 1). Each slave can be locked on the desired side-band by adjusting its gain curve through the bias current, and no spectral filtering of the carrier or of the other-side band is required. The beat note at 9.2 GHz between those two lasers is shown in Figure 5. Its FWHM is 1.7 Hz. This limitation corresponds to the resolution of our spectrum analyzer (HP8563E). This also shows that the phase noise in the microwave generation stage (synthesizer, multiplier, filtering) has no effect on the mutual coherence at the scale of the Hz. However, the mutual coherence of the Raman laser beams is not the only limiting factor for Raman cooling, where other effects like the shielding against stray magnetic fields play a central hole.

When one of the Raman beams is optically shut before the detector, the beat-note level decreases by 25 dB. The extinction of the beat-note when one of the slaves is absent cannot be complete, as the master light injected into the slaves contains all three optical frequencies; even if the beam of one of the slaves is prevented from arriving on the detector, a heterodyning of the master leak and the main frequency of the slave is still present. By decreasing the injection level into the slaves the extinction rate can reach 30 dB, but this is done at the expense of the long term stability of the device. In the context of the Raman spectroscopy, the parasitic modulation of one beam by two frequencies separated by 9.2 GHz drives non-velocity selective Raman transitions. Note, however, that it is possible to get rid of these stray frequencies, if needed, by performing optical filtering with a Fabry-Perot device of the master beam before injection into the slave lasers.

By shifting the DC bias current by about 5 mA, one can switch the slave frequency from one side-band to the other. This is a convenient way to quickly ($< 20\ \mu$s, [6]), exchange the frequencies of the two Raman lasers, which is required for Raman cooling [1]. Generation of Raman pulses can be simply achieved by acousto-optical modulators, and the Raman detuning can be scanned over $\pm$ 100 MHz without degradation of the injection locking or of the modulation depth. For cesium atoms, this range corresponds to 10^5 recoil frequencies of the D2 line, or to a variation of the gravitational energy of a cesium atom over 6 cm of vertical displacement.

5 Conclusion

In this paper, we described and characterized a setup designed to produce two intense, phase coherent, diode laser beams with a controllable frequency difference. This furnishes a cheap and relatively simple setup for performing Raman spectroscopy and Raman cooling of cesium atoms. We intend to use this setup for studying dynamical localization of atoms in a modulated standing wave. The Raman cooling of the atoms before interaction with the stationary wave and Raman velocity-selective spectroscopy at the end of the interaction are powerful tools to study quantum effects in ranges of parameters not explored by previous experiments [15]. The setup is also suitable for new experiments, such as for instance directly probing the time-dependent behavior of the atoms in the stationary wave (Floquet quasi-states spectroscopy [16]).

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