Laser frequency stabilization using fm optical pumping spectroscopy

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We show a novel method for laser stabilization using FM optical pumping spectroscopy with counter-propagating beams. This method uses a variation of FM saturation spectroscopy, where the saturation and probe beam are replaced by two laser beams with different frequencies. In this scheme, the probe beam is produced by a laser stabilized with FM saturation spectroscopy, whereas the saturation beam (pumping beam) is generated by a second laser, without any modulation. The spectra thus obtained lack the crossover lines and Doppler well that are characteristic of conventional saturation spectroscopy. We show the results in frequency stabilization of a laser diode using this technique and ^{133}Cs, finding relative stability values of the same order of magnitude as other traditional stabilization techniques.

Keywords: Saturation spectroscopy; optical pumping; semiconductor laser stabilization.

Se presenta un método novedoso para la estabilización de un láser empleando espectroscopia de bombeo óptico de FM con haces en contrapropagación. Este método emplea una variación de la espectroscopia de saturación, en donde el haz de prueba así como el haz de saturación son sustituidos por haces provenientes de dos láseres que emiten a distintas frecuencias. En este esquema, el haz de prueba es originado por un láser estabilizado por el método de espectroscopia de saturación de FM, mientras que el haz de saturación (de bombeo) proviene de un segundo láser, el cual se encuentra libre de modulación. Los espectros obtenidos de esta manera carecen de resonancias ficticias (*crossover lines*), así como de pozo Doppler, que son característicos de la espectroscopia de saturación convencional. Se muestran los resultados obtenidos en la estabilización en frecuencia de un diodo láser usando esta técnica en vapor de ^{133}Cs, encontrándose valores de estabilidad comparables a otras técnicas de estabilización tradicionales.

Descriptores: Espectroscopia de saturación; bombeo óptico; estabilización de láseres semiconductores.

PACS: 32.30.Bv; 32.80.Bx; 32.70.Jz; 42.55.Px

1. Introduction

Some scientific and technological applications need to use more than one frequency stabilized laser. A particular case is time and frequency metrology, where the definition of the unit of time, the second, is based on the hyperfine spectroscopy of the Cesium atom [1]. In these experiments it is usual to carry out the laser manipulation of the quantum states of Cesium, as in optically pumping atomic clocks [2,3], as well as in atomic fountain clocks [2,3], whose main component si the Magneto-Optical Trap [3,4]. In both cases we need at least two frequency stabilized lasers at different resonances of the Cesium D_2 line.

Typically these lasers are frequency stabilized independently using saturation spectroscopy [5, 6]. The shape of the spectra is the result of certain saturated optical transitions in an atomic gas by means of a saturation beam, so that the medium becomes transparent for a probe beam, resulting the well-know saturated spectra (lamb dips). In addition, crossover lines appear at the central point between pairs of these lamb dips, all inside the Doppler well [6].

In this work we present a novel method for stabilized semiconductor lasers using optical pumping spectroscopy with two counter-propagating laser beams and with different frequencies. In contrast to the saturated spectra, we obtained spectra without a Doppler well and crossover lines. Different groups have reported results in the same context [7,8], but no one has reported its application to laser frequency stabilization. This new technique uses a probe beam from a laser stabilized with FM saturation spectroscopy, and a pumping beam from a second laser, which in principle emits at a different frequency. In this way, the transmitted light from the probe beam is detected and its frequency variations (FM) are utilized to generate the dispersion-like signal and stabilize the pumping laser. We presented Cesium spectra using optical pumping spectroscopy with counter-propagating beams, as well as the dispersion-like signals and their use in the frequency stabilization of a laser diode (pumping laser). The beat frequencies resulting between the pumping and probe lasers and a third laser (reference laser) are shown. We found that laser stabilities were equivalent within an order of magnitude.

2. Optical pumping spectroscopy with counter-propagating beams in ^{133}Cs

A schematic diagram of this method is shown in Fig. 1*a*. This configuration is similar to saturation spectroscopy [6] however in this case, the saturation beam (pumping beam) and the probe beam are not necessarily of the same frequency. Let us suppose there is an interaction of these beams with ^{133}Cs gas. As an approximation, we do not take into account the Zeeman levels, which is the reason why the effects of magnetic fields and beams polarization are not considered. A diagram of the energy hyperfine levels of the Cesium D_2 line is illustrated in Fig. 1b.

