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Dye laser frequency locking to the hyperfine structure ($3S_{1/2}$, $F=2$–$3P_{1/2}$, $F=2$) of sodium D_1 line by using polarization spectroscopy

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The frequency of a single-mode dye laser is locked to a hyperfine structure of the sodium D_1 line without modulating the laser frequency. The frequency locking method uses the error signal from a dispersion curve generated from the polarization spectroscopic output. The servo loop provides a frequency fluctuation less than ± 0.3 MHz for more than 30 min.

A fixed laser frequency with a prominent stability and reproducibility has been required in various experiments such as high-resolution spectroscopy or frequency standardization. By choosing a resonant frequency of a reference cavity[1,2] or an atomic (molecule) transition frequency[3–7] as a fixed frequency, the frequency lockings have been realized. The saturated absorption and atomic beam method have been used to lock the laser frequency to the center of an atomic transition line. In most of these methods, frequency lockings have been achieved by modulating laser frequency,[3–5] also frequency locking methods without frequency modulation have been reported.[6,7] Wieman and Hänsch[8] have theoretically proposed a locking technique that used the dispersion curve generated by polarization spectroscopy. However, their method has a disadvantage in that the shapes of the dispersion curves have usually been obtained asymmetrically in the case of a strong pump beam, and also they shifted the center of the transition line. In the present work, we use the symmetrical dispersion curve, which seems more suitable to lock the laser frequency to a hyperfine line of the sodium D_1 line. This method is based on the polarization spectroscopic technique where the pump intensity is sufficiently low and comparable to the probe intensity. As this method does not use any cavity modulation, there is no problem of shift of transition line center except for the case where some neighboring transition line interferes.

The theory of optical pumping polarization spectroscopy in a four-level model was reported by Nakayama.[9] When the angle between the polarizer and the analyzer for the probe beam is $\pi/2-\theta$, the intensity of transmitted probe field (I_{ps}) is given by

$$I_{ps}=I_0[\theta^2+(f+f^*)\theta+ff^*],\qquad f=kl(\chi_{++}-\chi_{--})/4\,. \tag{1}$$

In Eq. (1), l is the length of the sodium cell and k is the wave number of the probe beam. I_0 is the input intensity of the probe beam, f^* is the complex conjugate of the f, and χ_{++} and χ_{--} are related to the susceptibilities for the left circularly polarized field and right circularly polarized field components of the probe beam, respectively. In Eq. (1), the first term is a dc field component of the transmittance of the probe beam through the analyzer. The second term gives a symmetric dispersion curve and the last term gives a Lorentzian curve which is generally much smaller than the second term when the pump beam is weak. But, in the case of considerable pump beam intensity, the dispersion curve becomes asymmetric[10] because of the large contribution of the last term in Eq. (1). To get a symmetric dispersion curve, the pump beam intensity should be lowered until the ff^* term can be neglected compared with $(f+f^*)$. In this case, I_{ps} is given by neglecting the last term in Eq. (1) as follows:

$$I_{ps}\approx I_0(f+f^*)\theta\propto\frac{(\omega-\omega_0)}{(\omega-\omega_0)^2+\Gamma^2}\,. \tag{2}$$

Here, the first term in Eq. (1) has been removed by using phase-sensitive detection electronics. The signal represented by Eq. (2) is the dispersion curve due to the birefringence of the probe beam. Accordingly, it is useful for frequency locking because it gives a zero crossing and symmetric signal at the transition center ω_0.

The experimental setup for the polarization spectroscopy, shown in Fig. 1, is similar to Wieman and Hänsch's[8] system. A linearly polarized probe beam from a single-mode tunable dye laser is sent to the sodium vapor cell whose optical anisotropy is induced by the circularly polarized pump beam from the same laser. By using a phase-sensitive detection technique, the dc first term of Eq. (1) is removed. Typical signals of the polarization spectroscopy for the sodium D_1 structure are shown in Fig. 2. Figure 2(a) shows a Lorentzian curve given by the last term of the Eq. (1) at $\theta=0$

