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OPTICAL PUMPING BY LASERS IN ATOMIC FREQUENCY STANDARDS*

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Summary

Single-mode, near-infrared diode lasers may improve the performance of atomic frequency standards. In the case of rubidium standards, the short-term stability may be improved by using laser diodes for optical pumping in place of conventional rf-excited lamps. In cesium beam standards, the lasers may replace both sets of state selection magnets, resulting in greater signal-to-noise, more reliable beam detection, easily reversed beam direction for cavity phase shift measurement, reduced Majorana transitions, and a smaller, more easily regulated C-field. The degree to which these improvements are realized depends upon the characteristics of available lasers. In this paper, we report measurements of laser intensity and frequency noise and their effects on clock performance. The light shift in a laser-pumped Rb clock is given, as well as the stability curve for that clock. Preliminary work on optical pumping in a cesium beam is also reported.

Key Words. Laser Diode, Atomic Frequency Standard, Optical Pumping, Light Shift, Laser Stabilization.

Introduction

The development of inexpensive, reliable, single-mode laser diodes within the communications industry has made the use of lasers in atomic frequency standards much more attractive. In particular, the use of these devices in vapor cells, atomic beams, and laboratory primary frequency standards is possible. The use of optical pumping by lamps and lasers in other types of standards, such as ion storage traps[1,2] will not be discussed in this article.

Table 1 gives typical stability and accuracy performance of existing commercial and laboratory atomic frequency standards. There are a number of ways in which laser diodes may help improve these specifications. In the case of Rb standards, the greater efficiency in optical pumping afforded by laser diodes over conventional lamps should improve signal-to-noise, resulting in better short-term stability. While long-term stability would still be limited by buffer gas or wall shifts, light shifts might be reduced by switching the laser diode and interrogating the microwave resonance while the light source is off.[7] In addition, since pumping by laser diodes is not dependent upon coincidence of hyperfine lines in different isotopes as conventional rubidium lamps are, cesium may be used in the vapor cell instead of rubidium. Cesium offers advantages of greater microwave resonance frequency, slower atoms (because of greater atomic mass) and natural isotopic purity.

Anticipated benefits to commercial cesium standards also include increased stability. Since atoms are converted to the desired hyperfine state instead of rejected by a state-selection magnet, more atoms contribute to the signal for a given beam intensity. Laser diodes can also be used for fluorescence detection of atoms, eliminating the second state-selection magnet, and relaxing requirements on alignment. Such a detection method should have good long-term stability, sensing nearly all atoms in the beam regardless of velocity and position. Using laser diodes for both state preparation and state detection results in a highly symmetric device in which the atomic beam direction can be rapidly reversed, or even maintained continuously in both directions.[8] This would permit correction for cavity phase shifts, which may limit long-term stability of commercial standards. Simplification of beam tube design could result in some weight savings as well.

The accuracy of laboratory primary frequency standards may be increased through the use of laser diodes.[10] Elimination of state-selection magnets permits the extension of the C-field region to include both the optical pumping and the optical detection regions of a standard, which should prevent Majorana transitions among magnetic sublevels. These transitions may produce frequency offsets of unknown magnitude in present cesium primary standard designs.[9] A more symmetric beam reversal is possible with optical pumping methods, since all atoms may be included regardless of velocity and position within the beam. This should permit a better cancellation of cavity phase shifts. Angle tuning of the laser may result in velocity selection of atoms in the cesium beam, favoring slower velocity atoms, which would give a narrower microwave resonance. Finally, two lasers can be used to pump all of the cesium atoms into a single magnetic sublevel,[11] giving better control of Majorana transitions, freedom from frequency pulling by adjacent Zeeman levels, still greater numbers of usable atoms for a given beam intensity, and permitting operation at a lower C-field and a lower magnetic shielding coefficient than would otherwise be possible.

Laser diodes also introduce new difficulties into any atomic standard. They must be cooled to a highly regulated temperature, and the electronics required to perform this function, as well as provide a regulated injection current to the laser, is appreciable. The long-term reliability and useful lifetime of laser diodes is unknown. While manufacturers' projections of life range as great as 100 years, this does not include an estimate of wavelength stability. Single-mode, cw lasers are available today for as little as $100 each, but this price does not guarantee the exact wavelength required for optical pumping of a given atom. Finally, use of such a narrow spectrum source complicates the problem of light shifts in both vapor cells and atomic beams, and may introduce short-term noise through frequency and amplitude noise of the laser.

General Characteristics of Laser Diodes

A recent review of single-mode GaAlAs laser diodes is given by Botez.[12] A more extensive treatment is found in the books by Kressel and Butler[13] and by Thompson.[14] We have made measurements with transverse junction stripe (TJS) lasers,[15] channeled-substrate-planar (CSP) lasers,[16] and other stripe geometry, double-heterostructure lasers. The most promising results have been obtained with the first two types and consequently the discussion here will concentrate on them.

The very small active region in these devices (0.4μm x 2μm for the TJS laser, and 2μm x 10μm for the CSP laser) results in a diffraction-limited beam which must be collimated for most applications. We found that large numerical aperture microscope objectives gave the best collimation, although a number of measurements were made using single aspheric lenses. In either case, reflected light is a problem, as it can seriously affect the mode structure of the laser.