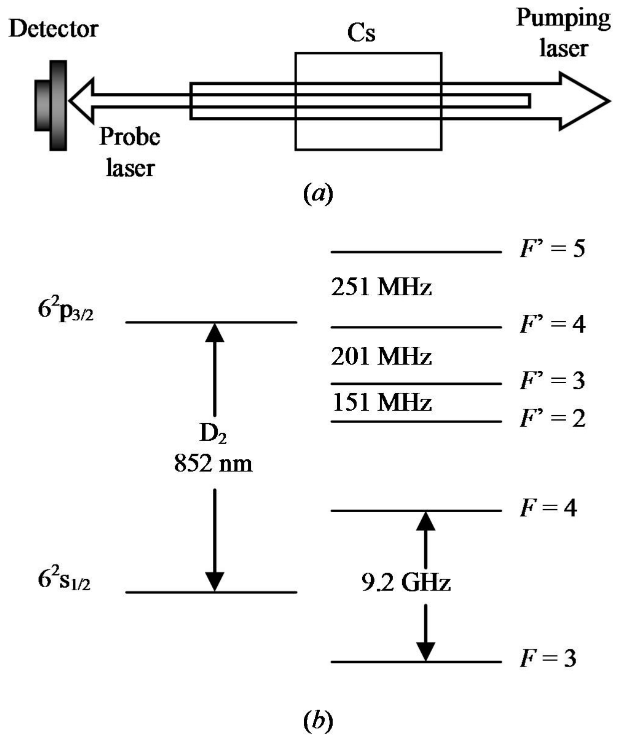

FIGURE 1. (a) Optical pumping spectroscopy with the experimental setup of the counter-propagating beams. (b) Hyperfine energy levels of the Cesium D_2 line.

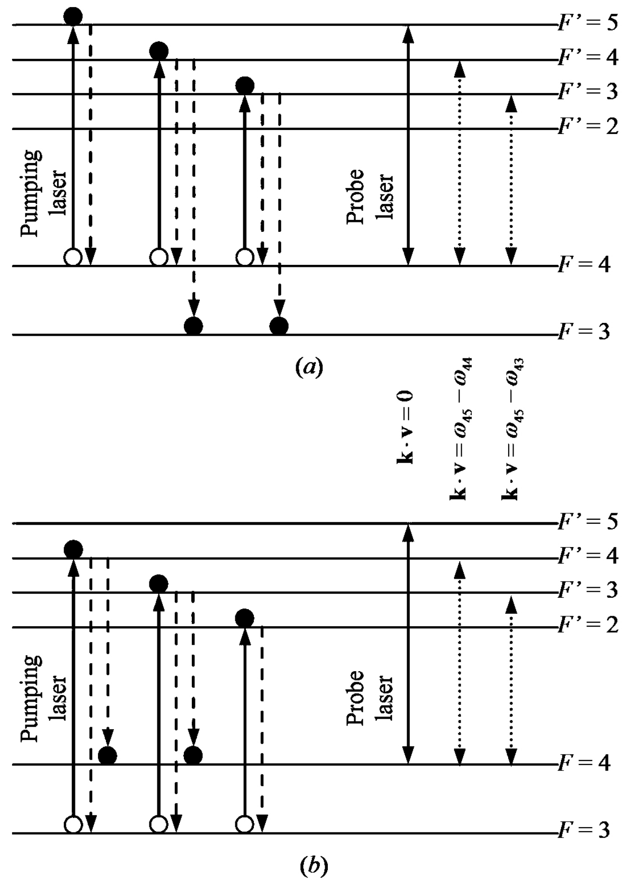

FIGURE 2. Optical pumping and saturation processes. The black circles represent an increase in atom population in this state, whereas the white circles represent a decrease in population (*a*) when the pumping laser frequency induces the $|F = 4\rangle \rightarrow |F' = 3, 4, 5\rangle$ transitions, (b) when the pumping laser induces the $|F = 3\rangle \rightarrow |F' = 2, 3, 4\rangle$ transitions.

The probe laser frequency, ω_P, is fixed to one of the resonance frequencies, $\omega_{FF'}$, of the D_2 line, whereas the pumping laser frequency, ω_B, can be tuned to any resonance frequency on this line (Fig. 1b). Under these conditions, the atom populations that move in a perpendicular plane to the propagation direction of beams are the major contributors to the spectrum formation (lamb dips), similarly to saturation spectroscopy. Nevertheless for this case, the intensity variation of the transmitted probe laser beam only depends on the pumping laser beam frequency, ω_B.

