A laser diode system stabilized on the Caesium D_2 line

G. D. Rovera, G. Santarelli, and A. Clairon
Laboratoire Primaire du Temps et des Fréquences, BNM-Observatoire de Paris, 61, avenue de l'Observatoire, 75014 Paris, France

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We describe a complete diode laser system stabilized at 852 nm on the D_2 line of Cs with a linewidth narrower than 100 kHz. This system is intended to be employed for optical pumping, cooling, and detection of Cs atoms in atomic frequency standards. The square root of the Allan variance, evaluated by measuring the beat-note of two similar systems, is better than 1×10^{-12} for τ up to 1000 s. A month of continuous locked operation has been observed.

I. INTRODUCTION

The advent of laser diodes in the near infrared has opened the way to the practical realization of optically pumped caesium clocks, and several laboratories in the world are working today on this new kind of standard.[1] Various laboratories use similar lasers for cooling purposes.[2–5] In metrology experiments, continuous operation over days or weeks is often required, which is a severe requirement for a laser diode employing external feedback to obtain a narrow linewidth. The linewidth of a single diode is larger than a few MHz because of the dimensions of the resonator. Various line reduction techniques can be employed to reduce this linewidth.[6–8] We use extended cavity operation,[6] because it is the simplest and most robust method of achieving a linewidth narrower than the natural linewidth of the caesium transition.[9,10] In order to stabilize the frequency and to reduce acoustic noise, the extended cavity laser is locked to the D_2 line of Cs by saturated absorption techniques, employing a controller with multiple feedback paths. The fractional frequency stability of the stabilized laser is measured by beating together two similar systems. The linewidth of the laser is also evaluated from the beat-note spectrum.

II. DESCRIPTION

A. Extended cavity laser

An extended-cavity semiconductor laser (ECL) is a laser diode (LD) in which the resonant cavity is longer than the diode itself. In our case the total cavity length is 10 cm and is formed by the highly-reflecting rear facet of the diode and a diffraction grating; the active region is only a small part of the total cavity length. The 1200 lines/mm grating is mounted in the Littrow geometry, with the first order beam retroreflected to the diode. In order to adjust the cavity length the grating is glued onto a piezoelectric ceramic, held in a commercial mirror mount. This enables the reflected beam to be aligned and the frequency to be selected. The LD, collimating optics, and grating mount are mounted on an aluminum base plate, around which is constructed an aluminum box which is temperature stabilized to better than 0.1 °C.

The output of the ECL is the zero-order beam, which contains 50% of the optical power incident on the grating. The active element is an AlGaAs LD type SDL5422, 150 mW optical power output, nominal wavelength 850 nm, with the output facet partially AR-coated as usual in high power lasers. The laser is powered by a low-noise current source and the junction temperature is controlled at the mK level using the internal Peltier cooler.[11] About the 25% of the optical power is coupled back to the diode. Fine alignment of the grating and collimating optics is obtained by minimizing the threshold current. When the optical output power is increased up to 50 mW (laser current about 5–6 times the threshold current) we observe unstable behavior, probably due to the fact that the diode starts to operate in a chaotic mode.[12] By changing the junction temperature and the grating angle, a tuning range of about 30 nm can be obtained. By adjusting the PZT voltage, a continuous tuning range of 3.5 GHz, that is more than twice the theoretical mode spacing of the extended cavity, can be obtained. By varying the current alone, continuous tuning over 200 MHz is obtained, with a slope of about 40–50 MHz/mA. If both the laser current and the PZT voltage are varied, it is possible to tune over about 10 GHz without mode-hopping. The fast linewidth of the free running laser (FWHM) is about 50 kHz.[13]

B. Optical setup

We employ a very simple scheme, depicted in Fig. 1, for the saturated absorption setup. The output of the ECL is passed through a Faraday isolator (40 dB) in order to avoid optical feedback from the saturated absorption setup and from the main output of the system. The beam is expanded by a telescope at a diameter of 5 mm and a few percent of the linearly polarized beam (600 μW) is picked off by a plate beam-splitter. This beam is used to saturate caesium vapor in a 3 cm long glass cell (pressure 10^{-6} Torr). The caesium cell is surrounded by a magnetic shield in order to avoid frequency instabilities due to the fluctuations of the magnetic field. The output from the cell is then retroreflected and used as the probe beam. It can be accurately superimposed on the pump because, taking the 40 dB of isolation of the optical isolator together with the 30 dB reduction due to the double sampling action of the beam-splitter plate, less than -70 dB is reflected back to the LD. If a cube followed by a $\lambda/4$ plate is used instead of the beam-splitter, better isolation can be achieved but the atoms will experience circularly polarized light.

