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We present two techniques to lock a laser frequency on an atomic transition line by using an electromagnetically induced transparency (EIT) signals, which give optical and electric feedback. We employed these methods to the D_2 line of ^{87}Rb atoms. Spectral characteristics of subnatural linewidth EIT allow us to improve frequency stability. By optical feedback of EIT signals, we were able to obtain locking bandwidths of 12 MHz, while frequency stability was 5×10^{-13} at best after 100 s of integration using a frequency modulation technique. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1713050]

Lasers locked on an atomic transition line have been used for various studies from fundamental to practical applications in fields of frequency standards, metrology, high sensitive analysis, and optical communications.[1–4] There are many techniques to lock laser frequency[5–12] and these can be divided into two classes, optical, or electrical feedback. Optical feedback is a technique completed by feedback of an optical signal generated by high-resolution spectroscopy into a laser cavity.[10] Electrical feedback can be classified into two techniques according to whether the frequency modulation is applied in order to obtain dispersion or dispersion-like spectra.[5–9] Frequency modulation spectroscopy following phase-sensitive detection is one means to obtain a dispersion-like spectrum, by which the first derivative of an absorption profile is obtained.[5] The second approach is a frequency modulation-free method based on the dichroism or the birefringence at the atomic transition.[7] Zeeman shift-induced or two-color light-induced dichroism can generate a dispersion-like spectrum by the difference of two slightly differently centered absorption profiles. The birefringence obtained by polarization spectroscopy can generate the dispersion spectrum, which can be directly used for electric feedback.[7] In both methods, the spectral linewidth at the resonant frequency must be required to be as small as possible since the limitation of the frequency stability is determined by this linewidth. Presently, frequency stabilization methods are limited by the natural linewidth of the atomic transition because of the limitation of the spectral resolution of high resolution spectroscopy.

The spectral linewidth of a typical electromagnetically induced transparency (EIT) signal is subnatural because it is generated by a coherent atom-field interaction.[13–17] The EIT signal is a good candidate for overcoming the limitation of frequency stability. Even though EIT signals have been used for many applications such as control of light speed,[18] photon storage,[19] very sensitive magnetometry,[20] and single photon detection.[21] In this letter, we report on optical and electrical feedback techniques for frequency locking using EIT signals.

Figure 1 shows experimental schemes for optical feedback [Fig. 1(a)] and electrical feedback [Fig. 1(b)] arranged for laser frequency locking on one transition in a ^{87}Rb D_2 line. In the two figures, the basic configurations are the equivalent of obtaining Doppler free EIT signals in a lambda type energy scheme. Two coherent laser beams operating in a single mode by a grating-feedback external cavity diode laser (ECDL) copropagate through the Rb vapor cell. The coupling laser is used to generate atomic coherence, and the probe laser, which will be locked, is used for detection of the EIT signal. The frequency of the linearly polarized coupling laser is locked on the coupling transition line by using a conventional frequency modulation technique for a saturated absorption profile. The weak probe laser is also linearly polarized, but orthogonal to the coupling field. Two laser beams can be overlapped and separated spatially by two polarizing

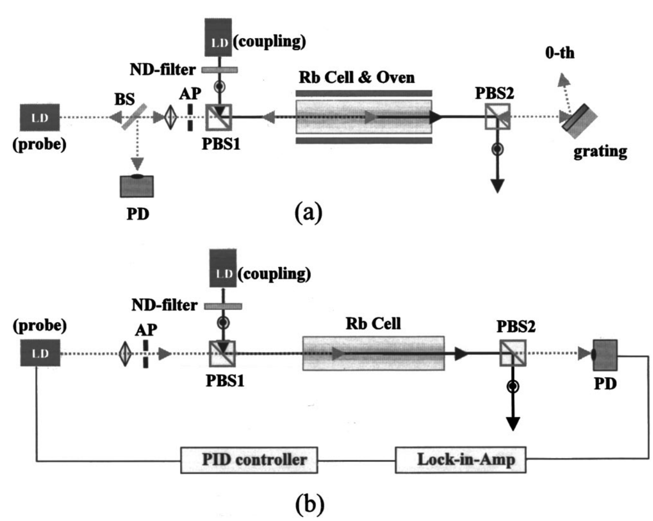

FIG. 1. Experimental setups for frequency locking using EIT: (a) Optical feedback (b) electrical feedback by frequency modulation of coupling laser.