Combining different frequency values of the lasers, we can obtain an increase or decrease in the transmitted intensity of the probe beam. Let us consider the case when the probe laser frequency corresponds to the $|F = 4\rangle \rightarrow |F' = 5\rangle$ transition ($\omega_P = \omega_{45}$). So, the probe beam interacts with three different atom populations. For the atoms whose velocity component is zero in the direction of the beams propagation, that is to say, the Doppler shift is zero ($\mathbf{k}\cdot\mathbf{v} = 0$), they carry out the $|F = 4\rangle \rightarrow |F' = 5\rangle$ transition. The atoms with Doppler shift $\mathbf{k}\cdot\mathbf{v} = \omega_{45} - \omega_{44}$ make the $|F{=}4\rangle{\rightarrow}|F'{=}4\rangle$ transition. Finally, the $|F = 4\rangle \rightarrow |F' = 3\rangle$ transition is carried out by those atoms with Doppler shift $\mathbf{k}\cdot\mathbf{v} = \omega_{45} - \omega_{43}$ (Fig. 2), where $\mathbf{k}$ is the wave vector of the probe laser and $\mathbf{v}$ is the atom velocity vector.

Under these conditions we found three particular cases:

i) The pumping laser induces the $|F{=}4\rangle{\rightarrow}|F'{=}3, 4, 5\rangle$ transitions. In this case the pumping beam reduces the population at the $F = 4$ level, with an increase being expected in the transmitted intensity of the probe beam (Fig. 2a).

ii) The pumping laser stimulates the $|F{=}3\rangle{\rightarrow}|F'{=}3, 4\rangle$ transitions and increases the $F = 4$ level population, with a derece being expected in the transmitted intensity of the probe beam (Fig. 2b).

iii) The pumping laser induces the $|F = 3\rangle \rightarrow |F' = 2\rangle$ transition. For this condition the transmitted intensity of the probe beam remains unchanged, because the atomic population at the $F = 4$ level remains constant (Fig. 2b). Figure 2 shows these saturation and optical pumping processes.

In this way the spectra obtained are the result of the superposition of the individual spectra associated with the atomic populations with Doppler shift $\mathbf{k}\cdot\mathbf{v} = 0$,

$$\mathbf{k}\cdot\mathbf{v} = \omega_{45} - \omega_{44} = 2\pi \times 251\text{MHz},$$

and

$$\mathbf{k}\cdot\mathbf{v} = \omega_{45} - \omega_{43} = 2\pi \times 452\text{MHz}.$$

Figure 3 shows the positions of the lamb dips of these individual spectra.

3. Dispersion-like signals

The dispersion-like signals, or error signals, that are used for frequency laser stabilization, consist basically of signals that are proportional to the derivative of the spectral line shapes. Thus, the lasers are stabilized using the maximum value of the lamb dips. The more usual technique in the generation of dispersion-like signals is frequency modulated (FM) saturation spectroscopy. This method consists in modulating the laser frequency, $\omega(t)$, around a certain frequency ω', so that:

$$\omega(t) = \omega' + A_\omega \sin(\omega_m t), \tag{1}$$

where A_ω is the modulation amplitude, and ω_m is the modulation frequency. The laser modulation is much smaller that the spectrum linewidth, so the transmitted intensity of the probe beam, $I(t)$, could be written approximately as:

$$I(t) = I(\omega') + \frac{d}{d\omega} I(\omega)\Big|_{\omega=\omega'} A_\omega \sin(\omega_m t). \tag{2}$$

