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Compact implementation of a scanning transfer cavity lock

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We describe an implementation of a scanning transfer cavity laser lock that is based on a commercial optical spectrum analyzer and an inexpensive computer microcontroller. The lock performs as well as a standard saturated absorption lock for frequency differences of several GHz. It offers the advantages of locking at arbitrary frequencies, having a large capture range, and allowing complex control mechanisms to be implemented via software. *© 2005 American Institute of Physics.* [DOI: 10.1063/1.2135278]

Many physics experiments require the frequency of a tunable laser to be held at a desired value. The most common way to achieve this is to lock the laser to an atomic or molecular resonance, often using saturated absorption techniques to obtain a narrow linewidth and correspondingly better frequency resolution.[1] Although effective, this technique has some disadvantages. For instance, it requires the desired frequency to be close to a convenient reference transition, which is not always possible. Also, the capture range of a saturated absorption lock is small, typically a few tens of MHz in frequency. This makes the system susceptible to coming unlocked in response to a perturbation and also makes the system difficult to relock automatically. This can be an annoyance for laboratory work or a serious problem for applications where user intervention is not possible.

One alternative technique is the scanning transfer cavity lock.[2–6] Rather than using an absolute reference, this method stabilizes the frequency difference between two lasers by passing beams from both lasers through a Fabry–Perot cavity. The mirror separation of the cavity is repeatedly scanned across one or more free spectral ranges (FSRs). As the separation changes, one laser eventually comes into resonance, resulting in a pulse of transmitted light. At a later time, the second laser comes into resonance. The lock works by determining the difference between the two pulses and controlling the frequency of the target laser to hold the difference constant. If one of the lasers is locked to an absolute reference, this stability can be transferred to the second laser. The second laser can be at any frequency and the lock's capture range is set by the cavity FSR, typically a few GHz. The transfer lock thus overcomes many of the problems of the saturated absorption lock.

The primary disadvantages of the transfer lock have been its expense and complexity. It requires a stable reference laser, a transfer cavity, and a control system. Because of this, it has been more common to use a conventional saturated absorption lock unless the special capabilities of the transfer lock are essential. However, in many experiments, a reference laser is already available. For instance, laser cooling experiments require one laser tuned near an atomic resonance to provide the cooling. If this laser is locked via saturated absorption, it can serve as the reference for any other lasers the experiment uses.

Other implementations of a transfer lock that we are familiar with use a dedicated, stabilized optical cavity. Typically, the two output pulses are separated using polarization or wavelength filters, though Rossi *et al.* detected the combined beams with a single photodiode.[5] Early designs used electronic control systems,[2,3] but more recent versions use a personal computer equipped with a digital-to-analog converter (DAC).

We believe that the transfer lock described here is the simplest and most cost-effective version demonstrated to date. For our cavity, we use an unmodified commercial spectrum analyzer system. In our experience, many labs already use a spectrum analyzer for other purposes. For instance, it is the best way to verify that diode lasers are operating in a single mode. Our control system is based on a microcontroller card that, once programmed, does not require a separate computer system. The entire control system costs less that \$200 and fits on a 2 in. rack panel. We believe that in many cases, this system can be a cheaper and better replacement for a saturated absorption lock.

Figure 1 shows a schematic of the servo loop for the lock. Our reference laser is a Coherent MBR Ti:Sapphire laser locked to the $F=2 \leftrightarrow F'=3$ transition in ^{87}Rb at 780 nm. The tunable laser is a home-built external cavity diode laser based on a Sanyo DL7140-201S, 80 mW, 785 nm laser diode. The laser is driven by a ThorLabs ITC502 controller and the cavity grating is positioned with a ThorLabs MDT694A piezoelectric controller. Beams from each laser are combined on a beamsplitter and directed into the spectrum analyzer. About 200 μW of power from each laser is used.

The spectrum analyzer is a Coherent Model 251, which is a scanning confocal cavity with a FSR of 1.5 GHz. It has a nominal finesse of 550 over the wavelength range 690–830 nm. The analyzer scans over two FSRs with a 20 ms period. The upper graph in the figure shows a typical output display. The lock operates by measuring the times t_1 and t_2 and ad-

