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Laser frequency stabilization using Doppler-free bichromatic spectroscopy

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ABSTRACT We report on a method of laser stabilization, Doppler-free bichromatic lock (DFBL) in which we use the differential signal of two Lamb-dips shifted in frequency by means of an AOM. We show that this method provides us with a tool for precision locking to a molecular or atomic transition and is relatively simple to implement in a diode or dye laser system without the use of a frequency modulation of the laser or lock-in amplifier. A simple model description of this method is presented and the experimental realization is shown for a dye laser at the Na D_1 and D_2 line.

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1 Introduction

In the field of laser cooling and trapping, a stable frequency close to resonance is an important requirement. On short time scales this can be accomplished by locking the laser frequency on an external cavity. However, to prevent a drift in frequency on larger time scales an absolute frequency reference is desired like an atomic or molecular transition. The existing methods of frequency stabilization can be divided in two classes: Doppler-broadened and Doppler-free. An example of the first class is the DAVLL method [1, 4], which relies on the differential $\sigma^+\sigma^-$ absorption in a magnetic field. The advantages of the Doppler-broadened methods is the wide capture range and large signals, but for locking on the center of atomic transitions or cross-over resonances a higher precision is necessary. Therefore Doppler-free schemes are preferred, for which saturated absorption spectroscopy [2] and polarization spectroscopy [2, 3] are the most commonly used methods. Locking with saturated absorption spectroscopy requires locking on a slope of a resonance peak, when detuning from the atomic resonance, which makes this method sensitive for fluctuations in beam power. Polarization spectroscopy is for this reason more suited, as this technique makes it possible to lock on a zero-crossing, yet it is very sensitive for many systematic errors due to external factors, e.g., small stray magnetic fields, strain-induced window birefringence etc.

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Wąsik et al. [5] report on a method of frequency stabilization based on the DAVLL-lock, but in a pump-probe and, therefore, Doppler-free configuration, which is called Doppler-free dichroic lock (DFDL). Below, we describe a simple and similar, Doppler-free frequency stabilization scheme in which we use two electronically subtracted, frequency-shifted Lamb-dips to provide us with a signal free of the aforementioned drawbacks. We call this locking method Doppler-free bichromatic lock (DFBL). We show that, despite its simplicity, this setup provides us with a tool to lock our dye laser system on any desired and reproducible detuning from the Na D_1 and D_2 lines for long times.

2 Principle of the method

Our method is an extension on saturated absorption spectroscopy, in which a pump-probe setup [2] in an atomic or molecular gas causes a velocity-selective saturation of a Doppler-broadened atomic or molecular transition. In the case of a simple model for a $J = 0 \rightarrow J' = 1$ transition, this results in a Gaussian absorption profile $G(\omega)$ with a dip (Lamb-dip) in the center at $\omega = w_0$, where ω_0 is the atomic resonance frequency. This gives us for the total signal

$$S_{\mathrm{sat}}(\omega) = G(\omega) - \mathcal{L}(\omega) \tag{1}$$

with $G(\omega)$ the Gaussian absorption profile

$$G(\omega) = A \exp \frac{-(\omega-\omega_0)^2}{\sigma^2}\,, \tag{2}$$

σ the width of this distribution arising from the Maxwell–Boltzmann velocity distribution of the atoms, A the amplitude of this distribution and $\mathcal{L}(\omega)$, the Lamb-dip corresponding to a Lorentzian line profile

$$\mathcal{L}(\omega) = \frac{(\Gamma/2)^2}{(\omega-\omega_0)^2 + (\Gamma/2)^2}\,, \tag{3}$$

with Γ the natural line width of the atomic transition.