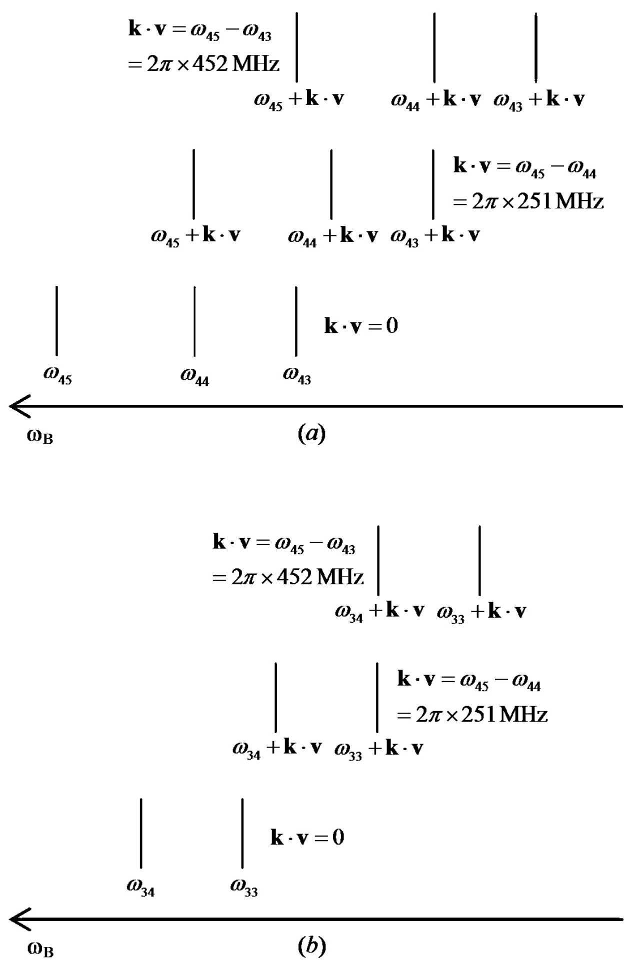

FIGURE 3. Positions of lamb dips associated with different atomic populations using optical pumping spectroscopy. (a) The pumping laser induces the $|F=4\rangle \rightarrow |F'=3,4,5\rangle$ transitions. (b) The pumping laser induces the $|F=3\rangle \rightarrow |F'=2,3,4\rangle$ transitions.

Multiplying the transmitted intensity given in the above equation by the modulation signal $\sin(\omega_m t)$, and eliminating the oscillating terms (using a low pass filter), the error signal, $E(t)$, is:

$$E(t) = \frac{A_\omega}{2} \frac{d}{d\omega} I(\omega)\Big|_{\omega=\omega'}. \tag{3}$$

This is the dispersion-like signal obtained by the FM saturation spectroscopy method.

The above analysis is applicable to the experiment shown in Fig. 1a, where the probe beam is frequency modulated. Thus, it is possible to generate the dispersion-like signals from the spectra obtained by optical pumping spectroscopy and to use them in the frequency stabilization of the pumping laser, which is modulation free.

4. Experimental results

Next we describe the experimental setup employed in the optical pumping spectroscopy with counter-propagating beams in ^{133}Cs vapour. We used two DBR laser diodes (YOKOGAWA, model YL85XTW), with 5 mW output power, 852 nm wavelength (near the Cesium D_2 line), and 1 MHz linewidth. The probe beam and pumping beam were 75 μW and 300 μW, respectively, and both lasers were linearly polarized. We used a cubic Cesium cell (1 cm $\times$ 3 cm $\times$ 1 cm) in order to stabilize the probe laser. The probe laser was frequency stabilized to the $|F=4\rangle \rightarrow |F'=5\rangle$ transition of the Cesium (Fig. 1a) using FM saturation spectroscopy [6], where the error signal was generated using a frequency modulation of 130 kHz and an amplitude of about 500 kHz. In order to generate the spectra, the pumping laser frequency was modulated via current modulation, with a frequency of 100 Hz and an amplitude of about 1 GHz. The saturation spectroscopy was made using the thinnest part of the cell in order to maximize the line associated with the $|F=4\rangle \rightarrow |F'=5\rangle$ transition [6].

Two cylindrical cells were utilized for the optical pumping spectroscopy. For the $|F=4\rangle \rightarrow |F'=3,4,5\rangle$ transitions a cylindrical cell 7 cm long was used, whereas for the $|F=3\rangle \rightarrow |F'=2,3,4\rangle$ transitions a cylindrical cell 5 cm long was employed in order to lessen the attenuation of the beam. Cell temperature was kept around 23°C with a vapour pressure near 10^{-6} torrs [9]. Figure 4 shows this experimental setup. Also Figs. 5 and 6 present the spectra obtained using optical pumping spectroscopy in ^{133}Cs and its respective dispersion-like signals.

These spectra are images taken from an oscilloscope, where the signals are variations in the transmitted light of the probe beam. The signals in Fig. 5 are taken directly from the photodetector output, whereas the dispersion-like signals (Fig. 6) come from the output of the low-pass filter (Sec. 3). The signal-to-noise ratio of the spectra (Fig. 5) is degraded due to the frequency modulation in the probe laser. In Fig. 5a we observe the spectrum obtained when the laser pumping frequency is modulated around the resonance frequencies

