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Laser frequency offset locking using a side of filter technique

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ABSTRACT We report on the demonstration of a novel scheme for laser frequency offset locking. Following standard techniques, a beat signal is generated between the laser to be frequency stabilized and a second laser with known frequency. A frequency dependent error signal is derived from this beat note by using the amplitude response of an electronic high pass filter. The steep slope of the error signal near the zero-crossing allows for precise frequency locking by a servo loop, while simultaneously a broad capture range of several hundreds of MHz is obtained.

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1 Introduction

Applications of lasers in the areas of spectroscopy, laser cooling and atom trapping usually require a precise control and stabilization of frequencies. A proven technique for laser frequency stabilization is to lock its frequency to the transmission resonance of a Fabry–Pérot resonator [1]. When absolute frequency stability is required, it is much more appropriate to lock the optical frequency to either an atomic or molecular standard, or alternatively relative to a further laser operating at a known frequency. For the latter method, a possible solution is the use of an optical phase-locked loop [2]. In this locking scheme, either a high bandwidth of the control loop or electronic circuits with large phase memory [3] are necessary to ensure the phase coherency of the two lasers, which makes the setup complicated.

However, it is not always necessary to ensure phase coherency in all applications. One thus often prefers technically simpler methods like frequency offset locking, where lower requirements to the control bandwidth of the circuit have to be satisfied. Experimentally, one usually generates a beat note by combining part of the light of the reference laser with part of the light of the laser one wishes to frequency stabilize (slave laser) on a photodiode. By locking the frequency of the beat note to a constant value, the servo system ensures a fixed frequency offset to the slave laser. The beat signal is often initially mixed down to a lower frequency which can be better handled electronically. The main difference between the published locking schemes is due to the method the error signal for locking the slave laser is generated from this mixed-down signal. Rutt [4] and more recently Schünemann et al. [5] have used an electronic delay line to produce a frequency dependent phase shift, which is then converted into an amplitude signal by an electronic phase detector. Both works have demonstrated successful frequency offset locking. A drawback however is the presence of several zero-crossings in the error signal, which results in multiple lock points. Moreover, the slope of the zero-crossing cannot be varied independently of the capture range. For example, a long delay line enhances the slope of the error signal, but reduces the capture range. Other approaches use a frequency-to-voltage converter [6]. Unfortunately, commercial frequency-to-voltage converters are hard to get at higher operating frequencies and are only available with limited frequency bandwidth. This imposes severe limits on the possible capture range of the lock. This point is of particular importance when one wishes to apply rapid temporal variations of the laser offset frequency during operation.

We have developed a novel scheme for frequency offset locking that is based on generating the error signal from the amplitude response of a sharp electronic rf high pass filter. The scheme allows for a steep zero-crossing of the error signal, while simultaneously the capture range can be as large as several hundreds of MHz. We have demonstrated the scheme by locking the frequency of two diode lasers to a difference frequency of 6.8 GHz. Moreover, we have successfully generated frequency jumps up to 200 MHz within ms time intervals by electronically varying the frequency of the microwave local oscillator.

2 Application of the locking scheme

The locking scheme is now successfully being applied in an atomic physics experiment [7, 8], which will be described briefly. In this application, cold ^{87}Rb atoms are captured in a magneto-optical trap (MOT) and after a subsequent temporal dark MOT phase transferred to an optical dipole trap, formed in the focus of an intense CO_2-laser beam. By lowering the intensity of the CO_2-laser beam, the potential depth of the optical dipole trap is reduced. This leads to

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evaporative cooling of the atomic sample, finally resulting in Bose–Einstein condensation of the atoms. For operation of the MOT, two diode lasers at wavelength near $\lambda = 780$ nm (Rb D2 line) are used as a cooling and repumping laser. The difference frequency of both lasers is near the hyperfine splitting of the ^{87}Rb ground state of $\Delta\nu_{hfs} = 6.835$ GHz. The frequency of the repumping laser has to remain constant during the whole experiment (tuned to the $F = 1 \rightarrow F' = 2$ component of the D2 line), while the frequency of the cooling laser is varied during the experiment. During the MOT phase, the cooling laser has to be red detuned by 18 MHz from the $F = 2 \rightarrow F' = 3$ transition of the D2 line and by 160 MHz during the dark MOT phase. Since part of the cooling light is also used to image the atoms, the cooling laser has to be tuned into resonance with the transition during the readout phase. These requirements can easily be fulfilled with the here described frequency offset locking technique. In our experiment, the repumping laser acts as the reference laser and is locked to an atomic absorption line. The cooling laser, being our slave laser, is locked relatively to the reference laser, as is described below. The cooling laser follows the frequency jumps successfully with a typical settling time of a few ms.