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beam splitters (PBS). The probe laser frequency can be scanned over the whole range of excited states to measure the locking bandwidth in the case of optical feedback or to obtain a dispersion-like spectrum in the electrical feedback case. The diameter of the probe beam passing through an aperture of 1 mm diameter was smaller than the diameter 3.5 mm of the coupling laser. Laser powers are controlled by neutral density filters for narrow spectral bandwidths of EIT spectra with comparable S/N ratio.

For optical feedback, as shown in Fig. 1(a), the Rb cell is installed in an oven to obtain a high contrast EIT optical signal. Instead of a mirror, a grating is inserted into the laser cavity for optical feedback of the transmitted probe beam. This grating is used to enhance the spectral purity of the feedback field.[10] We were not able to lock the laser frequency on the atomic transition line by the mirror because of feedback from nonresonant background photons.

For electrical feedback as shown in Fig. 1(b), a photodiode is used to measure the transmitted probe fields. The Rb cell is at room temperature. Without extra frequency modulation for the probe laser, we are able to obtain a dispersion-like spectrum by setting the phase sensitive detector of the lock-in amplifier according to the reference signal for the frequency modulation of the coupling laser. This is possible because the coupling laser frequency is already modulated for the coupling laser stabilization. The advantage of this method is that we can use one frequency modulation to obtain two dispersion-like spectra from the saturated absorption profile for the coupling laser and from the EIT profile for the probe laser, respectively. However, the disadvantage of this approach is that the frequency stability of the coupling laser is transferred to the frequency stability of the probe laser; the EIT signal depends on the coupling laser detuning from the resonant frequency of the atomic transition. Nevertheless, this could be another way to lock the laser frequency without direct frequency modulation. The error signals obtained by the lock-in amplifier, after being treated by the PID controller, are feedback for the compensation of the laser cavity length. We do not use current compensation for fast stabilization.

We can measure the high contrast EIT spectra by replacing the grating with a photodiode. Figure 2 shows, in a lambda-type energy scheme,[22] a typical high contrast EIT spectra dependent on cell temperature, while the coupling laser of 8.3 mW is locked on the transition between $F=1$ ground level and $F'=2$ excited level. The probe laser of 75 μW is scanned over the whole excited levels from $F=2$ ground level. Two laser wavelengths are near 780 nm, which is resonant to the $\mathrm{Rb}\,D_2$ line. We can clearly see the EIT signals at the transition $F=2$ to $F'=2$. The bottom spectrum is a saturated absorption profile for calibrating the probe laser frequency. By increasing the cell temperature, more vaporized atoms are involved in interactions. When we define the contrast as the ratio of the EIT signal height to the linear background transmission, at high temperatures, we are able to see EIT signals having a high contrast due to almost zero transmission at near resonant frequencies, indicating zero background. If the cell temperature is higher than the temperature causing zero transmission, the EIT signal height will decrease, which is unfavorable for optical feedback. Hence, it is necessary to determine the optimal temperature.

