Semiconductor laser excitation of Ramsey fringes by using a Raman transition in a cesium atomic beam

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An amplitude-modulated semiconductor laser is used to excite a 9.2-GHz Raman transition in a cesium atomic beam. Separated-field Ramsey fringes as narrow as 1 kHz wide are observed with a high signal-to-noise ratio, even for semiconductor laser linewidths as wide as 20 MHz. These narrow resonances have potential application in the development of high-accuracy, optically excited atomic clocks.

Recently there has been interest in the use of the laser slowed and trapped atoms for the development of high-accuracy atomic clocks.[1–3] For slow-atom clocks, employing separated field excitation, the use of a Raman transition may have advantages over direct microwave excitation.[4–6] This is because the two-zone Raman interaction has the demonstrated ability to reverse the sign of the ac Stark shift.[7] This property may be useful as a technique to cancel ac Stark shifts that can be produced when atoms in the Ramsey dark zone interact with stray fluorescent light.[8] Such dark zone interactions are likely to be important in slow-atom clocks because of the long dark zone transit times. Raman transitions are also of interest because the optical forces exerted by Raman resonant standing waves or related schemes may lead to the development of improved, high-density dark atom traps.[9,10] In this paper, we demonstrate that it is possible for one to excite narrow Raman–Ramsey fringes in a cesium beam, with a high signal-to-noise ratio, using a single, amplitude-modulated semiconductor laser. The ability to use a single semiconductor laser to replace a microwave cavity is also important for potential device applications.

The laser-excited resonance Raman interaction is illustrated in Fig. 1. Here, long-lived states $|a\rangle$ and $|b\rangle$ are coupled to a common excited state $|e\rangle$ by laser fields at frequencies ω_1 and ω_2, respectively. As is well known,[11,12] the Raman transition linewidth for weak copropagating laser fields is primarily determined by the decay rates of the long-lived states $|a\rangle$ and $|b\rangle$. Thus, the linewidth is set by the transit time. To achieve an effectively long transit time, Ramsey's technique of separated-field excitation is used.[13]

In our present experiment the long-lived states $|a\rangle$ and $|b\rangle$ in Fig. 1 are, respectively, the $6^2S_{1/2}$ ($F = 3$) and ($F = 4$) ground-state hyperfine levels in cesium, separated by 9.2 GHz, and state $|e\rangle$ is the $6^2P_{3/2}$ ($F = 4$) level. The optical transitions are components of the cesium D_2 line at 852 nm.

The experimental setup is shown schematically in Fig. 2. The laser diode is a single-frequency, AlGaAs laser (Hitachi HLP-1400 or Ortel SL-300) operating at 852 nm and mounted on a thermoelectric device. The Hitachi laser linewidth is ~20 MHz, whereas the Ortel laser linewidth, although initially much broader, is narrowed to less than 3 MHz (Ref. 14) by means of optical feedback, as described elsewhere.[15]

We generate the two optical fields at ω_1 and ω_2 by modulating the laser current at 4.6 GHz with a synthesized microwave signal, as shown in Fig. 2, yielding two amplitude-modulation sidebands[16] separated by the required 9.2 GHz. When one generates ω_1 and ω_2 in this manner the effect of laser jitter, and laser-intrinsic linewidth, can be greatly reduced.

Figure 3(a) shows the frequency spectrum of the modulated Hitachi laser as measured by a short, plane-parallel, scanning Fabry–Perot cavity with a free spectral range of 25 GHz. As can be seen, the separation between sidebands is 4.6 GHz. For comparison, Fig. 3(b) shows the spectrum of the unmodulated single-mode laser. The carrier-to-sideband ratio is typically approximately 4:1, where larger sideband amplitudes are not used because they lead to excessive broadening of the laser.

As indicated in Fig. 2, the output from the modulated laser interacts with the cesium atomic beam in zones A

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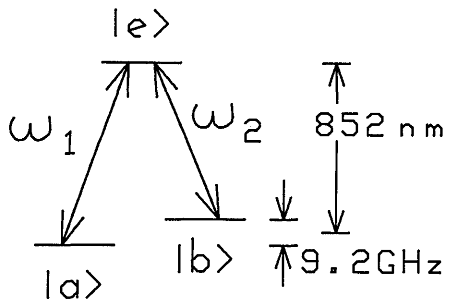

Fig. 1. Resonance Raman transition in cesium.

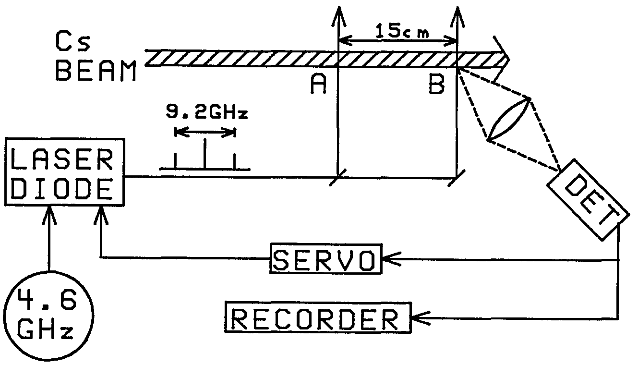

Fig. 2. Experimental setup.