3 Locking scheme

The scheme of our frequency offset lock is depicted in Fig. 1. Both the slave and the reference laser part of the optical power are split off with a beam splitter. Both portions are superimposed and then coupled into an optical fiber, which is connected to a fast photodiode (New Focus 1431-50) for measuring the beat frequency. The photodiode output signal at frequency ν_{beat} near 6.835 GHz is amplified by 20 dB with a microwave amplifier and mixed down (Mini-Circuits ZMX-10G) with the frequency-doubled output of a frequency synthesizer (Rhode & Schwarz SMT 06) operating at 3.348 GHz. Let us remark that at this point a voltage-controlled oscillator (VCO) could alternatively be used to generate the local oscillator frequency. After amplifying the radio frequency signal, part of the signal is split off for monitoring the mixed-down beat signal on a spectrum analyzer. The remaining signal is again amplified and subsequently divided into two parts of equal power. Both signals are fed to the error-signal-circuit (ESC), shown in Fig. 2. The signal of the first branch is filtered by a high pass filter (Mini-Circuits SHP200) with 3 dB point at frequency $\nu_{hp} = 164$ MHz and subsequently attenuated by 3 dB. The second part is used for normalization only and is attenuated by 6 dB. Both signals pass through the same configuration of diode, resistors and capacitors used to convert the ac signal to a dc signal. Note that the conduction direction of the diode in the normalization branch is inverted respectively to that in the filter branch, so that the former branch creates a negative and the latter one a positive dc signal. Finally, both the signal of the filter branch, which provides a frequency dependent response, and the signal of the normalization branch are added. The two attenuators in the error-signal-circuit are only used to adjust the offset of the error signal. By adjusting the attenuation of one of the two branches, the zero-crossing of the error signal, which is used as locking point, can be set to the middle of the steep slope. The resulting output voltage of the circuit serves as an error signal for the servo, which controls the frequency of the slave laser. The offset frequency of the slave laser can simply be tuned by varying the frequency of the synthesizer output signal. Due to the servo loop, the frequency of the slave laser will then follow the frequency variation of the synthesizer.

We operated the locking scheme with two different types of slave lasers. In a first version of the experiment, we used a low power, home made grating stabilized diode laser setup [9] as a slave laser. Stable frequency locking was achieved with the here described scheme using the piezo-mounted grating for control of the slave frequency. In a second version of our experiment, a higher optical output power was achieved by replacing this diode by a commercial "tapered laser" grating stabilized diode source (Toptica DLX 110). Here, the frequency of the laser was controlled both by a piezo-mounted grating and by variation of the diode current with a field effect transistor, which leads to an increased control bandwidth of the servo loop compared to the piezo bandwidth alone. Using a FFT Fourier analyzer (Tektronix TDS 2014), we investigated which frequency components of the error signal are suppressed when the servo loop is activated. We estimate the unity gain frequency of our servo to be around 50 kHz for the tapered laser source.

Detailed measurements on the frequency stability of our locking scheme have been carried out using this second optical source, and are reported in the remaining part of this paper.

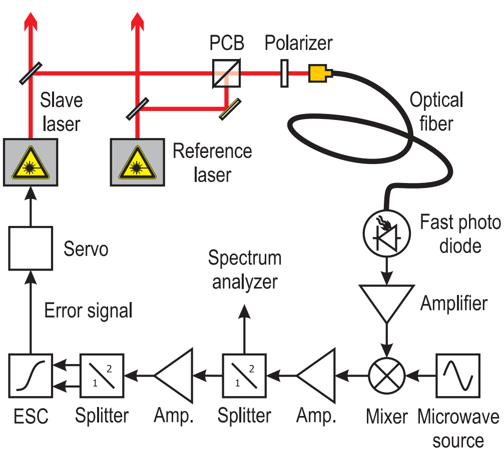

FIGURE 1 Scheme of the laser frequency offset lock

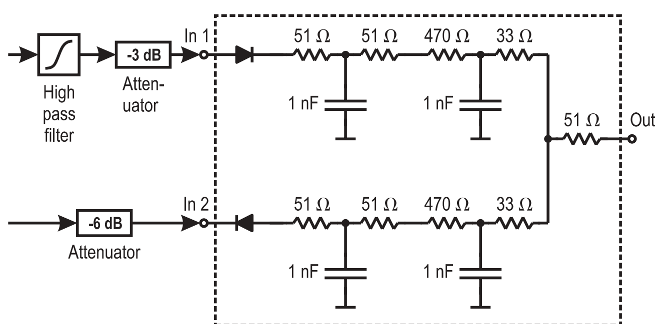

FIGURE 2 Electronic layout of the error-signal-circuit (ESC). The elements in the dashed rectangle are placed on one circuit board and implemented in SMD technique