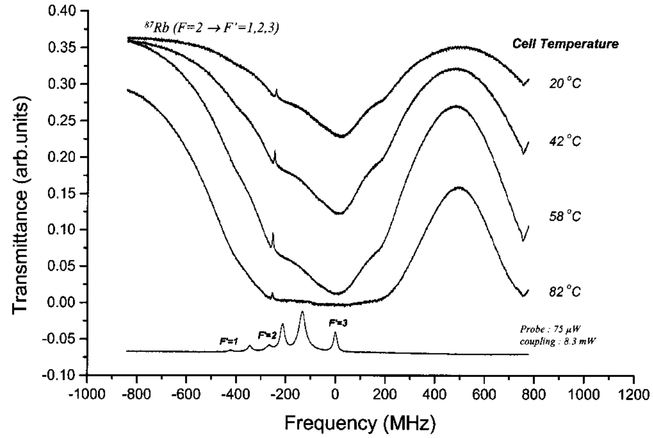

FIG. 2. High contrast EIT spectra depending on the cell temperature; $F=2 \rightarrow F'=1$, 2, and 3 transition of $^{87}\mathrm{Rb}\ D_2$ line while the coupling laser is locked to the transition $F=1 \rightarrow F'=2$. The bottom trace is the saturated absorption signal to monitor the probe laser frequency.

By installing the grating for laser frequency locking at the position for the photodiode, we are able to obtain optical feedback of the EIT photons into the laser cavity. The laser frequency is determined by feedback photons since the laser frequency is determined by the stimulated emissions of these photons. We can pick up some feedback signals by locating the beam splitter at the front of the probe laser, as shown in Fig. 1(a), and measure these by the photodiode. This allows measurement of the locking bandwidth. The solid curve in Fig. 3 shows the result of optical feedback as a function of the probe laser frequency. The cell temperature is about 85 °C. The dotted curve in Fig. 3 is a high contrast EIT spectrum without optical feedback. The inset of Fig. 3 shows the locking bandwidth. While the probe frequency is scanned, there is a sudden jump in the peak height of the EIT signal and a constant height at near EIT resonance. The frequency range showing the same level is called the locking bandwidth. Because the EIT linewidth is very narrow, the locking bandwidth is also expected to be small. However, the optimal locking bandwidth was about 12 MHz, which is much broader than the natural linewidth of about 5.6 MHz. We need to accurately measure the frequency stability by

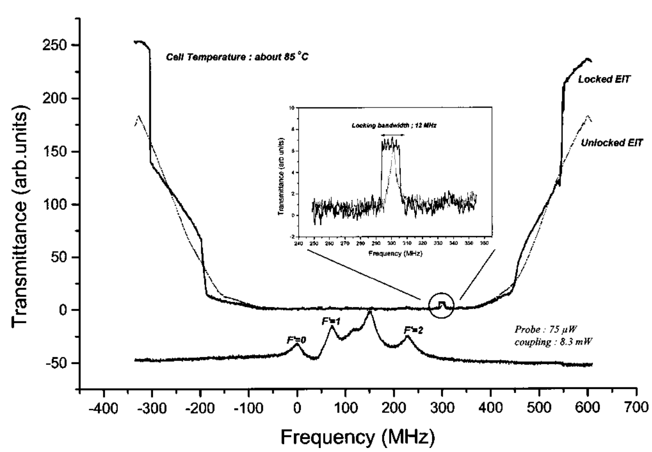

FIG. 3. Locking bandwidth by optical feedback (solid line) and the high contrast EIT spectrum (dotted line). The inset shows the locking bandwidth of 12 MHz. The bottom trace is the saturated absorption signal.

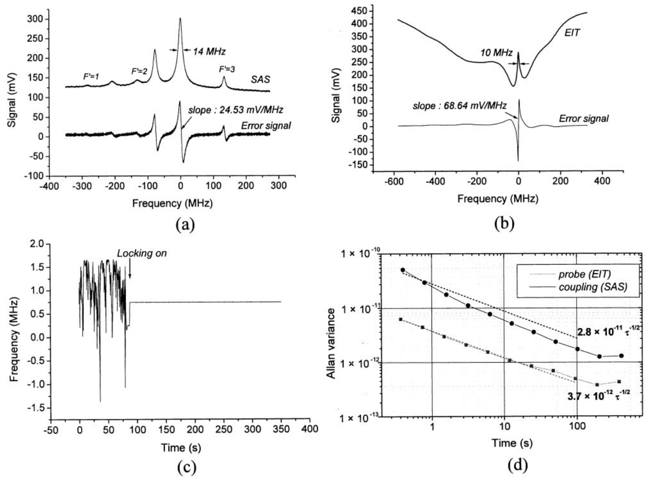

FIG. 4. Frequency stabilization by electrical feedback: (a) the saturated absorption spectrum and the phase sensitive detection signal of the coupling laser with direct modulation; (b) the EIT spectrum and the phase sensitive detection signal of the probe laser without direct modulation; (c) the frequency fluctuation of the probe laser before and after the electrical feedback; (d) Allan variances for the frequency stabilities of the coupling laser and the probe laser.