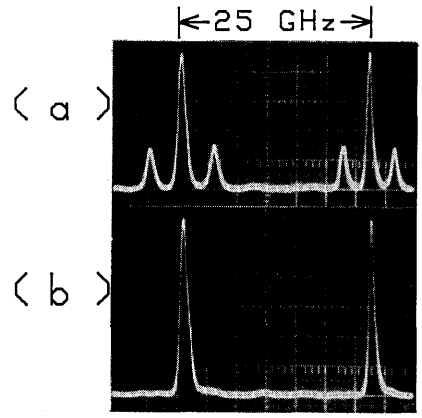

Fig. 3. Spectrum of (a) amplitude-modulated laser at 4.6 GHz and (b) unmodulated laser.

and B, and the fluorescence from zone B is collected with a low-noise photodetector. Figure 4(a) shows the zone B fluorescence obtained when the frequency of the modulated Hitachi laser is scanned (zone A blocked). Four resonances result because of the two-sideband excitation scheme. The transitions responsible for these resonances are illustrated in Fig. 4(b). The measured linewidth of each transition is ~35 MHz, which is primarily due to laser jitter. The natural linewidth of the cesium transition is only 5 MHz, and the residual Doppler broadening, due to atomic beam divergence, is estimated to be 2 MHz.

To observe the Raman transition, the laser frequency is locked to the peak of the resonance corresponding to the $F = 4$ excited-state component [see Fig. 4(b)] and the microwave frequency is scanned. The laser-frequency lock employs a frequency modulation, which is generated by a small-amplitude, 60-kHz rate, modulation of the laser injection current. The microwave frequency scan range is limited to less than ±30 MHz, to avoid splitting the fluorescence peak to which the laser is locked.

Figure 5(a) shows the discriminants of the seven allowed single-zone Raman transitions, corresponding to various m sublevels, as a function of microwave frequency. To produce these discriminants, the microwave frequency is modulated at a rate of 550 Hz. One uses ac detection because of the large fluorescence background signal, which results from transitions among the many m sublevels. These line shapes are obtained with circularly polarized laser fields propagating along the direction of an applied 6-G magnetic bias field. The large bias field is needed to overcome stray magnetic fields and to separate clearly the magnetic sublevels (4-MHz separation).

Figure 5(b) shows an expanded scan[17] of the magnetic-field insensitive $m = 0$, $\Delta m = 0$ Raman clock transition. The linewidth of this single zone transition is ~450 kHz, which is consistent with power broadening from the 1 mW of total optical power (carrier and sidebands) input to zone B.

To achieve a narrow Raman transition, a Ramsey zone A and B separation of 15 cm is employed (see Fig. 2). The

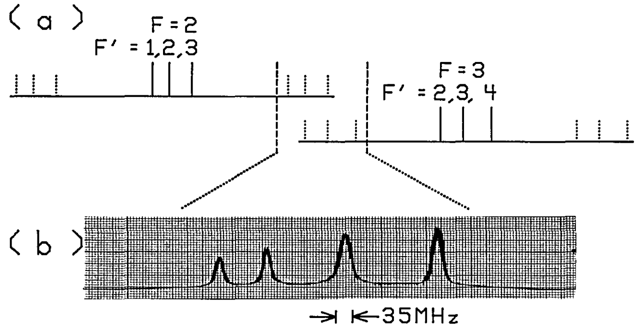

Fig. 4. (a) Cesium transitions excited by the two laser sidebands. (b) Single-zone cesium fluorescence corresponding to overlap of the $F = 3 \leftrightarrow F = 2, 3, 4$ and $F = 4 \leftrightarrow F = 3, 4, 5$ transitions, as shown in (a).

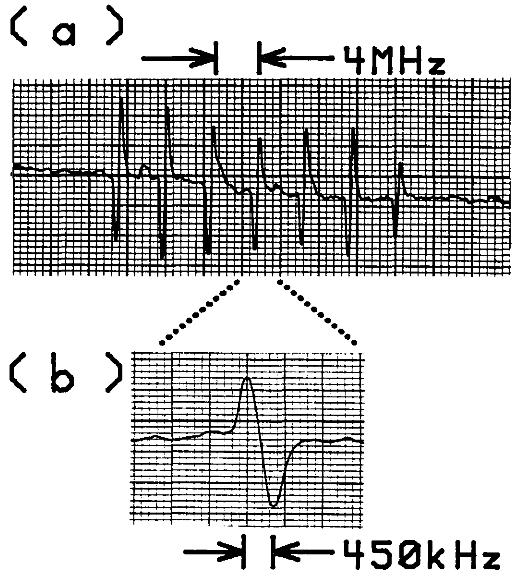

Fig. 5. (a) Single-zone Zeeman-split Raman transitions in cesium ($F = 4$ intermediate state). (b) Single-zone Raman transition corresponding to the $m = 0 \leftrightarrow m = 0$ magnetic field insensitive clock transition.