Both types operate in nearly single transverse and longitudinal modes, although the CSP type tends to stay longer in a given longitudinal mode as the injection current and temperature of the diode are changed. Longitudinal mode spacing is about 0.35 nm in both devices. Laser linewidth is about 150 MHz for the TJS laser (about 3 mW typical output), and less than 30 MHz for the CSP laser (about 10 mW typical output) as measured both with the Fabry-Perot spectrum analyzer, and with atomic resonance fluorescence curves. A detailed study of line broadening in CSP lasers has been made by Fleming,[17] who concluded that the spectral width was not in agreement with the Schawlow-Townes expression[18] based on quantum phase fluctuations.

Varying the amount of aluminum and dopants in the semiconductor alloy produces laser diodes of different wavelengths, ranging from about 780 nm to 905 nm in commercially available devices. Coarse tuning of the wavelength is achieved by changing the temperature (about 0.2 nm/°C) and fine tuning is accomplished through adjustment of the injection current (about 0.02 nm/mA).

Circuits have been designed and constructed at NBS to control the laser injection current to one part in 10^6, and the laser temperature to about 1 millidegree centigrade for times in excess of one day. Further laser frequency stability has been obtained by locking the laser to an atomic absorption line for periods of days. This method has given long-term frequency stability of better than 100 kHz.

Although a given laser diode may operate near a desired wavelength at a reasonable value of current and temperature, it may not be possible to tune to an exact wavelength. As current and temperature are changed, the laser may hop to an adjacent cavity mode, leaving sizable gaps in the tunable spectrum. About half of the ten TJS diodes without package windows which we tested could be tuned to the Rb D_2 resonance at 780 nm. Only one of the ten TJS lasers with windows, which we studied, could be tuned exactly to that wavelength. It may be that the windows reflected enough light back to the laser to interfere with tuning. When a particular laser is tuned to the Rb resonance, the laser may change to a new cavity mode later for reasons which are not well understood. Even though manufacturers project lifetimes for laser diodes in excess of 100 years, this mode-hopping problem may limit their usefulness in atomic frequency standards. Measurements are in progress at the National Bureau of Standards (NBS) to determine how long these lasers can be locked to an atomic absorption line.

With typical operating currents of about 40 mA and 100 mA repectively, the TJS and CSP lasers themselves consume about 80 mW and 200 mW each. However, a system which includes temperature regulation, as well as current control, could require as much as 5 watts.

Stability of a Laser Pumped Rb Clock

The short-term stability of a conventional Rb clock is usually limited by the shot noise associated with the light detected by the photocell after the Rb vapor cell.[19] A typical value of signal to background of as little as 0.1% means that large improvements in short-term stability might be obtained by increasing the fraction of detected light which contributes to useful signal. As long as other noise sources do not become relatively large, the stability of the clock should improve as the square root of signal/background.

We have taken a commercial Rb clock and replaced the rf-excited rubidium lamp with a laser diode. Various sources of noise have been examined, and the short-term stability measured. Our most interesting results were obtained with a CSP-type laser operating at the D_2 transition (780 nm). Since the commercial Rb vapor cell contains both ^{85}Rb and ^{87}Rb, the best measurements were obtained for the F=1 transition in ^{87}Rb, which is well isolated from the ^{85}Rb lines. The output from the laser diode was roughly collimated to a 1 cm diameter beam, where the power density increased by about a factor of two from the perimeter to the center of the beam. The average laser power was varied from about 0.1 mW/cm^2 to 1.0 mW/cm^2 by inserting neutral density filters. The frequency of the laser was controlled both by temperature and injection current regulation, and by locking the laser to the center of the Rb absorption line.

Figure 1 shows the microwave resonance obtained by sweeping the commcercial clock's crystal oscillator over a small range, while pumping the cell with about 0.23 mW/cm^2 of D_2 light. While the sweep is somewhat nonlinear, it is clear that the linewidth of the resonance is approximately 1300 Hz, which gives a Q of only 5 x 10^6. It is believed that this large linewidth is due to broadening associated with the rather high laser power density. Figure 2 shows the dependence of microwave resonance linewidth on laser power density. The increase in linewidth due to an input laser light of 1 mW/cm^2 is about 1400 Hz. A rough estimate of the effective laser power in the Rb cell may be made from that linewidth. The change in microwave linewidth is given by

$$\delta(\Delta\nu_\mu) = \frac{1}{2\pi}\gamma_\ell \frac{\Delta\nu_\ell}{\Delta\nu_{Rb}} \qquad (1)$$

where γ_ℓ is the laser pumping rate on resonance, and $\Delta\nu_\ell/\Delta\nu_{Rb}$ is the ratio of the laser linewidth to the rubidium optical resonance linewidth in the cell. The ratio of the laser pumping rate to the spontaneous emission rate γ_n is just

$$\frac{\gamma_\ell}{\gamma_n} = \frac{B_{21}\, u(E)}{1/\tau_n} = \frac{\lambda^3}{8\pi\, h}\; u(E) = 2.9 \times 10^{19}\; u(E) \qquad (2)$$

where B_{21} is the Einstein B coefficient, τ_n is the natural decay time of the excited state (~ 30 ns), u(E) is the laser energy density per unit bandwidth, in joule-s/cm³, and λ is the wavelength of the optical transition. Combining this expression with the previous equation , and assuming a laser linewidth of ~ 30 MHz and a Rb optical linewidth of 1 GHz, gives a laser power density of

$$\rho = u(E)\cdot c\cdot \Delta\nu_\ell \qquad (3)$$

$$= \frac{2\pi\; c\delta(\Delta\nu_\mu)\; \Delta\nu_{Rb}}{\gamma_n\; (2.9 \times 10^{19})} = 0.27\ \text{mW/cm}^2\ . \qquad (4)$$

Note that the final expression is independent of the actual laser linewidth, as long as $\gamma_n/2\pi << \Delta\nu_\ell << \Delta\nu_{Rb}$.