beating with another stabilized laser. However, we believe the frequency locking by optical feedback of EIT signals is adequate for many real applications.

Experimental results for the frequency locking by electrical feedback are shown in Fig. 4. Figure 4(a) shows the dispersion-like profile obtained by saturated absorption spectroscopy accompanying the frequency modulation for the frequency locking of the coupling laser. The frequency modulation is only necessary for the frequency locking of the coupling laser; we do not need extra frequency modulation for the probe laser to obtain a dispersion-like profile from the EIT signal as shown in Fig. 4(b). For the phase sensitive detection of the EIT signal without direct frequency modulation of the probe laser, we only used the signal modulating the coupling laser as the reference signal. This is possible because the EIT signal contains frequency modulation components of the coupling laser. The EIT signal depends on the detuning of the coupling laser. This is a sort of modulation-free frequency stabilization. Figure 4(c) shows the frequency stability of the probe laser before and after the electrical feedback. The integration time of the phase sensitive detector is set to 1 ms, which is larger than the response time of the PZT for the laser cavity. Figure 4(d) shows Allan variances for the frequency stabilities of the coupling laser and the probe laser. After 100 s, the frequency stabilities are 2×10^{-12} for the coupling laser and 5×10^{-13} for the probe laser. The Allan variances are based on closed loop measurements including servo electronics, and therefore represent a best case for the locking stability. Since the error signal represents the frequency deviations of the laser frequency weighted by the electronic servoloop transfer function, in principle it is possible to retrieve from this signal the frequency stability of the locked laser. The estimated level of the laser stability of EIT locking case was $\sigma(\tau)=3.7\times10^{-12}\tau^{-1/2}$ and that of the saturated absorption signal (SAS) locking case was $\sigma(\tau)=2.8\times10^{-11}\tau^{-1/2}$.

The probe laser using the EIT signal is much more stable than the coupling laser using the saturated absorption signal, mainly due to the narrow linewidth and the good signal-to-noise ratio of the EIT signal, if the servoelectronics are the same. The spectral linewidth of the saturated absorption spectrum is 14 MHz, which is much broader than the natural linewidth of 6 MHz, as shown in Fig. 4(a). However, the linewidth of the EIT as shown in Fig. 4(b) is 10 MHz. The EIT linewidth was broadly measured because of the modulation effect of the coupling laser and the linewidth of LD (less than 3 MHz at 2 s). The EIT spectral shape is not a single Lorentzian profile because EIT in a vapor cell include the EIT signals of the atoms with all velocity components. The noise level of the case of EIT is clearly smaller than the case of the saturated absorption signal as shown in Figs. 4(a) and 4(b). Although the slope of the EIT signal is only 3 times larger, the stability of EIT is 7 times better than the saturated absorption spectroscopy because of signal-to-noise ratio.

In conclusion, we are able to lock laser frequencies using EIT signals, which have the benefit of the subnatural linewidth. We have tested two methods, optical feedback, and electrical feedback. We can conclude that for frequency stabilization a subnatural EIT signal having low noise because of indirect modulation is better than a saturated absorption spectroscopic signal limited by the natural linewidth. Ideally, we would simultaneously use the EIT signal for frequency stabilization of two lasers. However, we do not know which laser is unstable when error signals occur. However, if we use both these error signals together along with the saturated absorption signal for long-term frequency stabilization of the coupling laser, we should be able to determine which laser is unstable.

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