ELSEVIER

1 December 1997

Optics Communications 144 (1997) 50–54

OPTICS
COMMUNICATIONS

Injection locking of diode lasers to frequency modulated source

K. Szymaniec [1], S. Ghezali, L. Cognet [2], A. Clairon *

Laboratoire Primaire du Temps et des Frequences, 61 Avenue de l'Observatoire, 75014 Paris, France

Received 3 April 1997; accepted 2 July 1997

Abstract

We present a laser system which in a simple way generates two Raman beams for a velocity selection or cooling experiment. A narrow-band diode laser is frequency modulated by an electro-optical device. Two slave diodes are injection locked to the carrier and sideband frequencies, providing two powerful (130 mW) beams offset by 9.2 GHz. The stability of the frequency offset (limited by the rf source) has been demonstrated in a Raman velocity selection experiment. By changing the operating conditions of the slave laser we can switch its output frequency (< 20 μs) to any of several discrete frequencies of the injected master laser. This switching applied to Raman frequencies would significantly simplify The optical set-up in a cooling experiment. © 1997 Elsevier Science B.V.

PACS: 42.50.Vk; 42.55.Px
Keywords: Diode lasers; Injection locking; Raman velocity selection; Raman cooling

1. Introduction

During the last decade narrow band diode lasers have become a very popular and versatile tool in many areas of modern physics such as spectroscopy, metrology and quantum optics. The use of diode lasers has significantly simplified laser cooling experiments. Great achievements have been made with the exclusive use of diode lasers. An example could be the operation of a caesium fountain clock [1], which is at present the most accurate frequency standard, with a fractional accuracy of 3×10^{-15}. Various methods have been used to reduce the diode laser linewidth. The most common use the optical feedback from an external cavity [2] or a diffraction grating [3] (extended cavity laser, ECL). The diode is then *self injected* by a (spectrally) selected part of the light it is emitting. An alternative method is to use a weak beam originating from an external, narrow-band master laser (e.g. another diode laser) to inject to a powerful slave diode [4]. The slave diode reproduces the frequency and phase characteristics of the master. It can be regarded as an optical amplifier working in the saturation regime with a gain of typically 30–40 dB.

The original motivation of this work was to improve the present Cs fountain performance, which is limited in particular by collisions between cold atoms [5]. The collision frequency shift can be significantly reduced by rejecting from the fountain atoms which increase the shift but do not contribute to the detection signal; that is, those with large horizontal velocities [6]. This can be achieved by applying Raman velocity selection [7], or Raman cooling [8] techniques. To stimulate the velocity selective Raman transitions between the ground state hyperfine levels, one needs two counter-propagating laser beams tuned to the vicinity of an optical resonance and offset by the hyperfine splitting frequency (9.2 GHz in the case of caesium). While the absolute linewidth of the lasers is not important, the relative linewidth must be smaller than the atomic recoil frequency $\nu_R = \hbar k^2/2\pi M$ (4.1 kHz for Cs; M is the atomic mass of ^{133}Cs, k is the wave number of the D_2 line). Two techniques for generating Raman beams for

---

* Corresponding author.

[1] Permanent address: Instytut Fizyki, Uniwersytet Jagiellonski, Reymonta 4, 30-059 Krakow, Poland.

[2] Present address: Institut d'Optique, BP 147, 91403 Orsay, France.

PII S0030-4018(97)00390-8

caesium experiments have been reported in the literature. One uses heterodyne optical phase locking of two ECLs [9] and the other employs a unique, high frequency acousto-optical modulator [10]. Here we present a novel solution which seems to be simpler, more robust, and may find broader application. In our system a beam from an ECL is externally phase modulated by an electro-optical crystal. The resulting sideband frequencies, as well as the carrier, efficiently injection lock two slave diodes, providing powerful Raman beams.

In the following section a detailed description of our experimental setup is given. In Section 3 we show our results and demonstrate an application of the system to the Raman velocity selection experiment. Section 4 presents an extension of the method where all the frequencies resulting from the frequency modulation are injected simultaneously to the slave diodes.

2. Experimental system

Our experimental set-up is shown in Fig. 1. As a master laser (ML) we use an SDL 5412 diode coupled to an extended cavity formed by the rear facet of the diode and a diffraction grating. The power of the master laser is 20 mW and the spectral linewidth is less than 100 kHz. An optical isolator (isolation loss ≈ 35 dB) protects the diode from optical feedback.