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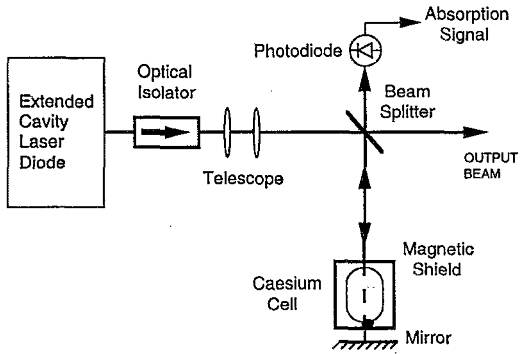

FIG. 1. Optical setup.

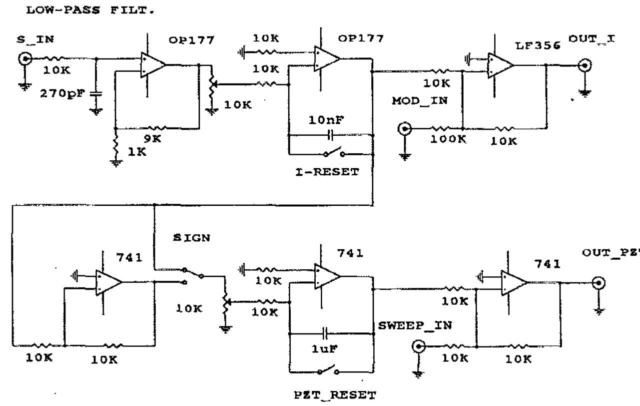

FIG. 3. Circuit schematic of the controller.

C. Servo system

In order to stabilize the laser frequency on the caesium saturated absorption line, a low frequency modulation scheme is adopted, i.e., the modulation frequency is much lower than the linewidth. A schematic diagram of the stabilization system is given in Fig. 2. The laser frequency is modulated with an index of 6 at a rate of 80 kHz by a sinusoidal signal added, via the controller circuit, to the laser current. The absorption signal from the photodiode detector is amplified, filtered, and then demodulated by a homemade synchronous demodulator. The output of the demodulator, which is the error signal of our servo loop, is fed to a controller circuit with two outputs. One output controls the laser current via the modulation input of the current supply, the second controls the extended cavity length by tuning the high voltage supply of the PZT ceramic.

Figure 3 depicts the electrical scheme of the controller circuit. The input signal passes through a passive low-pass filter which rejects the 2-f component resulting from the synchronous detection process. The signal is then amplified by a variable gain stage. To raise the loop gain in the acoustical frequency range an active integrator is needed. The output of the integrator circuit, which can be reset for unlocked operation, is then used to control the laser current and is also the input for the PZT controller section. A variable gain stage is provided for the PZT control and a second integration is then performed. This is to keep the average current correction signal at zero to avoid laser mode hopping. This double integral action allows frequency drift to be compensated for, for increased long-term operation of the servo system. The circuit also provides the possibility of changing the sign of the PZT correction signal. The sign of the error signal can be selected by the synchronous demodulator and the relative sign between the current control and PZT action can be chosen for stable operation. The stability of the servo loop depends on the gain value because of the high order of the system. To find the optimum gain setting, we have used a FFT analysis of the error signal at the output of the synchronous detection. Figure 4 shows the output of the synchronous detector under (a) weak control and (b) quasi-optimum setting. The rule of thumb is to achieve a good trade-off between control bandwidth and loop damping factor. As the gain is increased, noise sidebands appear on the laser spectrum due to an overshoot in the loop response. If the gain value is to low, the resulting control bandwidth is reduced and acoustical disturbance rejection is poor. Under near optimum operation conditions the loop bandwidth is about 7 kHz. For the PZT control path, the limited frequency response of the PZT ceramic due to mechanical resonance and the grating mass forcing us to have a low control bandwidth (100–300 Hz).

III. RESULTS

The first system built has now been working almost without interruption for two years and only a few grating

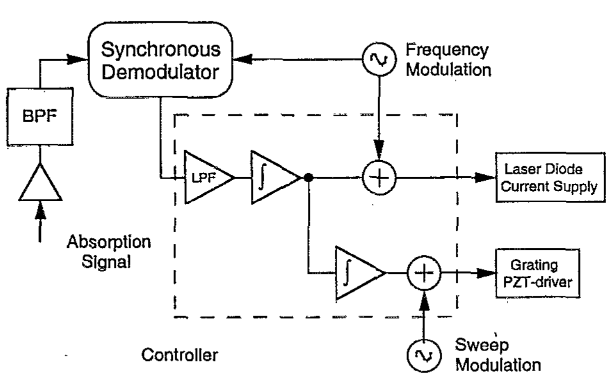

FIG. 2. Block diagram of servo loop system. BPF= Band pass filter, LPF =Low pass filter.