In our scheme we use two probe beams, which frequencies are shifted with $\pm\Delta$ with respect to the resonance frequency ω_0 and which are counter-propagated by a pump beam with the same frequency. Consequently, this results in

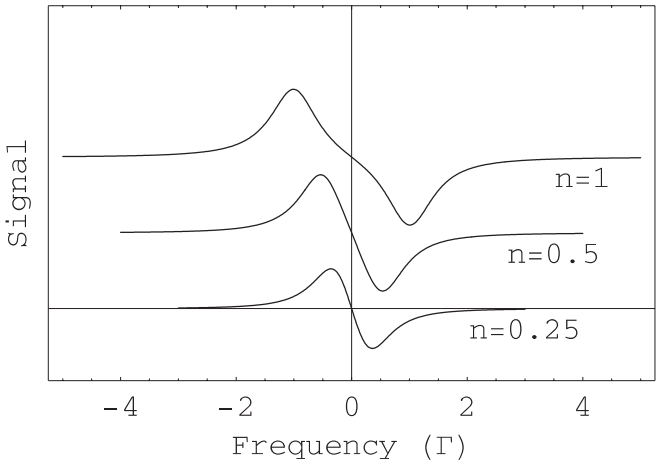

FIGURE 1 Calculated signal $S(\omega)$ for a $J = 0 \rightarrow J' = 1$ transition for $\Delta = n\Gamma$, with $n = 0.25, 0.5, 1$

two saturated absorption signals, $S_1(\omega) = S_{\text{sat}}(\omega - \Delta)$ and $S_2(\omega) = S_{\text{sat}}(\omega + \Delta)$. Subtraction of these two signals gives

$$S(\omega) = S_1(\omega) - S_2(\omega) = (G_1(\omega) - G_2(\omega)) + (\mathcal{L}_1(\omega) - \mathcal{L}_2(\omega)) \quad (4)$$

For $\Delta, \Gamma \ll \sigma$ it can easily be shown that at $\omega \approx \omega_0$, $(G_1(\omega) - G_2(\omega)) \ll (\mathcal{L}_1(\omega) - \mathcal{L}_2(\omega))$. Consequently, the signal is dominated by the subtraction of the two frequency shifted Lamb-dips. Figure 1 shows the calculated signal $S(\omega)$ for a $J = 0 \rightarrow J' = 1$ transition, where $\Delta = n\Gamma$, with $n = 0.25, 0.5$ and 1.

3 Experiment

The experimental arrangements used to stabilize the dye laser (Spectra-Physics, model 380D) is shown schematically in Fig. 2. A small fraction of the laser light (light power ~ 10 mW; beam diameter ~ 3 mm) is split off to the DFBL-setup. This linear polarized beam passes through an acoustic optical modulator (AOM), with a frequency of 80 MHz, optimized in order for the zeroth and first order to have equal power. Two probe beams are split off from the zeroth and the first order beam respectively, each passing through a quartz sodium cell (length 100 mm, diameter 25 mm), kept at a temperature of 150 °C and with a vapor pressure $< 10^{-6}$ Torr. The two main beams are led into the vapor cell from the opposite direction, overlapping the probe beams in such a way that the zeroth and the first order beam act as a pump beam for the zeroth and the first order probe beam, respectively. A beam splitter cube splits off 50% of each probe beam and sends it to a photodiode after which the signals are amplified, electronically subtracted and sent to the feedback loop of the laser.

Figure 3 shows a typical recorded differential photodiode signal (solid line) at the Na D_2 line, which includes the $F = 2 \rightarrow F' = 1, 2, 3$, the $F = 1 \rightarrow F' = 0, 1, 2$ transitions and the cross-over resonances. The broken line in this figure represents the calculation according to (4) including all hyperfine and cross-over transitions, which is fitted to the experimental data to deduce the amplitudes of the hyperfine and cross-over transitions. To account for the power broadening, pressure broadening and residual Doppler effects, it is necessary to introduce an effective line width parameter, $\Gamma_{\text{eff}} = 15$ MHz. Figure 4 shows an enlargement of the signal for