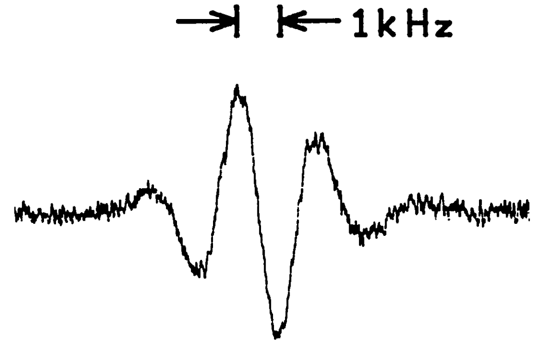

Fig. 6. Ramsey fringes for a 15-cm interaction zone separation and a free-running Hitachi laser (20-MHz intrinsic linewidth).

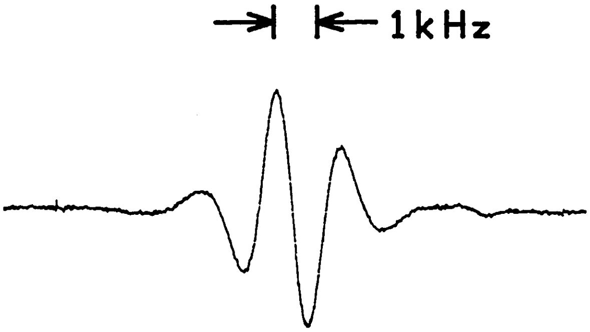

Fig. 7. Ramsey fringes for a 15-cm interaction zone separation and an optical feedback stabilized Ortel laser (less than 3-MHz linewidth).

discriminant of the resulting Ramsey fringes (obtained with the Hitachi laser) is shown in Fig. 6. The central fringe has a width of just under 1 kHz, which is in good agreement with that predicted for a 15-cm interaction zone separation and a 200 °C oven temperature. In addition, the Ramsey fringe shape is consistent with a thermal velocity distribution, and the fringe amplitude is nearly equal to the amplitude of the single-zone line shapes, which indicates no loss of coherence between the interaction zones.

The Ramsey fringes in Fig. 6 correspond to a 0.1-s time constant. For a 1-s time constant, the measured Ramsey fringes' signal-to-noise ratio is 400. This is ~10 times less than the calculated shot-noise limit. The primary source of this noise is the fluorescence intensity fluctuations caused by frequency jitter of the Hitachi laser. To reduce this noise, we first replaced the broad-linewidth Hitachi laser by an Ortel laser that is narrowed by optical feedback. We then stabilized the Ortel laser frequency by adding a servo to lock the laser to a reference Fabry–Perot cavity. Finally, we also added magnetic shielding, so that the magnetic bias field can be reduced (to ~60 mG). This also improves the signal-to-noise ratio, because the background fluorescence is reduced when the seven single-zone Raman dips overlap.[18]

The Ramsey fringes obtained with the stabilized Ortel laser are shown in Fig. 7 (0.1-s time constant). The measured signal-to-noise ratio for a 1-s time constant is ~1800. This signal-to-noise ratio is limited by detector noise but is only a factor of 2 smaller than the shot-noise limit. The measured fringe width (~1 kHz) and signal-to-noise ratio translate to a projected fractional frequency clock stability of $6 \times 10^{-11}/\tau^{1/2}$, which compares well with the stability of commercial cesium clocks.[19] The signal-to-noise ratio can of course be improved with a second laser to increase the flux of atoms in the $m = 0$ sublevels.[20,21]

In summary, we have excited narrow Raman–Ramsey fringe line shapes in a cesium atomic beam, with a high signal-to-noise ratio, using only a single, modulated semiconductor laser. We find that the broad linewidth of a semiconductor laser (20 MHz) does not prevent the observation of narrow linewidth fringes and results in only a factor-of-4 decrease in signal-to-noise ratio compared with a narrower laser (3 MHz). Future work includes the development of novel designs for traps and slow atomic beams (with Raman resonant optical standing waves[9]) to provide a high-density source of cold atoms for clock applications.

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14. The laser linewidth measurement is limited by the 3-MHz instrumental linewidth of a confocal, scanning Fabry–Perot cavity.
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16. In general, when the injection current is modulated, the diode

laser undergoes both amplitude and frequency modulation. At gigahertz modulation rates, however, we saw evidence only of amplitude modulation.

17. The discriminants in Fig. 5 appear inverted because they were recorded during the increasing and decreasing legs, respectively, of a triangle-wave scan.
18. Note that although the probe-zone Raman absorption minima overlap, the bias field is large enough so that the Ramsey fringes corresponding to the field insensitive $m = 0$, $\Delta m = 0$ transition is isolated from the others.
19. This projected stability can also be compared with the observed fractional stability of $4 \times 10^{-10}/\tau^{1/2}$ in a sodium atomic beam Raman clock, with a linewidth of 2.6 kHz (Ref. 6) and with the observed fractional stability of $2 \times 10^{-10}/\tau^{1/2}$ for an rf-excited sodium fountain clock, with a linewidth of 2 Hz.[1]
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