It is reasonable that the effective laser power in pumping the Rb should be less than the input laser power because of absorption and variation in microwave power through the cavity. The above result is therefore taken as support of this mechanism of line broadening.

The peak change in detected current across the microwave resonance was about 10^{-6} A. The average detected current was 10^{-5} A. This gives a maximum signal-to-noise in a one hertz bandwidth of

$$\frac{S}{N} \sim \frac{I_{sig}}{\sqrt{2e\; I_{bkg}}} = 5.6 \times 10^5 = 115\ \text{dB}\ . \qquad (5)$$

Taking into account the relatively small microwave modulation amplitude, the expected signal to shot noise was greater than 100 dB in a one hertz bandwidth. This should result in an Allan variance stability of

$$\sigma(\tau) \sim \frac{0.2}{Q\; (S/N)}\; \tau^{-\frac{1}{2}} = 4 \times 10^{-13}\; \tau^{-\frac{1}{2}}\ . \qquad (6)$$

Figure 3 gives the actual performance of the clock from 10^{-2} to 10 seconds, using a laser diode locked to the center of the ^{87}Rb, F=1 transition, as seen in the mixed isotope cell of the clock. At times much greater than 10 seconds, the clock frequency stability leveled out at the 10^{-12} level. The stability at one second is about 1.5×10^{-11}— comparable to the clock performance with the original Rb lamp installed, but considerably worse than the performance limited by shot noise should be.

The probable cause of the limit in short-term stability, and the 10^{-12} floor on stability at longer times, is frequency noise on the laser, mediated through the light shift.[20] The light shift in this particular device was measured by tuning the laser diode in steps of 100 MHz across the F=1 resonance, while recording the clock's output frequency. The light shift for an input laser power of 0.23 mW/cm² is given in figure 4. This curve gives a peak-to-peak shift on the dispersion curve of about 550 Hz, in rough agreement with the predictions of Mathur,[21] if one uses the reduction factor for light intensity obtained from the microwave resonance broadening calculations above. An accurate measurement of the light shift in rubidium would require thorough knowledge of the laser beam profile within the vapor cell as well as information about the microwave modes in the cavity, neither of which was available. It is probably more accurate to use the light shift measurements as an indication of the effective laser power than to estimate the light shift from measured laser power.

Bearing the above caveats, figure 5 gives the light shift dependence upon input light intensity in this particular clock measured at the laser frequency of maximum light shift. The curve is linear, with slope ~ 1.2 kHz/mW/cm². A similar curve was obtained for the F=2 transition, but with a slope minus one-half that of the F=1 curve. The magnitudes of the two slopes should be equal, but differ because of the presence of ^{85}Rb, which reduces the laser light intensity at the F=2 transition.

Similar light shift measurements have been performed in cesium by Arditi and Picqué,[22] also using a laser diode, with results of the same magnitude.

The clock stability in figure 3 was obtained with a laser input power of 0.23 mW/cm^2. At this light level, the change in microwave frequency with laser frequency at the optical resonance peak is about -0.67 Hz/MHz, or a fractional frequency change of 10^{-10}/MHz. The long-term stability of the clock could thus be accounted for by a 10 kHz floor on the lock of the laser frequency to line center. (Which means the laser frequency is locked to a part in 10^5 of the resonance linewidth. A better lock might be obtained by using either saturated absorption or atomic beam techniques).

Figure 6 gives the frequency noise spectrum of the CSP laser diode. The TJS lasers tested gave a factor of three larger frequency noise, with a similar spectral dependence. These figures should be treated as an upper limit to the noise in these lasers. Since the cavity modes of the devices are very sensitive to reflected light, it is possible that a different testing procedure may give better results. However, Dandridge,[23] has obtained results with an interferometric testing method which agree within a factor of two with these measurements.

Our frequency noise curves were obtained by tuning the laser diode to the side of a Rb absorption line, and interpreting the intensity noise on the transmitted light in terms of frequency noise. The intensity noise observed, both away from the absorption line and on the peak of the resonance, was much smaller than that seen on the side of the line. The frequency noise at 127 Hz of ~ 100 kHz/$\sqrt{Hz}$ would limit the clock's frequency stability at one second to about 2×10^{-11}, in agreement with figure 3. The attack time on the servo loop which locked the laser diode to line center was not fast enough to significantly improve the stability of the laser at one second. In order to remove frequency noise as a limiting factor in short-term stability, a tighter laser lock is required. Also, if a lower temperature vapor cell is used, the laser intensity can be reduced with a proportional reduction in sensitivity to light shifts, without loss of signal.

No attempt is planned at this time to reduce the effect of laser frequency noise in this particular system because the crystal oscillator itself reaches a minimum stability of $\sim 10^{-11}$ at 0.3 second. Consequently, very little improvement could be expected over the results of figure 3 without other modifications of the clock.