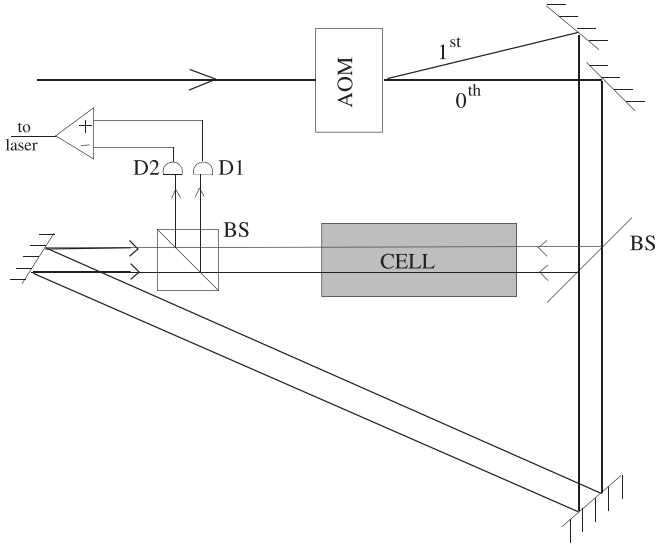

FIGURE 2 Schematic diagram of the experimental arrangements where BS is a beam-sampler and D1 an D2 are the photodiodes

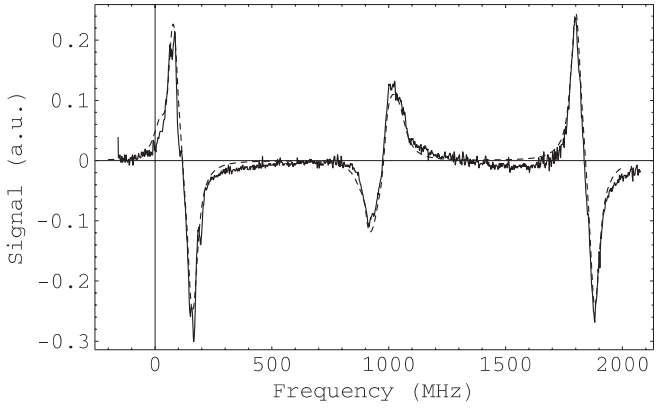

FIGURE 3 Signal (*solid line*) detected at the Na D_2 line, which shows the $F = 2 \rightarrow F' = 1, 2, 3$, the $F = 1 \rightarrow F' = 0, 1, 2$ transitions and the cross-over resonances. The *broken line* presents the fit to the calculated signal

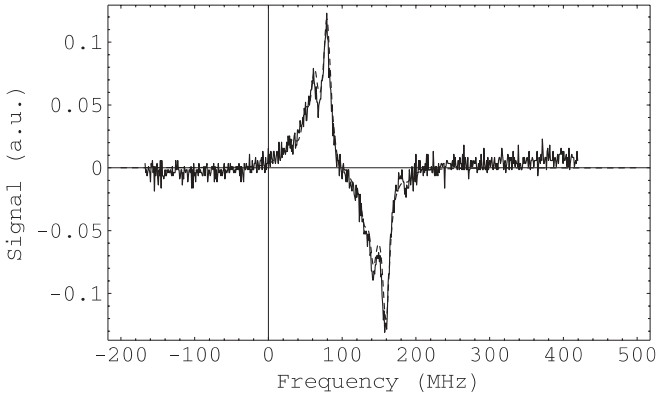

FIGURE 4 Signal (*solid line*) at the Na D_2 line for the $F = 2 \rightarrow F' = 1, 2, 3$ transitions, where the *broken line* shows the fit to the calculated signal

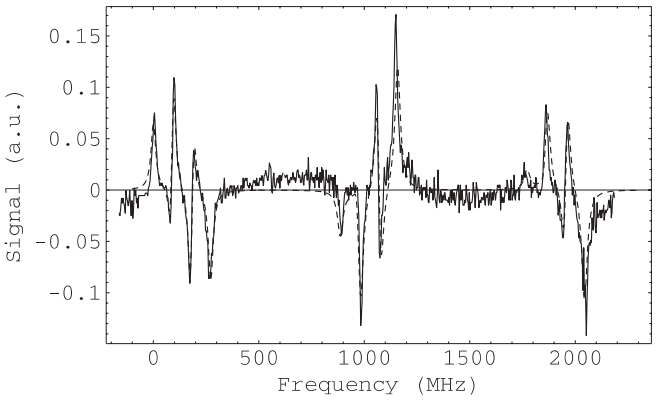

FIGURE 5 Signal (*solid line*) at the Na D_1 line for the $F = 2 \rightarrow F' = 1, 2$ and the $F = 1 \rightarrow F' = 1, 2$ transitions and the cross-over signals. The *broken line* shows the fit to the calculated signal