4 Results

Figure 3a shows the output voltage of the ESC as a function of input frequency for different powers (4 dBm, 8 dBm and 12 dBm) supplied to the power splitter before the ESC. For this measurement, the input signal was generated with a frequency synthesizer and was scanned from 10 MHz to 500 MHz. The error signal shows a steep slope near the zero-crossing, which allows for precise frequency locking, while the capture range is large. Even though the over-all shape of the error signal changes with varying power, the position of the zero-crossing is only weakly dependent on the power (Fig. 3b). The dependence is non-linear and approximately 30 kHz/dB for input powers from -16 dBm to 0 dBm. For higher input powers (up to 12 dBm), the variation increases to roughly 100 kHz/dB. Thus, fluctuations of the output power of reference or slave laser only weakly modify the position of the lock point. For high precision applications, one may in the future eliminate the residual dependence by introducing an electronic limiter into the rf signal.

To estimate the frequency stability of our offset lock, we examined the mixed-down beat signal with a Hameg HM8021-3 frequency counter. Figure 4 shows a graph of the frequency of the mixed-down beat signal recorded with the frequency counter with gate time 1 s. The effect of switching from unlocked to frequency-locked state of the slave laser is clearly visible. We estimated according to [10] the square root Allan variance of the mixed-down beat signal in the frequency-locked state. In Fig. 5, the square root Allan variance in frequency units is plotted as a function of the integration time. After several seconds of integration, the Allan variance drops well below a kHz.

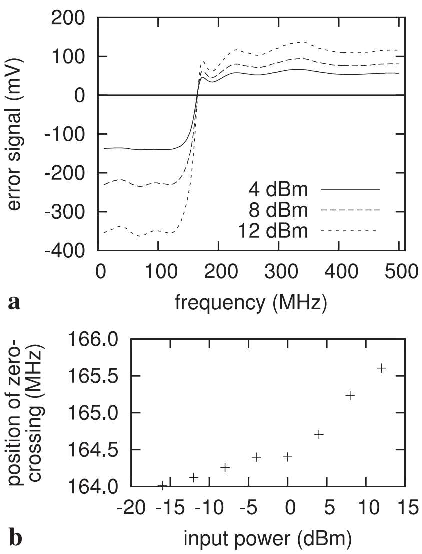

FIGURE 3 **a** Error signal as a function of the frequency for different powers supplied to the power splitter before the ESC. **b** Frequency of the zero-crossing of the error signal as a function of the input power

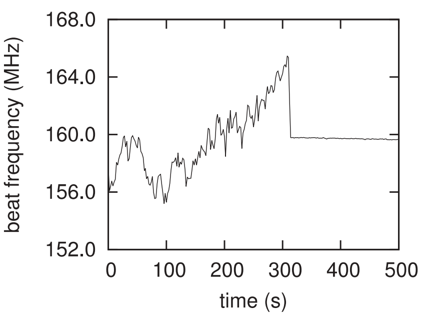

FIGURE 4 Plot of unlocked and frequency-locked mixed-down beat signal versus time. The frequency locking servo loop was activated at $t = 312$ s

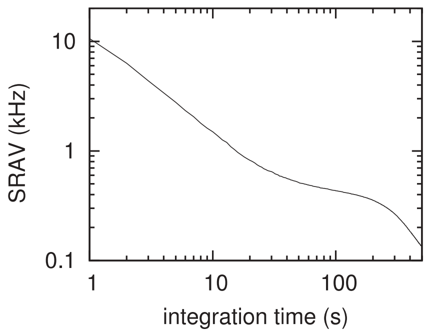

FIGURE 5 Square root Allan variance of the mixed-down beat signal (frequency locked) as a function of integration time

To quantify the timescale on which frequency jumps can be performed, we measured the time needed for the error signal to return to a value near zero after such a frequency variation was induced. For a frequency jump of e.g., 56 MHz we measured a settling time of 6 ms. This value increases for larger frequency variations. E.g., for a 160 MHz jump, we measured a 11 ms settling time of the error signal. These times do not represent a principal limitation of the locking scheme but rather are determined by limitations of the laser system slew rate and the servo bandwidth.

5 Conclusion

To conclude, we have demonstrated a simple and reliable scheme for frequency offset locking of a laser source. The technique allows for a sharp frequency slope of the error signal while simultaneously providing a large capture range. For the future, it would be interesting to investigate the possibility of using sharp microwave filters in the locking scheme, which would make extremely large capture ranges possible and furthermore avoid the need for high frequency local oscillators.

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