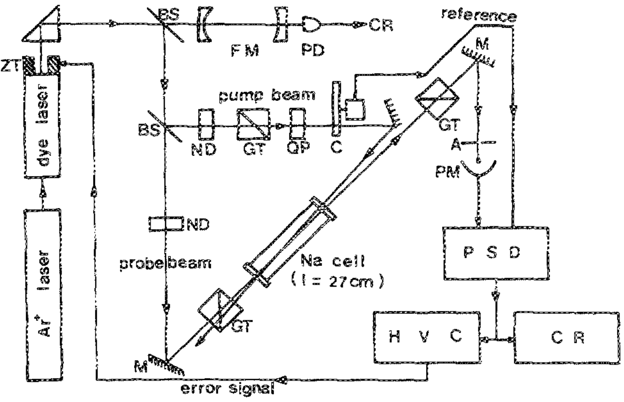

FIG. 1. Experimental setup for obtaining the error signal by using the polarization spectroscopy for locking the dye laser frequency to a hyperfine structure of sodium D_1 line. BS: beam splitter, FM: frequency marker (free spectral range 150 MHz), PD: photodiode, M: mirror, GT: Glan–Thompson polarizer, ND: neutral density filter, QP: quarter-wave plate, C: chopper, A: aperture, PM: photomultiplier tube, PSD: phase sensitive detector, HVC: high voltage converter, CR: chart recorder.

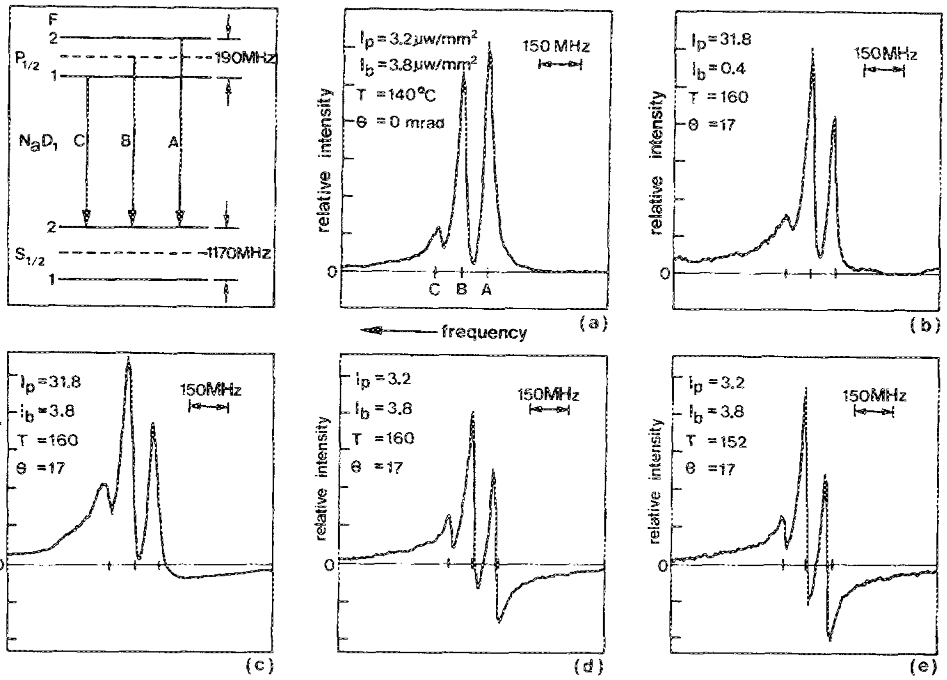

FIG. 2. Line profiles for various pump (I_p μW/mm²) and probe (I_b μW/mm²) beam intensities, and cell temperature [(a)–(e)]. T(°C) is the cell temperature and θ (mrad) is the angle between the polarizer and analyzer from the right angle for the probe beam. The left-upper figure represents the corresponding transition lines (A, B, and C) of sodium D_1 line.

mrad. Indicated points (A,B,C) on the frequency axis correspond to the transition lines (A,B,C) of the inserted energy level diagram in Fig. 2. When the pump beam intensity (I_p) is much greater than the probe beam intensity (I_b) at $\theta = 17$ mrad, the effect of the last term in Eq. (1) becomes dominant as seen in Fig. 2(b). Upon decreasing the intensity of the pump beam and the temperature of the cell, the dispersion curve becomes dominant as shown in Figs. 2(c)–2(e), and finally the I_{ps} takes only a symmetric dispersion shape as shown in Fig. 3. This signal shows the symmetric dispersion curve which is very similar to the theoretical curve of the $(f+f^*)$ term in Eq. (1).[10]