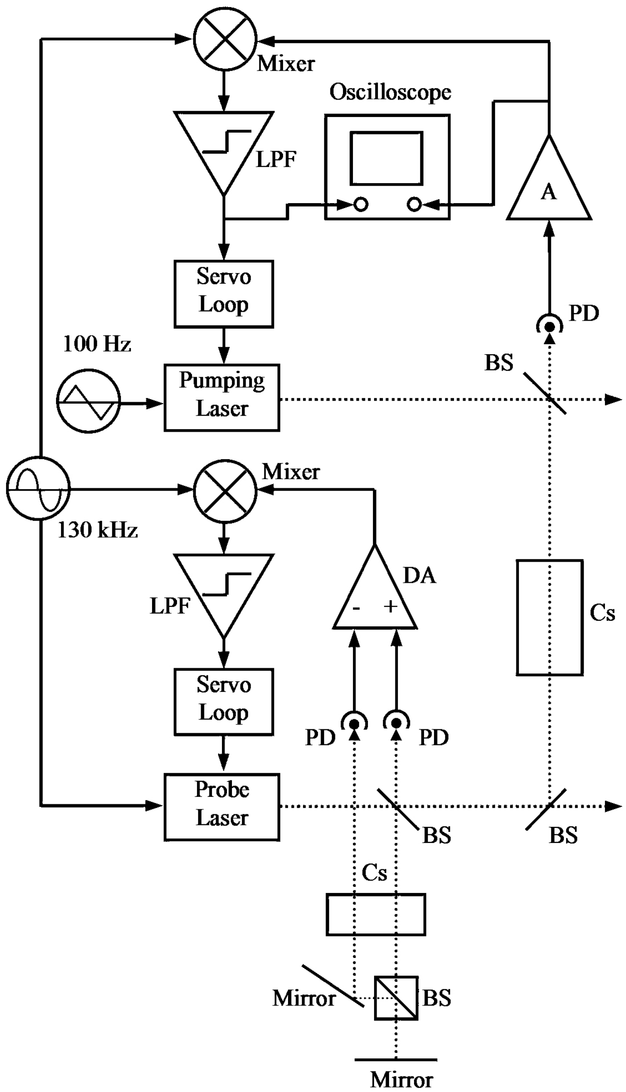

FIGURE 4. Optical pumping spectroscopy with counter-propagating beams and generation of dispersion-like signals: experimental setup, where BS is a beam splitter, PD is a photodiode, A is an amplifier, DA is a differential amplifier and LPF is a low-pass filter.

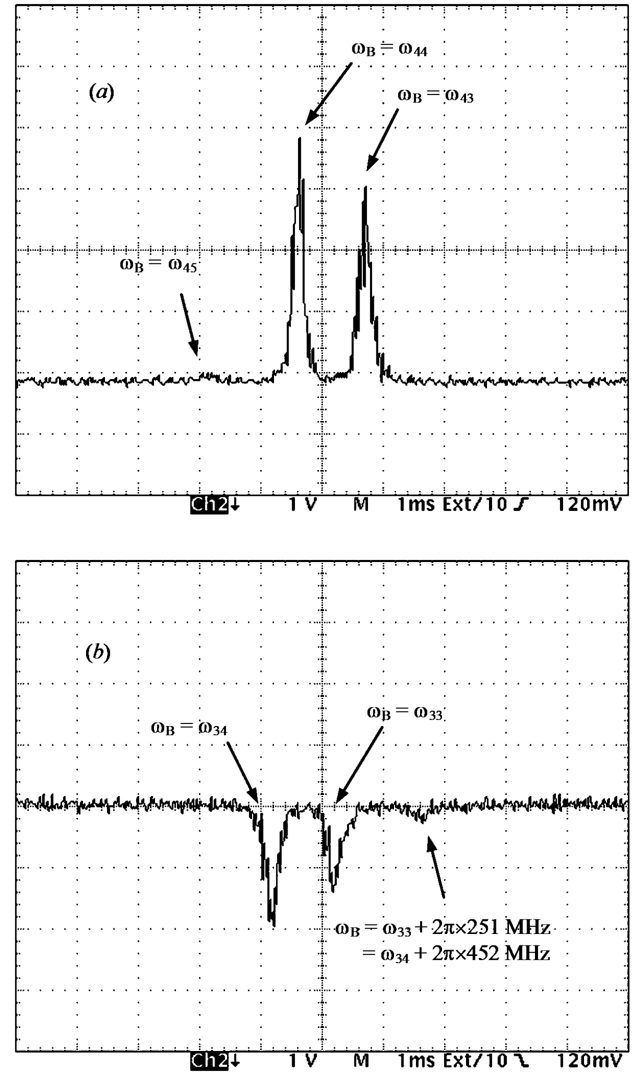

FIGURE 5. Cesium D_2 line spectra obtained with optical pumping spectroscopy with counter-propagating beams. (a) The pumping laser frequency is modulated around ω_{43}, ω_{44}, ω_{45}. (b) The pumping laser frequency is modulated around ω_{32}, ω_{33}, ω_{34}.

associated with the $|F = 4\rangle \rightarrow |F' = 3, 4, 5\rangle$ transitions. We notice an increase in the transmitted intensity of this probe beam (lamb dips), just when the pumping laser frequency is ω_{45}, ω_{44} and ω_{43}, where the lamb dip associated with the $|F = 4\rangle \rightarrow |F' = 5\rangle$ transition is almost imperceptible, due to the cell size [6]. In addition, we observed that the shifted lines are not appreciable.