A system of lenses focuses the master beam to a waist of 200 mm diameter on the input of the electro-optical modulator (EOM). The modulator (New Focus 4841 M) is driven by 2 W of a 9.2 GHz rf power signal. The rf signal is derived from a high stability (fractional frequency stability better than 10^{-8}) multiplied quartz oscillator and amplified. The optical spectrum of the light emerging from the EOM can be analysed using a spherical Fabry-Perot cavity (FP). The efficiency of our EOM is rather poor and the heights of the first order sidebands are less than 10% of the carrier (inset in Fig. 1).

By locking the FP cavity (FSR ~ 12GHz) to one of the sideband peaks (+1 or −1 order) we can filter the chosen frequency and amplify it by injection locking in one of the slave lasers (S1), (SDL 5422). Taking into account all the losses in the system the injected beam power is still 0.3 mW, which is far above the optimum for stable operation [11].

The other slave diode (S2) is injected directly by a small part of the master laser beam (not modulated). In order to analyse the microwave spectrum of the beat-note between the two slave lasers we mix their outputs on a fast photodiode (New Focus 1431). Similarly, we can observe the optical spectrum of each slave using a second FP cavity.

It should be mentioned here that the sidebands can be generated in a simpler way, by direct high frequency modulation of the master diode current [12]. The modulation index is resonantly enhanced when the driving frequency approaches the free spectral range of the laser extended cavity (~ 1.5 GHz). Higher order sidebands are generated and one could inject the slave lasers, for example, by +3 and −3 order sideband. We successfully tried this technique, however a more detailed study is required to discover whether the absorption of the rf power by the diode does not affect its long term behaviour.

3. Results

The system described above produces two powerful beams (130 mW each) which differ in frequency by exactly the Cs ground state hyperfine splitting frequency. The beat-note between the two slave lasers is shown in Fig. 2. The 3 dB linewidth (< 20 Hz) is limited by the spectrum analyser resolution. The two sidebands appearing at $\nu_{\mathrm{hfs}} \pm 60$ kHz arise from the modulation required for locking the FP cavity, and are 30 dB below the carrier beat-note level and so do not affect our experiment. The injection locking range was measured using the second FP cavity by varying the current of the slave laser diode. In this way we can evaluate the quality of the injection even for large detunings (tens of GHz) from the absorption line. We observed a 3 GHz bandwidth for 50–60 μW injected power.

To demonstrate the stability of our laser system we performed a one dimensional Raman velocity selection

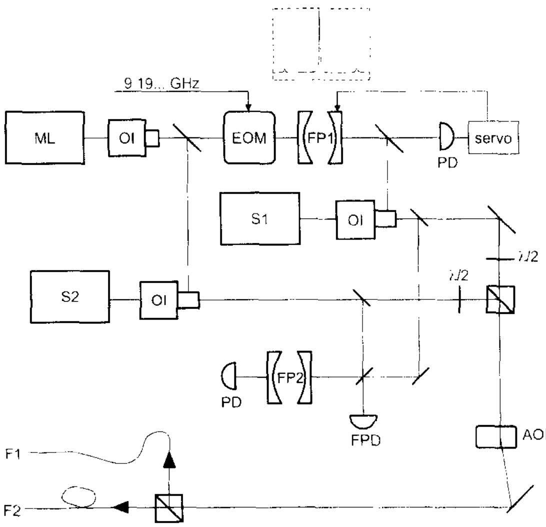

Fig. 1. Diagram of the laser system producing the two Raman beams. The cavity FP1 is modulated at 60 kHz and locked to the sideband peak using a servo loop. The AOM crystal serves as a fast interrupter. Small parts of slave beams are coupled to another cavity (FP2) and a fast photodiode (FPD) to analyse their optical and rf spectrum. Inset: Optical spectrum of the laser beam after the EOM, measured by FP1.