Another source of noise in the laser-pumped Rb clock is intensity noise in the laser light. Figure 7 gives the CSP laser diode intensity noise spectrum; this spectrum was limited by the noise in the detection electronics and must be considered an upper limit only. Other measurements in CSP lasers have been made by Dandridge[24] who obtained fractional intensity noise as small as -145 dB/$\sqrt{Hz}$ at 100 Hz.

Using our limit of -120 dB/$\sqrt{Hz}$ at 127 Hz, and a signal-to-background ratio of 2%, the limit to stability due to laser intensity noise in this system would be about $\sigma(\tau) \sim 2 \times 10^{-12}/\sqrt{\tau}$. Using Dandridge's results, with a signal-to-background of 10%, and a microwave Q of 10^7 gives $\sigma(\tau) \sim 1 \times 10^{-14}/\sqrt{\tau}$. In this case, other sources of noise will limit the clock stability.

These results suggest that using a laser diode pump source with proper adjustment of Rb clock parameters, it may be possible to obtain stabilities of a few parts in 10^{13} at one second. A clock with such excellent short-term stability might find application as a local oscillator for a stored ion standard.[1] The clock's long-term stability would still be limited by the problems which plague conventional Rb clocks[7]—light shift changes due to light source intensity changes (which could be minimized either by adequate laser locking or by chopping the light[7]), buffer gas or wall shifts, and changes in the microwave spectrum. However, since laser pumping can be used in a system with higher Q than that of conventional standards, some relief from even these problems is expected.

Laser Pumped Atomic Beam Frequency Standards

Laser diodes may be useful as both a pumping source and a state detector in atomic beam frequency standards. Arditi and Picqué have demonstrated the use of a laser diode for these two purposes in a Ramsey-structure cesium beam clock. The work at NBS has proceeded along somewhat different lines, leading toward implementation of two or more lasers in a single clock, as is described below. While the preliminary Cs work at NBS has been done with dye lasers, the above results for laser diodes may be used in order to estimate noise in planned atomic beam devices.

Figure 8 is a sketch of a beam apparatus which has been used to measure optical pumping, detection, and microwave transitions in cesium. In the early experiments, one krypton ion laser pumped dye laser (HITC dye @ 852 nm) was used to pump the D_2 transition of atomic cesium. A second laser, pumped by the same krypton ion laser, was used to monitor the state of atoms which passed to the second region of the beam tube. The fluorescence signal in this region is an indication of the number of cesium atoms in a particular ground-state hyperfine level (figure 9). For example, figure 10 is a dispersion curve of the downstream cesium beam fluorescence detected by a frequency modulated laser swept across the $F=4 \rightarrow F'=5,4,3$ lines. Total data acquisition for this curve was one minute. The fact that the $F=4 \rightarrow F'=5$ transition is much larger than the other two lines is due to optical pumping on the two lesser transitions. The selection rule $\Delta F=\pm1,0$ prevents atoms from entering the F=3 ground state, which results in fluorescence of many photon per atoms. The $F=4 \rightarrow F'=4,3$ transitions move atoms to the F=3 state, where they no longer contribute to the fluorescence signal.

This detection laser can be left on the peak of the $F=4 \rightarrow F'=5$ dispersion curve, while a second laser is tuned to a pumping transition, the fluorescence signal downstream decreases. This is demonstrated in figure 11, where the $F=4 \rightarrow F'=4$ transition is pumped. Use of a cycling transition, such as $F=4 \rightarrow F'=5$, for fluorescence detection can result in 100% quantum efficiency, even when the light collection efficiency is small. The disadvantage of this method is that intensity noise in the laser appears in the detected signal. If the detection laser is tuned to a pumping transition, such as $F=4 \rightarrow F'=4$, the quantum efficiency may decrease, but every atom contributes an equal number of photons to the fluorescence signal, regardless of the atom's velocity, or of the laser's intensity (above a minimum value required for complete pumping).

If a microwave resonance between F=4 and F=3 of the ground state is now induced between the two laser regions, the fluorescence signal in the second region will be partially restored. This signal as a function of microwave frequency is shown for a Rabi-type resonance structure in figure 12 for two values of C-field. The peak which did not change frequency with change in C-field is the $m_F=0 \rightarrow m_F=0$ clock transition. The adjacent lines are π transitions present because the C-field is not precisely parallel to the magnetic field vector, $\vec{H}$, of the microwaves. As the C-field is increased, its direction becomes more nearly parallel to $\vec{H}$, enforcing the selection rule $\Delta m_F=0$. The outmost microwave resonances are the $m_F=\pm1 \rightarrow m_F=\pm1$ transitions.

In a cesium standard with a microwave Q of 10^7 and an effective beam current of 10 pA, the expected stability would be about $4 \times 10^{-12}\ \tau^{-1/2}$, if the limiting noise is shot noise associated with the atomic beam. If a cycling transition is used for fluorescence detection, the intensity noise in the laser light must be less than about $10^{-5}/\sqrt{Hz}$ in order that shot noise dominate. As seen above, this condition holds with the CSP-type laser diodes.

A more difficult problem arises with detector noise. Typical best performance at room temperature for a silicon PIN diode is a NEP $\sim 10^{-14}$ watt/$\sqrt{Hz}$. At one photon/atom, the 10 pA beam current used above would emit shot noise of about 2×10^{-15} watt into 4π steradians. The use of a cycling transition with perhaps 10^3 photons/atom would bring this noise level above the detector noise level without requiring great collection efficiency or the use of photomultiplier tubes.