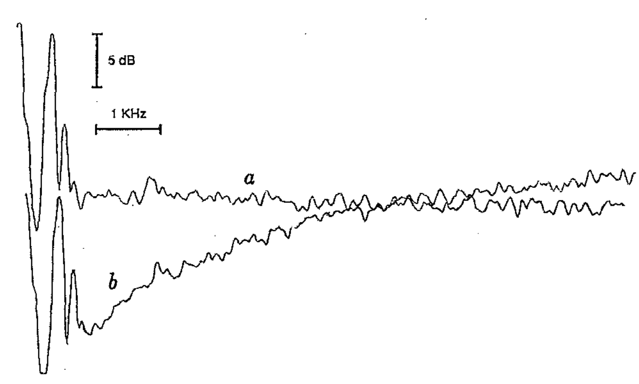

FIG. 4. Spectrum of the error signal in weak (a) and quasi-optimum (b) lock.

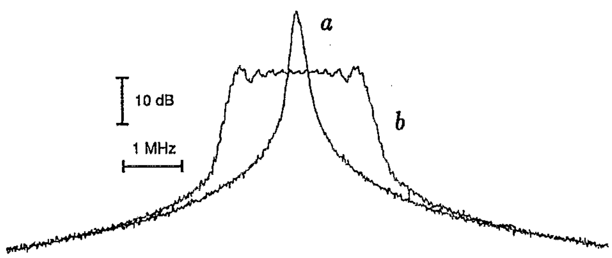

FIG. 5. Spectrum of the beat-note from two identical systems. In (a) the two lasers are modulated synchronously, in (b) with opposite sign.

realignments have been required over this period to keep the laser in proper operation. The lasers routinely remain locked for several days. A month of continuous operation has been observed in a quiet environment. In order to evaluate the frequency stability and the linewidth of the stabilized laser diode we mix the output of two ECLs on a fast photodiode (model FORD 4502) after they have been stabilized on two different peaks of the Cs saturated absorption spectrum (D_2 line). In our case we choose the F=4−F'=5 line and the cross-over between F=4−F'=5 and F=4−F'=4, which are separated by about 126 MHz. The beat signal is then amplified and counted. Figure 5 shows the beat-note spectrum of two ECLs frequency modulated by the same generator. In (a) the two lasers are modulated in phase, in (b) with opposite sign. The aim of this figure is to show that the real spectrum of a laser locked to the caesium line is broadened by the modulation. Figure 6 gives the Allan variance versus the integration time of the beat-note under different experimental conditions. First we consider the fractional frequency stability of the free-running lasers. The short-term square root of the Allan variance is at the 10^{-9} level up to 1 s then increases, apparently showing random walk frequency noise. When the lasers are stabilized, the measured Allan variance of the beat note shows a white frequency noise of $4\times10^{-13}/\sqrt{\tau}$ with a flicker floor at 5×10^{-13}. For times longer than 300 s, the variance increases again, showing a drift probably related to the cell temperature.

IV. DISCUSSION

The system was initially developed to operate an optically pumped Cs beam[14] and a Cs fountain clock.[2] Using the results of Dimarcq,[15] a relation can be established between the frequency stability of the laser and the maximum signal-to-noise ratio that can be detected in a caesium atomic beam. In our case, supposing that the equivalent linewidth of the locked laser is mainly due to the white frequency noise, we can deduce that the laser frequency stability is largely adequate for the stability of the clock, limited only by the atomic shot noise. A similar assumption can be made for the atomic fountain clock.

The measured frequency stability is then sufficient for our purposes and for many other applications. Further improvement in the laser's frequency stability is seriously limited by some systematic effects. In our set-up we modulate the laser current with power modulation effects which can change the signal amplitude, degrading the frequency stability. In addition, the Doppler background makes the system more sensitive to laser amplitude variations and electronic offsets. To avoid this kind of problem, an external modulation configuration is needed. One possible solution is the use of an external electro-optical modulator generating RF sidebands. This scheme requires a more complex setup but can give better stabilization without modulation of the output radiation. If we want to improve the short-term stability, i.e., the laser linewidth, and also the long-term frequency stability, wideband electrical stabilization on a stable high-finesse Fabry-Perot is necessary. The central frequency of the cavity itself must be locked to an atomic resonance for long-term stability.

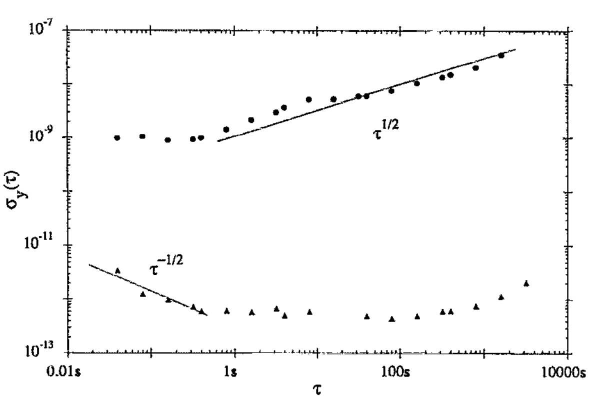

FIG. 6. Square root of the fractional Allan variance.

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