In order to lock the frequency of the dye laser to one (locking point L in Fig. 3) of atomic transition line, we use a symmetric dispersion curve shown in Fig. 3. The locking point L, the zero crossing point in Fig. 3, is slightly different from the center of the atomic transition line A because the dispersion curve of transition A is superposed by the tails portion of the symmetric dispersion curves of the nearby transitions (B and C). The linear slope at the locking point L in Fig. 3 is measured to be 5.0 MHz/V, where $I_p = 3.2\,\mu$W/mm,² $I_b = 3.8\,\mu$W/mm,² $T = 140\,°$C. The phase-sensitive detector output voltage error signal, which is fed back to drive the PZT of dye laser output coupler for frequency locking, is a measure of the frequency fluctuations. Figure 4

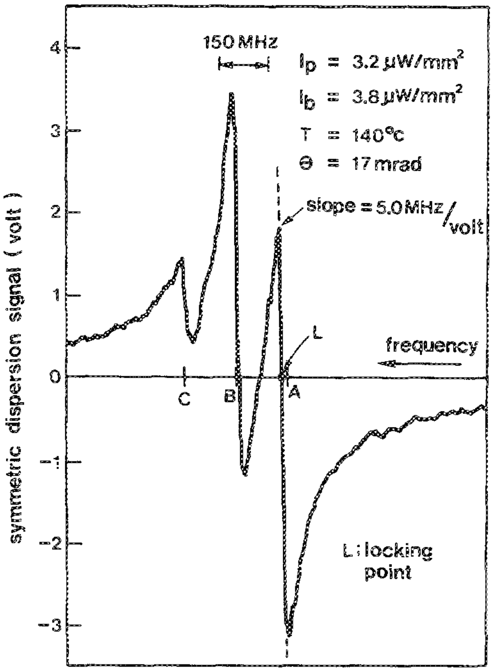

FIG. 3. Zero crossing L differs from the line center (A) as a result of overlapping of the three symmetric dispersion curves centered at A, B, and C. The error signal, a measure of the frequency fluctuation, is proportional to the slope at locking point L. The slope at point L is 5.0 MHz/V.

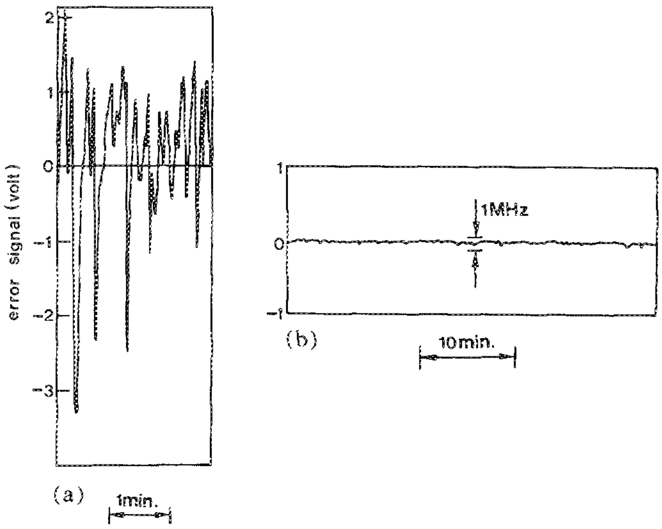

FIG. 4. Error signals (a) before and (b) after frequency locking. The frequency fluctuation after locking is less than ±0.3 MHz for more than 30 min.

shows the frequency fluctuations before and after the frequency locking. The free-running fluctuation during 2 min without locking is shown in Fig. 4(a). In locking the frequency, the integration time of the phase-sensitive detector is set to 100 ms, which is slower than the response time (approximately 10 ms) of the PZT for the laser output coupler. This servo loop provides frequency fluctuation less than ± 0.3 MHz for more than 30 min as shown in Fig. 4(b).

In conclusion, without frequency modulation in the laser, frequency locking to a hyperfine structure of sodium D_1 line is achieved by using the error signal from the symmetric dispersion curve obtained by polarization spectroscopy, where both the pump and the probe intensities are so sufficiently low that the absorption term [ff^* of Eq. (1)] can be ignored. This method is generally useful to lock to any transition line to which optical pumping is applicable. A more detailed theoretical analysis for the behavior of the dispersion curve for various intensities of the pump and probe beams is in progress.

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