A saturating laser intensity ($\sim$ 10 mW/cm^2) over a 1 cm length of the atomic beam should produce such a large number of photons. If the collection efficiency is increased, the interaction region may be correspondingly reduced in length.

An additional feature of the cycling fluorescence is that is tends to weight slower atoms more heavily, since they remain within the laser beam longer. This should result in a somewhat higher microwave Q for the system.

It is anticipated that frequency noise in the laser diode light will not introduce additional noise into an atomic beam standard, since the microwave region is separate from the pumping and detection regions. However, a systematic offset will be produced due to the light shift induced by fluorescent radiation entering the microwave region.[26] Using a value of 20 Hz $cm^2/\mu W$ for the light shift in Cs as an upper limit,[22] and 2×10^{-8} watt/4π steradian as the fluorescence emitted from a cycling detection region 1 cm from the microwave region, the resultant light shift would be about 3×10^{-2} Hz, or a fractional shift of 3×10^{-12}. Since the intensity of the laser light should not change over a period of a year, this probably does not present a problem for commercial applications, but it is a serious consideration for primary standards, where an accuracy of 10^{-14} is sought. A detailed calculation is in progress at NBS.

Further increase in both signal-to-noise and immunity from certain systematics should be obtained by pumping the cesium atoms into a single magnetic sublevel. One way of accomplishing this rearrangement of energy level populations is through the use of two lasers.[11] One laser is tuned to the $F=3 \rightarrow F'=4$ transition (figure 9), pumping atoms into the F=4 hyperfine level. A second laser, with electric field polarization parallel to a weak magnetic field in the same pumping region, is adjusted to the $F=4 \rightarrow F'=4$ line. In this case, the atoms from the F=4 level are pumped into F=3 level, with the exception of the F=4, $m_F=0$ magnetic sublevel, which remains unaffected by either laser. This may be seen by considering the Clebsch-Gordon coefficient which connects the F=4, $m_F=0$ level with the excited state:

$$\langle j_1 j_2 m_1 m_2 | JM \rangle = \langle 4100 | 40 \rangle = 0, \qquad (7)$$

where the notation used is the same as that of Messiah.[27] In this case, $j_1=F$, $m_1=m_F$, $J=F'$, and $M=m_{F'}$. The photon's quantum numbers are given by $j_2=1$ and $m_2=0$. Ultimately, all atoms are pumped into the F=4, $m_F=0$ sublevel. This results in a factor of sixteen increase in signal over conventional state selection, and removes adjacent transitions from the microwave spectrum. A similar arrangement may be used to pump atoms into the F=3, $m_F=0$ sublevel, since Eq. 7 holds for any two levels with $j_1=J$ and $m_1=m_2=M=0$.

Experiments are in progress at NBS to demonstrate this new pumping technique. At present, the individual selection rules involved for the method have been demonstrated using dye lasers. Figure 13 illustrates the most critical rule. In this example, the detection region laser is tuned to the $F=4 \rightarrow F'=5$ cycling transition. The upstream, pumping laser is tuned to the $F=4 \rightarrow F'=4$ line (852 nm). A microwave spectrum is displayed as in figure 12. In curve A, the electric field of the laser radiation is parallel to the static magnetic field in the pumping region. Some small signal is present at the $m_F=0 \rightarrow m_F=0$ microwave frequency because the optical pumping from the other magnetic sublevels changes the population of the F=3, $m_F=0$ level. In curve B, however, the polarization of the laser is rotated by about 6° from the magnetic field orientation. This removes the $m_F=0$ selection rule, and results in a marked increase in the population of the F=3, $m_F=0$ sublevel relative to the F=4, $m_F=0$ level. This produces a larger microwave transition signal at $m_F=0 \rightarrow m_F=0$. The next effort to actually pump all of the cesium atoms into a single magnetic sublevel will be made with diode lasers.

Conclusions

The properties of some commercial laser diodes have been studied. The frequency and intensity noise characteristics of these lasers place some restrictions on the short-term stabilty of both vapor cell clocks and atomic beam standards. These difficulties probably can be overcome and laser diodes may be used to improve the performance of atomic frequency standards. The frequency stability and light shift offsets in a laser-diode-pumped rubidium clock have been measured, and the short-term stability compared to that of a conventional Rb clock. A preliminary investigation has been made of optical pumping in a cesium beam using dye lasers and the selection rules necessary to pump all of the cesium atoms into a single magnetic sublevel have been verified.

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TABLE 1. Performance of Atomic Frequency Standards

	Short-Term Stability	Long-Term Stability	Accuracy
Commercial Rb Clock (3)	$2 \times 10^{-11}/\sqrt{\tau}$	3×10^{-11}/month	---
Commercial Cs Clock (4)	$10^{-11}/\sqrt{\tau}$	3×10^{-12} (2×10^{-13} @ 1 day)	---
Laboratory	$5 \times 10^{-13}/\sqrt{\tau}$ (5)	10^{-14} @ 1 week (6)	10^{-13} (5)

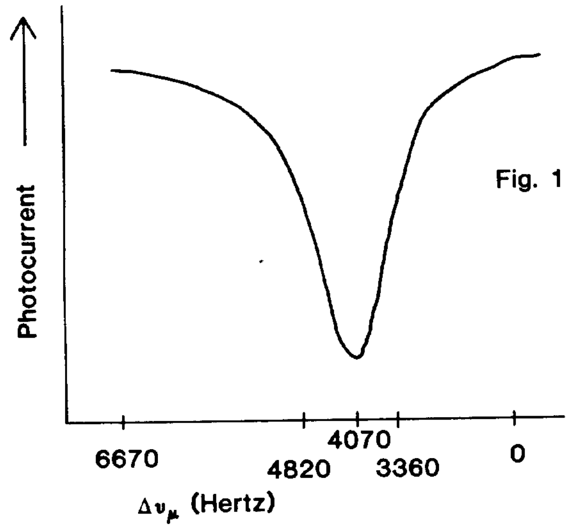


Figure 1. Rubidium $m_F=0 \rightarrow m_F=0$ microwave resonance in a laser pumped cell. The laser is tuned to the F=1, D_2 transition in ^{87}Rb.