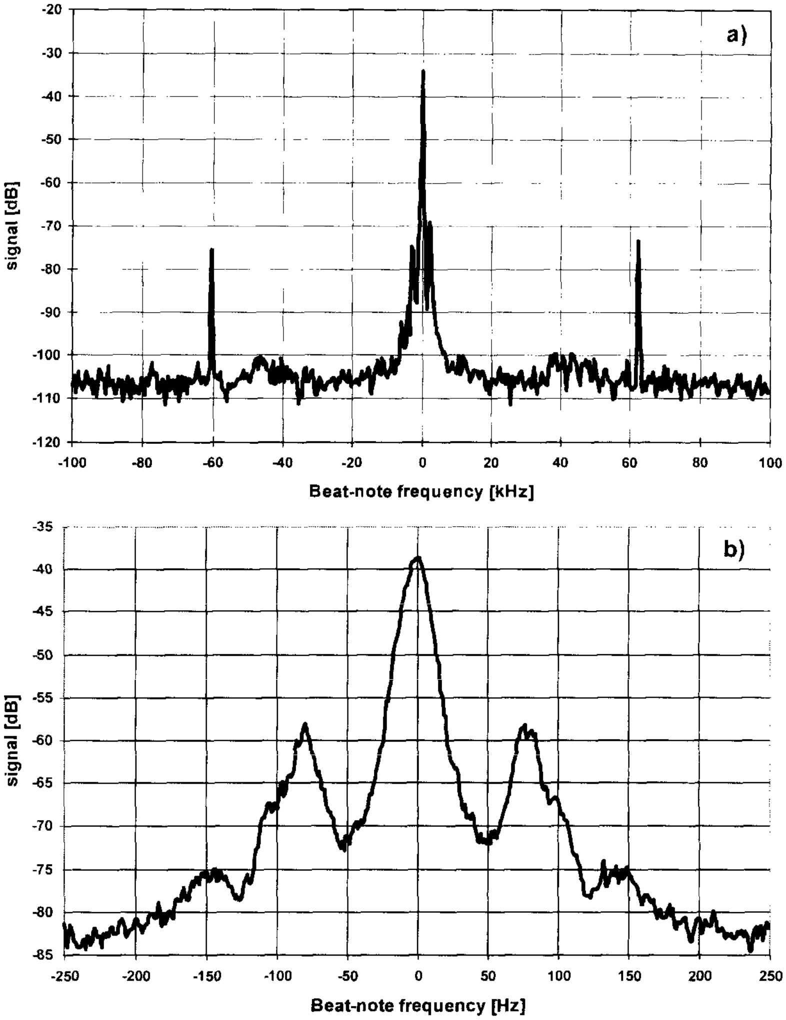

Fig. 2. Beat-note spectrum of the two slave diodes. The horizontal scale is shifted by 9192631770 Hz. (a) At large span (200 kHz) the 60 kHz sidebands due to the modulation of FP1 are visible. (b) The central feature measured at 500 Hz span. The 3 dB linewidth (< 20 Hz) is limited by the spectrum analyser filter. The 80 Hz sidebands are mainly due to the acoustic noise produced by a vacuum pump.

experiment. Some 10^7 caesium atoms were captured and cooled down to 3 μK in a standard magneto-optical trap (MOT). After switching off the magnetic field gradient of the trap and the cooling lasers, the atoms prepared in one of the ground hyperfine sublevels (usually $F = 4$) were exposed to the Raman pulses. Those atoms that due to the Doppler shift were resonant with the Raman pulses could be transferred to the other hyperfine sublevel, acquiring a momentum "kick" of $2\hbar k$. To control the temporal shape and duration of the pulses the two Raman beams were overlapped in a polarising cube and sent through an 80 MHz acousto-optical modulator (AOM, Fig. 1). The first diffraction order beam was then decomposed in another cube and coupled to a pair of polarising fibres (F1 and F2, Fig. 1). After spatial filtering by the fibres, the light was collimated at the output by doublet lenses. The two counter-propagating Raman beams (detuned 15 GHz below the resonance) were orthogonally linearly polarised and had a maximum intensity of 70 mW/cm^2 each. In Fig. 3 we show a 1D velocity distribution of an atomic group selected by a 50 μs square Raman pulse. The distribution was measured by applying a second, 2.5 ms long Blackman pulse, for which the driving microwave frequency was changed each cycle. The un-selected atoms were removed by a radiation pressure pulse applied after the first Raman pulse. The atoms were detected 14 cm below the MOT. In this region the background Cs pressure was 2 orders of magnitude below than in the trapping region. Our detection system [13] enabled an exact measurement of the normalised ratio of the $F = 3$ and $F = 4$ populations $\Pi(3,4)/(\Pi(3) + \Pi(4))$ to be made. By removing the *selected* atoms we obtained the initial velocity