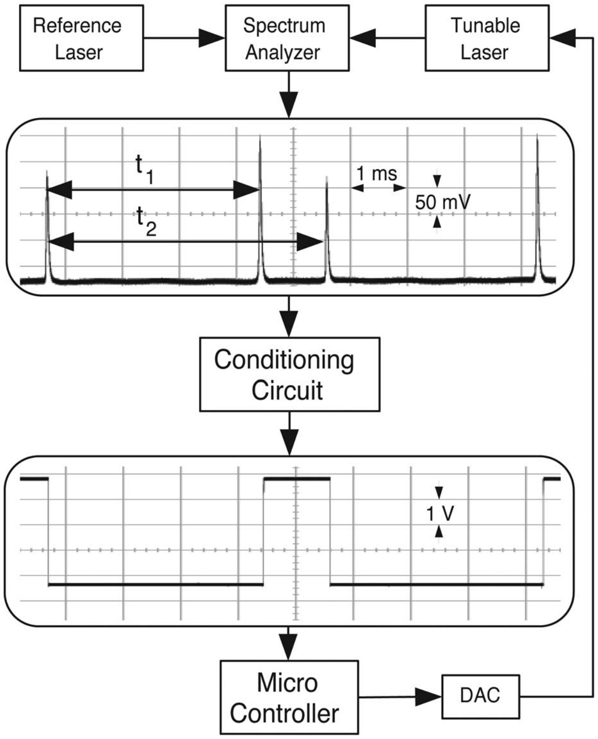

FIG. 1. Schematic of a lock system. Beams from a stabilized reference laser and a tunable laser are sent into a spectrum analyzer. The upper graph shows a typical output signal. The conditioning circuit of Fig. 2 converts this to a digital signal as shown. The microcontroller inputs the signal, calculates the feedback voltage, and applies it to the tunable laser via a digital-to-analog converter.

justing the feedback to keep t_1/t_2 constant. By controlling the ratio, variations in the scan rate cancel out.[4]

The time measurements and feedback calculations are made using an IsoPod V2-SR1 microcontroller card from New Micros, Inc. The IsoPod has a function that measures digital pulse durations, so we use a signal-conditioning circuit to convert the timing information from the spectrum analyzer to logical pulses, as shown. The signal-conditioning circuit is shown in Fig. 2. Noise on the input signal causes the conditioning circuit to make a spurious transition about once every 500 scans. This is detected and handled by the microcontroller.

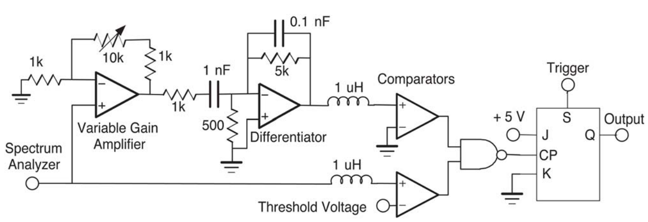

FIG. 2. Conditioning circuit. The spectrum analyzer signal is amplified, filtered, and differentiated to produce a signal that crosses zero at the peak of the pulse. A comparator is used to locate this zero crossing. Since the differentiated signal is noisy when no pulse is present, it is gated with a second comparator that is high only when the original signal exceeds a fixed threshold, typically about 50 mV. The resulting pulses trigger a flip-flop to produce a digital signal that changes state at the peak of each pulse. The S input to the flip-flop is derived from the trigger output of the spectrum analyzer. The trigger is low during the forward scan of the cavity and high during the backward scan. The analyzer output is zeroed during the backward scan to avoid hysteresis, so we suppress the pulse sequence during that time.

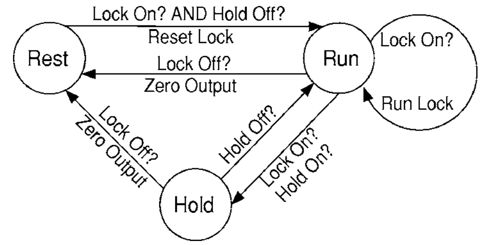

FIG. 3. State diagram of the control program. Circles represent states and arrows represent transitions. Transitions are labeled with their conditions and commands.

The microcontroller is a state machine, which allows it to run in parallel several programs simultaneously without the need for multiple on-board CPUs or a multitask-oriented operating system. We do not effectively use this ability because we only need to lock one laser, but if required the microcontroller should be able to manage several locks at once.[4] A state machine works as follows: for any state there are some number of transitions to and from the state. Each transition has a condition that when met requires the machine to move to the new state and execute any programing defined in the transition. The machine continuously checks the conditions for exiting the current state.

The controller uses a language derived from FORTH. The program definitions are uploaded to the device from a desktop PC through a serial connection. Once loaded, they are stored in persistent memory and run automatically when the controller is turned on. Since state machines may be less familiar than ordinary computers, we explain the structure of our program below. A copy of the program can be obtained from the authors on request.

Figure 3 is a state diagram for our program. The system begins in the Rest state. The Lock On condition is set by a switch on the front panel and the Hold Off condition is an external input. When the lock is turned on, the Reset Lock routine measures t_1 and t_2 using two successive scans from the spectrum analyzer. The timing resolution of the counter is 0.4 μs. For our scan rate and FSR, this corresponds to a frequency resolution of 120 kHz. The controller has two routines to reject signal-conditioning errors. Most errors from the circuit are double triggers where the circuit produces two transitions under one spectrum analyzer pulse. The program tests for and ignores any ratio that corresponds to this type of error. Further, each ratio measured must agree with the previous two to within 10%. Once three good measurements are obtained, they are averaged and assigned as the set point for the lock.