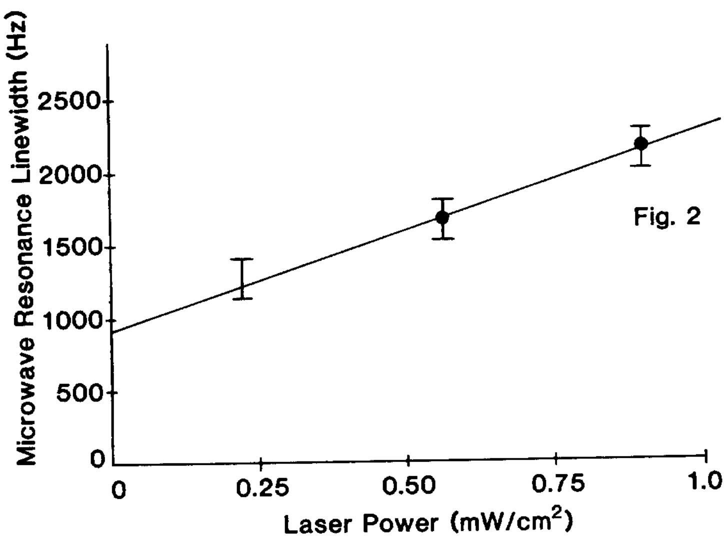


Figure 2. Rubidium microwave resonance linewidth as a function of input laser power density.

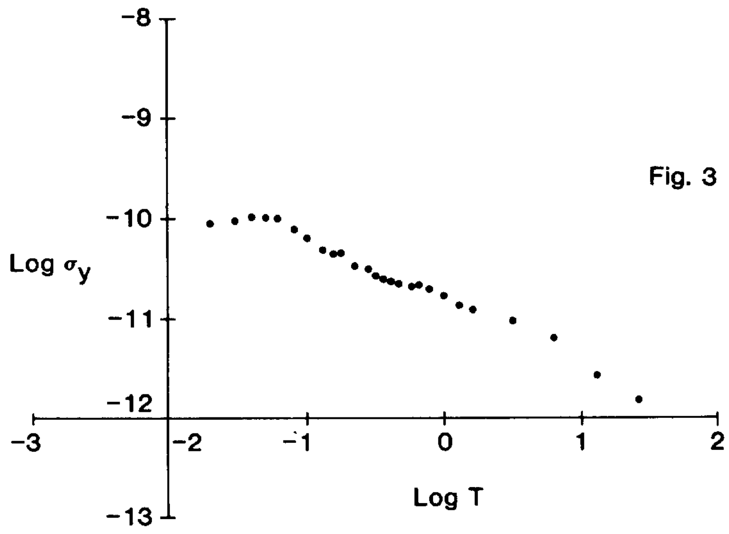


Figure 3. Allan variance stability curve for a laser-pumped rubidium clock. The laser is locked to the F=1, D_2 transition in ^{87}Rb.

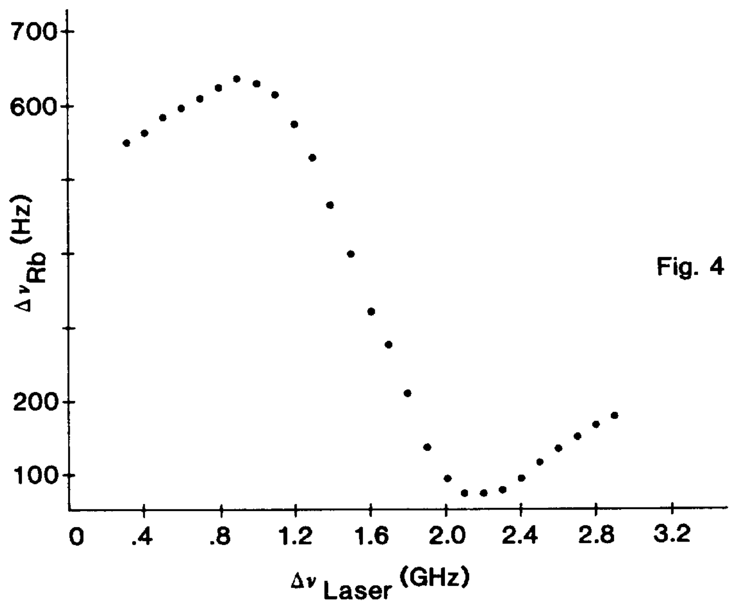


Figure 4. Light shift in ^{87}Rb clock. Input laser light of 0.28 mW/cm^2 is tuned across the F=1, D_2 transition.