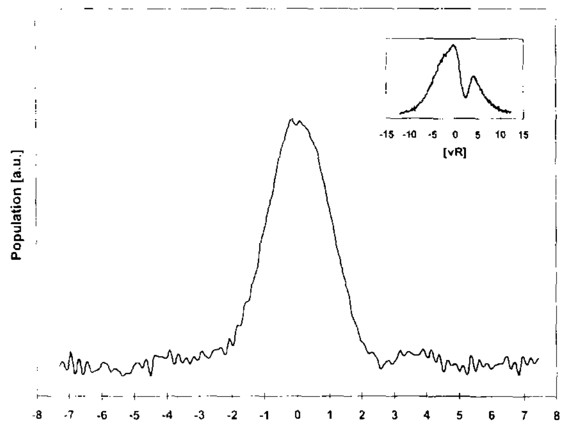

Fig. 3. One dimensional velocity distribution of the atomic class selected by a single 50 μs Raman pulse. The distribution was measured by a second tuneable pulse of 1 kHz resolution. The 1D "temperature" of the sample depends only on the duration of the selecting pulse and in this case is around 200 nK ($v_{rms} = v_R$; where $v_R = hk/2\pi M$ is the recoil velocity). The inset shows the initial velocity distribution (3.2 μK; $v_{rms} = 4v_R$) with a "hole", as the selected atoms were removed. The data represent a single scan (no averaging). The efficiency of the Raman transfer is 60% ($F = 4 \rightarrow F = 3$) and 70% ($F = 3 \rightarrow F = 4$).

distribution with a "hole" (inset of Fig. 3). The conditions for optimum Raman transfer (intensity of the laser beams, pulse duration) were determined in a co-propagating configuration, i.e. when the two Raman beams were mixed on a polarising cube before entering the MOT cell. In this configuration, as all the atoms contribute to the signal (Doppler shift of the Raman frequencies is cancelled), we also compensated the stray magnetic field to 50 nT by narrowing the residual resonance width (down to 1.2 kHz FWHM).

4. Multifrequency injection

In the Raman cooling experiment it is necessary to alternate the propagation directions of the two Raman beams. This is usually done using Pockels cells, which can quickly (in few μs) rotate the light polarisation by 90° and, in combination with a polarising cube, change the direction of propagation. However, this solution would not be convenient in our system because we use polarising fibres. We propose to alternate not the direction of propagation but the frequencies of the Raman beams. This can be done by injecting to the slave lasers all the frequencies arising at the output of the EOM simultaneously [14]. The slave laser frequencies can be selected by a proper matching of the injection current. Simply by changing the latter, one can switch between discrete values of the laser frequency.

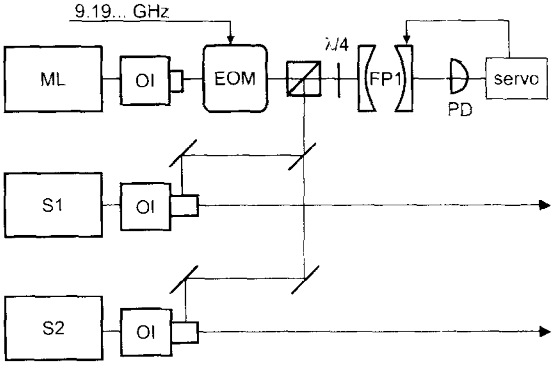

Fig. 4. Diagram of the modified laser system. The beam reflected from the cavity FP1 is injected to both S1 and S2 simultaneously. FP1 is now locked to the carrier, thus the reflection of light at this frequency is suppressed. The slave laser frequencies are determined by the diode current.

Modifications of the laser system are shown in Fig. 4. We do not abandon the FP cavity that is now locked to the carrier peak and we inject to the slave diodes the *reflected* beam. The FP cavity serves as a "selective absorber" and, in our case of poor EOM efficiency, it is necessary to improve the carrier/sideband ratio by 20 to 30 dB.

Fig. 5 presents the transmission signal of the analysing FP (i.e. the slave frequency) as a function of the slave diode current. The flat regions represent locking ranges corresponding to the injection by the carrier and +1 and −1 sideband, respectively. The distance of 6 mA between them is equivalent to 9.2 GHz detuning of a free running diode. Fig. 6 displays the time response of the slave frequency to a square wave applied to the modulation input of the diode current supply. The current was toggled between one stable region ("0", Fig. 5a) and the other ("+1"). The time needed for the supply and the diode to establish the new steady state is less than 20 μs. This is not a limitation in our case, because after each Raman

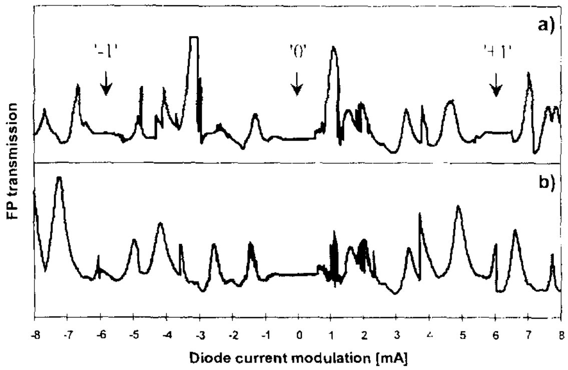

Fig. 5. (a) Injection range of a slave diode. The three flat regions "−1", "0", "+1" correspond to stable injection by −1 sideband, carrier and +1 sideband, respectively. (b) The same, when the driving rf is switched off and the master beam is *not* modulated. The data were taken by sweeping the diode current by 16 mA and measuring the transmission of FP2.