Similaly, in the spectrum shown in Fig. 5b we notice a reduction in the transmitted intensity (lamb dips) when the pumping laser frequency is ω_{33} and ω_{34}. Also we can observe a shifted lamb dip located at

$$\omega_B = \omega_{33} + 2\pi \times 251\text{MHz} = \omega_{34} + 2\pi \times 452\text{MHz}.$$

It is important to mention two special characteristics of these spectra in comparison with the saturation spectroscopy spectra [6]. Because the probe laser frequency remains fixed, except for a small modulation, the Doppler well is absent, since the frequency sweeping is only made in the pumping laser. Also the crossover lines do not appear in the spectra, except for a small contribution of the shifted lamb dips (Fig. 5).

On the other hand, the error signals are shown in Fig. 6, and are proportional to the derivative of the signals shown in Fig. 5. A good signal-to-noise ratio is observed due to the filtration stage; also the derivatives of the smallest lamb dips are not appraised.

5. Stability

The pumping laser frequency and the probe laser frequency were compared with the frequency of a third laser (reference laser), with the same characteristics as the first ones. This laser was frequency stabilized in the same way as the probe laser (FM saturation spectroscopy). The crossover line that is

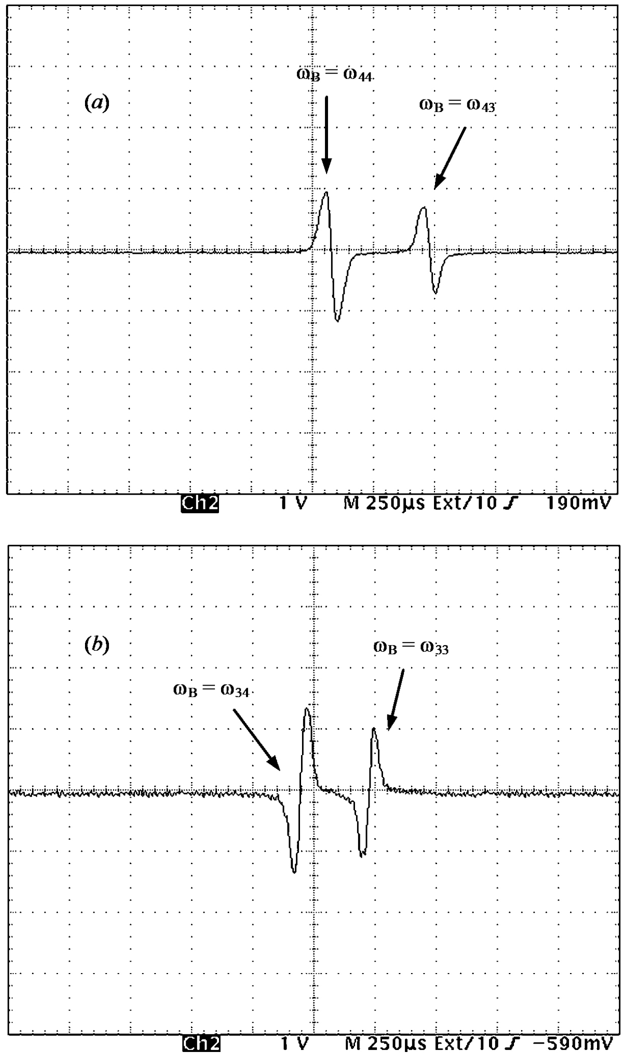

FIGURE 6. Cesium D_2 line dispersion-like signals using optical pumping spectroscopy with counter-propagating beams. (a) The pumping laser frequency is modulated around ω_{43}, ω_{44}, ω_{45}. (b) The pumping laser frequency is modulated around ω_{32}, ω_{33}, ω_{34}.

at the middle of the $|F{=}4\rangle{\to}|F'{=}5\rangle$ and $|F{=}4\rangle{\to}|F'{=}4\rangle$ transitions was used for the stabilization of this laser [6]. Also the pumping laser was stabilized to the ω_{44} resonance frequency (Fig. 6a). A beat frequency between each pair of lasers was produced for approximately 16 hours, during which the measurements were carried out every 3 seconds with the help of shutters. The schematic diagram for this experiment is presented in Fig. 7.