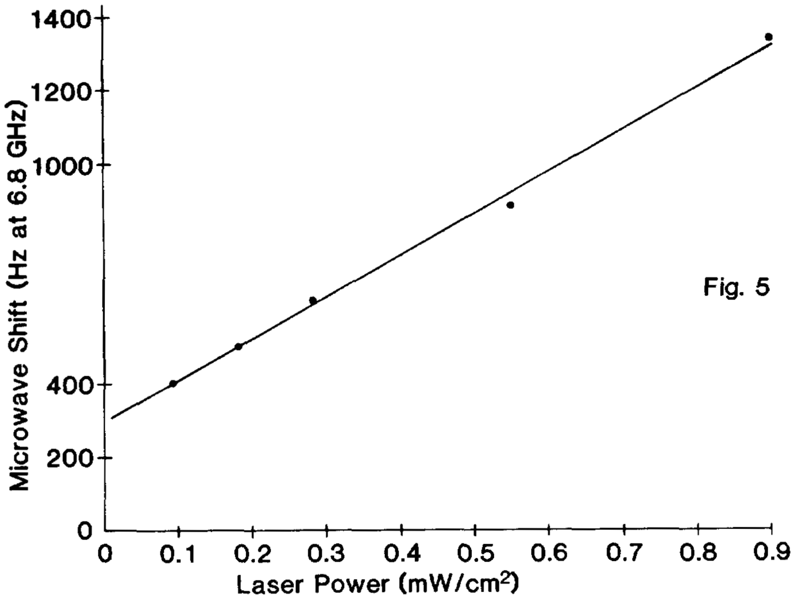


Figure 5. Maximum light shift in a ^{87}Rb clock as a function of laser power density. The laser is tuned to the low frequency dispersion peak of the F=1, D_2 transition.

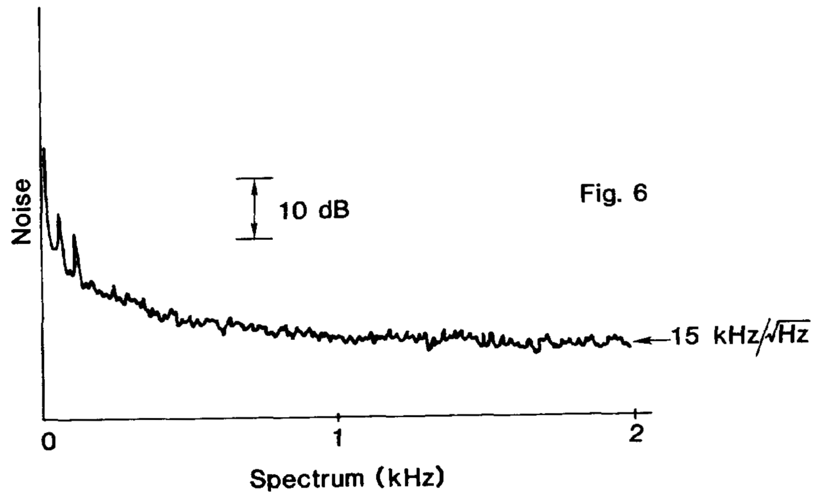


Figure 6. Frequency noise spectrum of a CSP laser diode. The curve was obtained by tuning the laser to the side of a Rb absorption line.

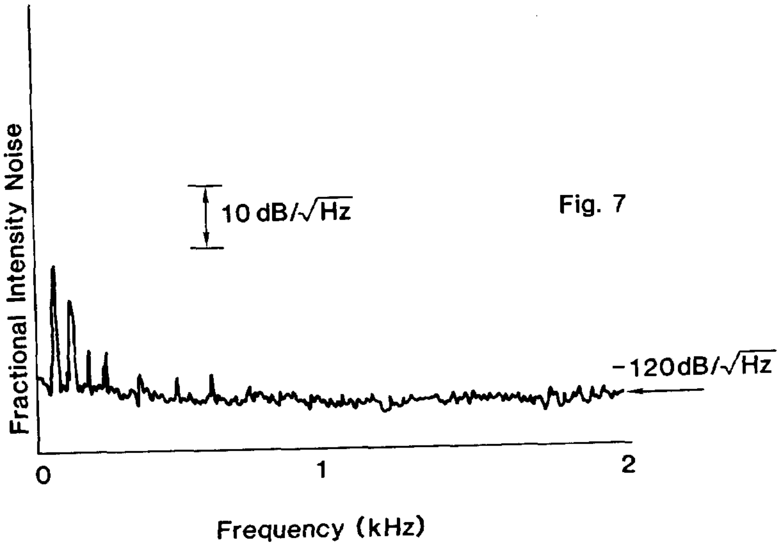


Figure 7. Intensity noise spectrum of a CSP laser diode. The curve is only slightly greater than the noise level of the measuring system and must be regarded as an upper limit only.

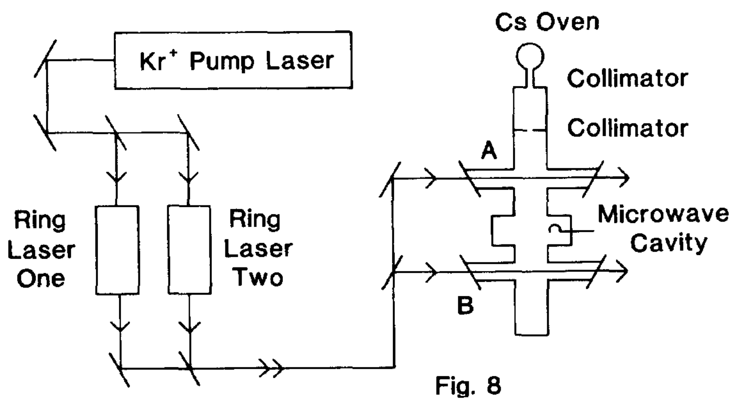


Figure 8. Laser pumped/detected atomic beam.