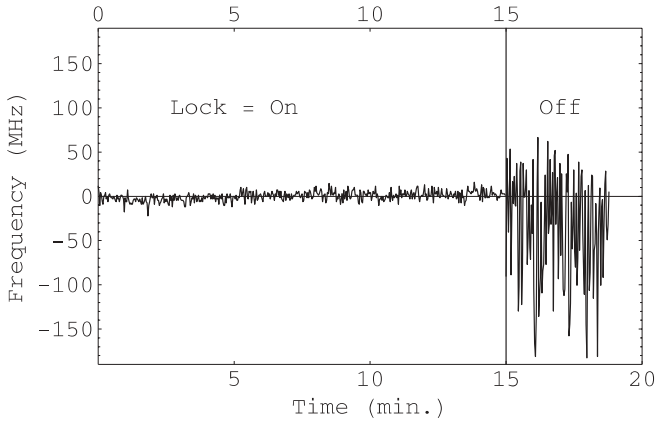

FIGURE 6 Recorded absorption signal of a laser beam through an iodine cell with the locking loop closed and open. The fluctuations in absorption are converted to fluctuations in the frequency (y axis) using the slope of the absorption profile of the iodine line

the $F = 2 \rightarrow F' = 1, 2, 3$ transitions and its cross-over resonances at the Na D_2 line. The hyperfine levels of this transition are almost unresolved due to this effective line width, which is in the same order of magnitude as the splitting of the hyperfine levels and its cross-over signals. This results in a saturated absorption signal with a total width of around 70 to 100 MHz. For this reason we used a frequency shift $\Delta = 80$ MHz resulting in a signal corresponding to $n = 0.5$ in Fig. 1.

The hyperfine splittings of the D_1 transition are an order of magnitude larger than this effective line width. Consequently, this makes it easier to resolve these levels, which is clearly depicted in Fig. 5. This figure shows the signal at the Na D_1 line, with the $F = 2 \rightarrow F' = 1, 2$, the $F = 1 \rightarrow F' = 1, 2$ transitions and the cross-over signals.

There are three ways to tune the laser with respect to a resonance frequency when using this signal for locking. First, an offset voltage can be added to the signal, which shifts the zero-crossing and thereby the locking frequency. Second, a different AOM-frequency, Δ, also shifts the zero-crossing of the signal. Finally, it is possible to use a different combination of orders of the AOM. For example, in our setup we used the order 0 and $+1$. This configuration gives a zero-crossing at a frequency of $+3$ MHz from the $F = 2 \rightarrow F' = 3$ transition at the D_2 line, as deduced from the fit of the calculated signal. By using these fit parameters, we calculated the zero-crossings for different combinations of orders of the AOM, which gives a zero-crossing at -72 MHz for the order 0 and -1 and a zero-crossing at -42 MHz for the order -1 and $+1$.

Finally, we use the DFBL-signal to lock our dye laser at the Na D_2 line. The signal is sent via an integrator to the external input of the laser-control box of the laser, without the necessity of a lock-in amplifier. A laser beam is split off from the main beam and sent through an iodine cell and its absorption is observed with a photodiode. The laser is locked on the DFBL-signal at the cross-over frequency, which is at the slope of a iodine absorption profile. By observing the absorption signal in time an independent measurement can be obtained of the laser frequency drift. Figure 6 shows this calibrated absorption signal as function of time with and without the feed-back loop closed, which clearly shows the long term frequency stabilization.

4 Conclusions

We discussed a new Doppler-free locking scheme called the Doppler-free bichromatic lock, which is relatively simple to implement and for which the electronic signal only uses a differential amplifier, without the requirement of a lock-in amplifier or frequency modulation of the laser. The method proves to be a tool for precision locking to an atomic transition and is flexible with regard to locking with a detuning from atomic resonances. Furthermore, the method is insensitive for fluctuations in beam power and external factors like stray magnetic fields.

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