Figure 8 shows the frequency differences between these lasers. We notice a frequency shift in the pumping laser near 600 kHz at 16 hours (Figs. 8a and 8b). This drift in the pumping laser frequency is due to a progressive misalignment between the pumping beam and the probe beam. The angle formed between these two beams is not zero, inducing therefore a frequency shift due to the Doppler effect [6]. For each degree in the angle formed between the beams a shift of around 2 MHz is obtained. In addition, the beam trajectories

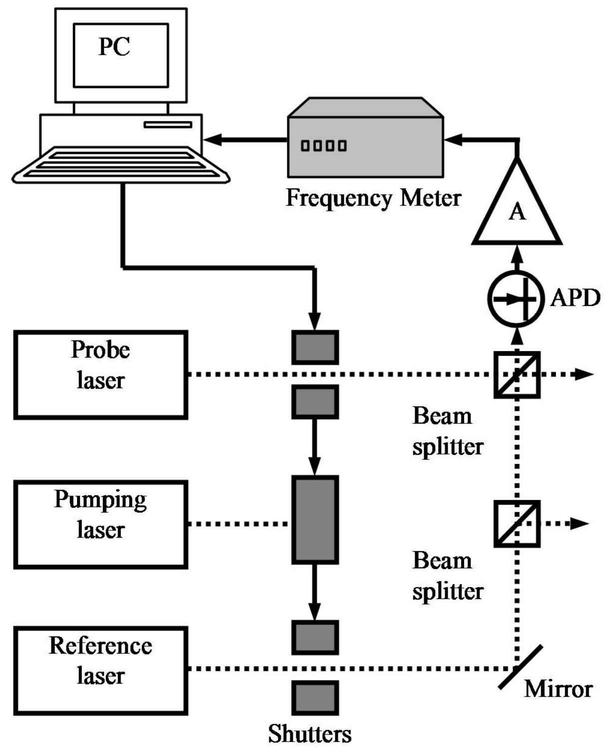

FIGURE 7. Beat frequencies: experimental setup in which A is an amplifier and APD is an avalanche photodiode.

in the optical pumping spectroscopy are longer than the beam trajectories used in saturation spectroscopy (Fig. 4), which is the reason why this experiment is more sensitive to temperature variations and vibrations.

On the other hand, a graph of the frequency differences between the probe laser and the reference laser are present in Fig. 8c; in contrast to graphs 8a and 8b, we observed a much smaller drift in the beat frequency of these lasers. Also we noticed a systematic shift in the frequency difference between the probe laser and the reference laser around 1.5 MHz, due to misalignments in the saturation spectroscopy (Doppler shift). Finally, the relative stabilities found with these data are shown in Fig. 9. On this graph we noticed that the best relative stability is for the probe laser versus reference laser, in agreement with the qualitative analysis made with Fig. 8. In addition, we observed that the stability behavior in the three cases follows a typical tendency of an oscillator, finding an optimal stability region (minimum) in the Allan variance. In this particular case, this zone is located around 400 s.

For this averaging time the relative stabilities of the probe laser versus pumping laser and the reference laser versus pumping laser are 2.19×10^{-11} and 2.77×10^{-11}, respectively. Also for the probe laser versus reference laser the stability found is 1.36×10^{-11} (Fig. 9). If the slopes of graphs 8a and 8b are eliminated, we found that the relative stabilities corresponding to the averaging times smaller than 400 s do not change significantly, but for greater times the stability