Most of the activity takes place in the Run state. During the Run Lock routine, the controller first measures t_1 and t_2 as above and checks for errors. Once a good value is obtained, the error signal is computed as the difference between the ratio and the set point. Integral feedback is implemented by adding the error signal to a running sum, which is then multiplied by a gain factor and output to the DAC. We used the MAX507, a standard 12-bit converter. A voltage divider reduces the analog signal by a factor of 3 before it is applied to the external input of the piezoelectric controller.

The Hold state is not needed for the lock, but we required the capability to unlock the laser so that it could be externally scanned to a different frequency during an experiment and then tuned back to the original frequency and relocked when the experiment is complete. This permits us to use the laser for two purposes during the experiment. The Hold On/Off conditions are set by an externally applied logic signal that comes from the main control system for the experiment. In the Hold state, the IsoPod maintains its current output level and set point, but does not make any new measurements. The ease with which a capability such as this can be added illustrates the versatility of a computer-controlled system.

We evaluated the performance of the transfer lock using three tests. First, we locked the diode laser to the $F=1\leftrightarrow F'=2$ transition of ^{87}Rb and used it as the repump laser for a magneto-optical trap (MOT). The MOT performance was no different than observed using a saturated absorption lock. The diode laser generally lost its lock only when the reference laser itself came unlocked. A second test used a heterodyne measurement with the reference laser. We locked the two lasers about 300 MHz apart and directed the combined beams from the lasers onto a photodiode attached to a rf counter. The short-time stability is determined by the lasers themselves rather than the lock, so we averaged using a 6 s counting time. The measurements fluctuated by about 1 MHz and drifted by about 300 kHz per hour. For the third test, we ran the lock in an open loop mode. The diode laser was locked via saturated absorption to the ^{87}Rb $F=1\leftrightarrow F'=2$ transition and the error signal from the transfer lock was monitored. The microcontroller program was modified so that instead of outputting a running sum of the error signal, a running average was calculated with a 2.4 s time constant. (As above, this was an experimentally convenient time scale for averaging out short-time noise in the laser.) The output signal indicated frequency fluctuations at this time scale of about 3 MHz, consistent with the noise on the error signals of the saturated absorption locks. There was no significant drift observed using this method, with a sensitivity of about 1 MHz/h.

These tests indicate that the transfer lock controlled the long-term stability of the laser frequency to about 1 MHz accuracy, comparable to the performance achieved with previous systems. It should be noted that the tunable laser is required to have good short-term stability, since the transfer lock cannot provide feedback faster than the 25 Hz data acquisition rate. Faster data rates have been implemented in Refs. 3,6.

Our simple implementation has several limitations. Because we detect both lasers with a single photodiode, the lock will not work if the frequency difference is close to an integer number of FSRs. This could be overcome by separating the transmitted beams and using two detectors. The lock is also sensitive to drifts in the optical cavity length, in two ways. First, a change in the FSR can cause the target laser frequency to vary if the detuning between the two lasers, Δ, is large. Typically, the FSR of our cavity drifts at a rate of $R\approx 1$ kHz/h. The resulting drift in the target laser frequency is

$$\dot{\nu}=\frac{\Delta}{\mathrm{FSR}}R. \tag{1}$$

In our case, $\dot{\nu}$ is less than 1 MHz/h for $\Delta<1.5$ THz, or about 3 nm at 780 nm. Locking two lasers with considerably different wavelengths would therefore require a stabilized cavity. For smaller detunings (notably including atomic hyperfine splittings), this effect is negligible.

Even for small detunings, cavity drift causes the peak locations in the output trace to shift. With reference to Fig. 1, eventually one of the peaks will drift off the display and a new peak of neighboring order will reappear on the other side. When this occurs, the microcontroller no longer measures the correct times and the lock fails. To prevent this, it is necessary to adjust the offset control of the spectrum analyzer every few hours. If this were not possible, a more sophisticated program could be used to detect the change in timing and automatically compensate for it.

In summary, we have demonstrated a simple version of a scanning transfer cavity lock. It was able to successfully stabilize a target laser's frequency to better than 1 MHz over long time scales. Given that a reference laser and a spectrum analyzer were already available, the lock system was inexpensive and required no space on the optical table. Further benefits include the ability to lock a laser at arbitrary frequencies and to permit complex lock control via software. We hope that this work will make it easier to take advantage of the transfer technique.

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