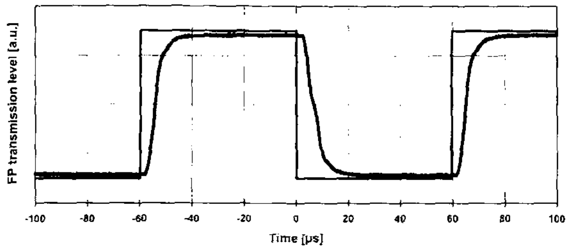

Fig. 6. Time response of the slave optical spectrum to a square wave applied to the modulation input of the diode current supply. The current "jumps" between the two stable regions. The transient time is about 20 µs. The initial 3 µs delay is due to delay in the current supply.

pulse a repumper pulse lasting about 30 µs is required [15].

5. Conclusions

We have presented a laser system suitable for a Raman velocity selection and Raman cooling experiment, consisting of two slave diode lasers injected by a master laser beam phase modulated by an electro-optical crystal. The system provides two powerful beams frequency offset by exactly the Cs ground state hyperfine splitting. The stability of this frequency difference is very high – probably limited only by the noise of the rf source driving the EOM. We have demonstrated an application of our system to a velocity selection experiment aimed at ameliorating the Cs fountain clock performance. We have also shown that it is possible to inject a multifrequency beam and rapidly switch between the slave diode frequencies by controlling the diode current. This possibility can be an important simplification of the Raman cooling experiment.

A perspective for this work is to use a 4.6 GHz EOM instead of 9.2 GHz. At this frequency range a much more efficient generation of sidebands is expected (they can even be stronger than the carrier) and no filtering will be necessary. One can expect a further simplification with the advent of compact, fibre-coupled EOMs. Such systems with a low power EOM for 1.3 µm optical wavelength are already commercialised for optical communication.

Acknowledgements

We thank Ph. Laurent for his help with software problems and S.N. Lea for critical reading of the manuscript. K.S. acknowledges support from the French Ministère d'Enseignement Supérieur et de la Recherche and the Observatoire de Paris.

References

[1] A. Clairon, S. Ghezali, G. Santarelli, Ph. Laurent, S.N. Lea, M. Bahoura, E. Simon, S. Weyers, K. Szymaniec, in: Proc. 5th SFSM, Ed. J.C. Berquist (World Scientific, 1996) p. 49; Bulletin du BNM 104 (1996) 15.
[2] L. Holberg, M. Ohtsu, Appl. Phys. Lett. 53 (1988) 944.
[3] C. Wieman, L. Holberg, Rev. Sci. Instrum. 62 (1991) 1; K.C. Harvey, C.J. Myatt, Optics Lett. 16 (1991) 910.
[4] L. Golberg, H.F. Taylor, J.F. Weller, D.M. Bloom, Electron. Lett. 19 (1983) 491.
[5] S. Ghezali, Ph. Laurent, S.N. Lea, A. Clairon, Europhys. Lett. 36 (1996) 25.
[6] S.N. Lea, A. Clairon, C. Salomon, P. Laurent, B. Lounis, J. Reichel, A. Nadir, G. Santarelli, Physica Scripta T51 (1994) 78.
[7] M. Kasevich, D.S. Weiss, E. Riis, K. Moler, S. Kasapi, S. Chu, Phys. Rev. Lett. 66 (1991) 2297.
[8] M. Kasevich, S. Chu, Phys. Rev. Lett. 69 (1992) 1741.
[9] G. Santarelli, A. Clairon, S.N. Lea, G. Tino, Optics Comm. 104 (1994) 339.
[10] P. Bouyer, T.L. Gustavson, K.G. Haritos, M.A. Kasevich, Optics Lett. 21 (1996) 1502.
[11] J.P. Bouyer, C. Breant, P. Schanne, Proc. SPIE 1837 (1992) 324.
[12] C.J. Myatt, N.R. Newbury, C.E. Wieman, Optics Lett. 18 (1993) 649.
[13] A. Clairon, Ph. Laurent, G. Santarelli, S. Ghezali, S.N. Lea, M. Bahoura, IEEE Trans. Instrum. Meas. 44 (1995) 128.
[14] P. Kohns, W. Suptitz, Meas. Sci. Technol. 6 (1995) 979.
[15] J. Reichel, F. Bardou, M. Ben Dahan, E. Peik, S. Rand, C. Salomon, C. Cohen-Tannoudji, Phys. Rev. Lett. 75 (1995) 4575.