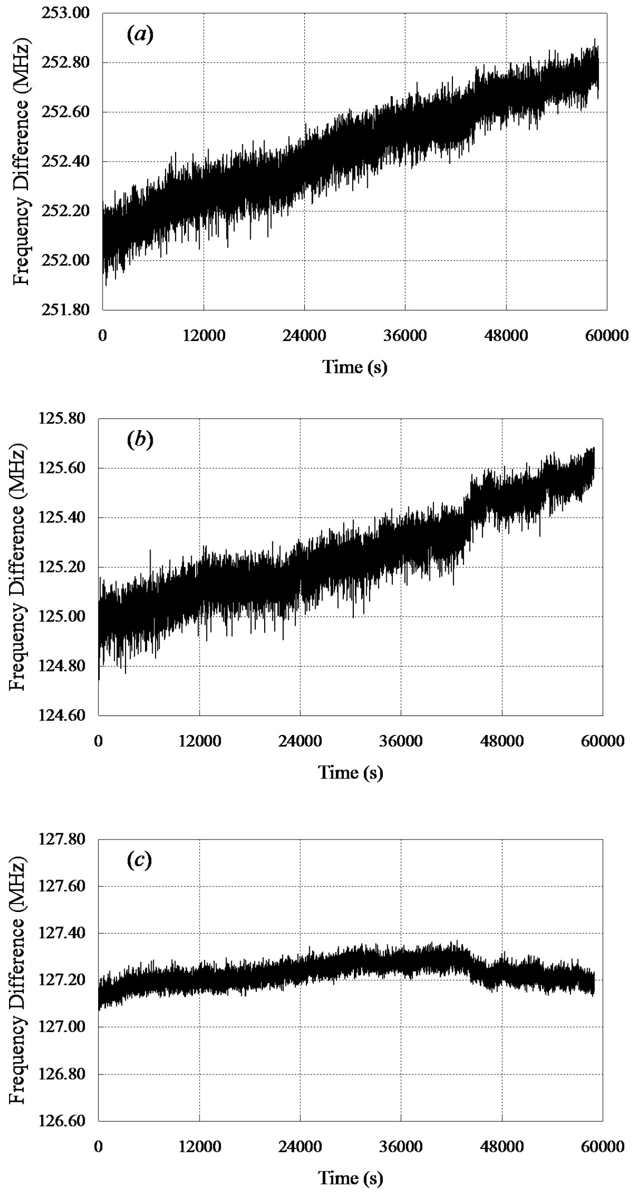

FIGURE 8. Beat frequency measurements. (a) Probe laser − Pumping laser. (b) Reference laser − Pumping laser. (c) Probe laser − Reference laser.

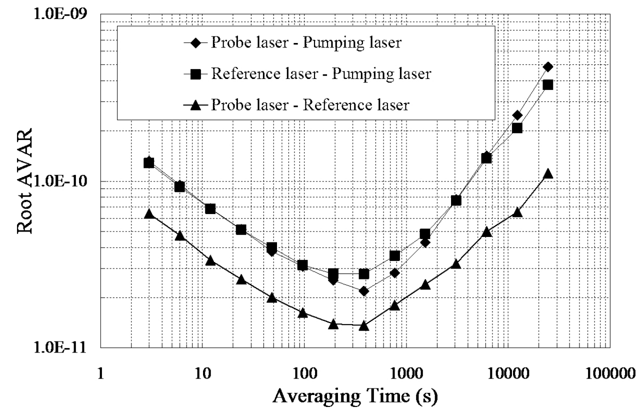

FIGURE 9. Allan variance corresponding to the frequency differences between pairs of lasers.

improves. For example, for an averaging time of 6000 s we found that the stabilities corresponding to Figs. 8a and 8b (without slope) are 4.33×10^{-11} and 5.95×10^{-11}, respectively, whereas the stability of the probe laser versus reference laser (Fig. 8*c*) is 4.99×10^{-11}. That is to say, if the temperature variations in the laboratory are controlled and the laser frequency drift is minimized then we expected the laser pumping stability to be equivalent to the stability of the probe and reference lasers for averaging times of more than one hour.

6. Conclusions

We presented a novel method for stabilizing semiconductor lasers using optical pumping spectroscopy with counter-propagating beams in ^{133}Cs. This technique uses a laser stabilized with FM saturation spectroscopy (probe laser), whereas the pumping beam comes from a second laser (pumping laser) with a different frequency from the first one. In comparison with saturation spectroscopy, the crossover lines as well as the Doppler well are absent in the spectra. The frequency modulation of the probe laser is used to generate the dispersion-like signals with which the pumping laser is stabilized. Thus the pumping laser is modulation free. We found that the frequency stability of this laser agrees in parts in 10^{11} with respect to the stability of the lasers stabilized with the FM saturation spectroscopy (Fig. 9). This discrepancy is caused by the experiment sensitivity to temperature changes and vibrations due to the beam trajectories. Reducing these distances would improve the pumping laser stability, giving stability values similar to the stabilities obtained with saturation spectroscopy.

This novel method can be used in experiments in which it is necessary to have two or more lasers stabilized to an atomic reference. Specific examples are the optically pumping atomic clocks [10] and the Magneto-Optical Traps, since these use two lasers stabilized to different Cesium resonances. For example, for a Cesium MOT we needed a laser stabilized to the ω_{45} frequency (cooling laser), as well as a laser stabilized to the ω_{33} or ω_{34} frequency (re-pumping laser). The laser stabilization method proposed in this work can be used in directly in a Cs Magneto-Optical Trap.

Acknowledgements

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