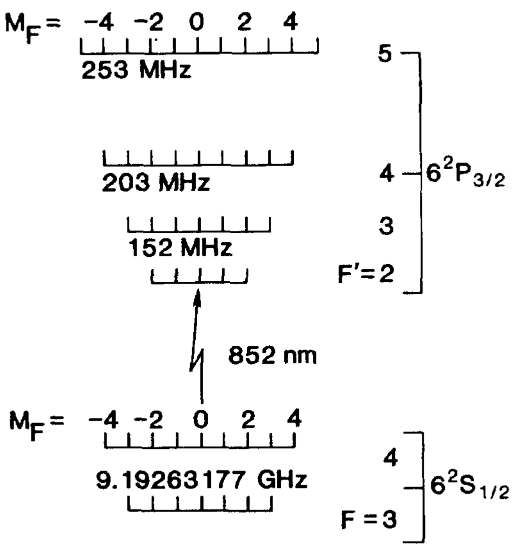
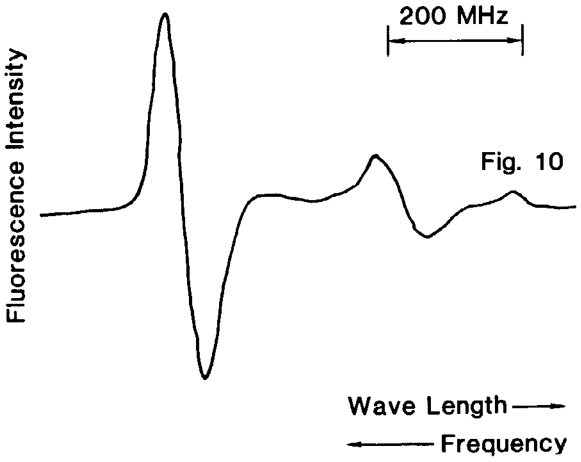
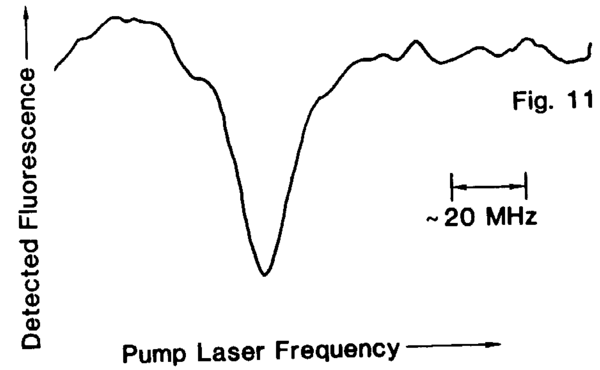


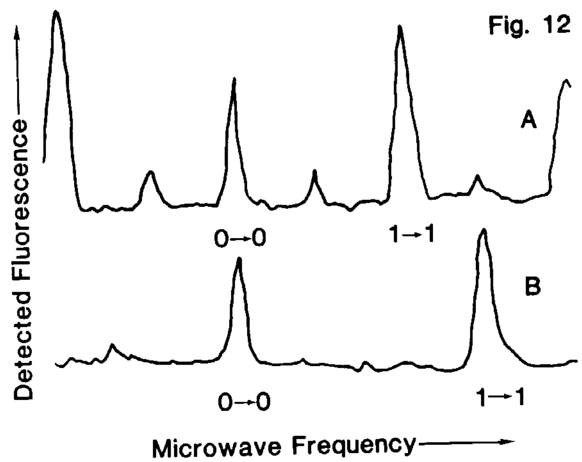
Figure 9. Term diagram for ^{133}Cs.



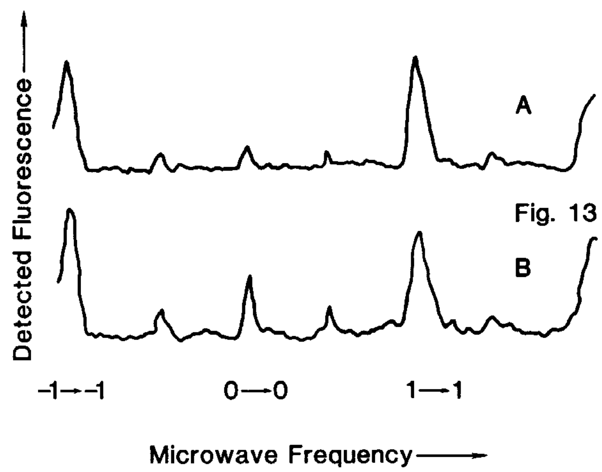
Fluorescence dispersion curve in cesium atomic beam. From left to right, the peaks are F=4 → F'=5,4,3.



Optical pumping upstream of the F=4 → F'=4, D_2 cesium line with fluorescence detection downstream of the F=4 → F'=5 line.



Microwave Rabi spectra for laser pumped cesium beam. The C-field is greater in Curve B.



Microwave Rabi spectra for laser pumped cesium beam. The F=4 → F'=4 pump laser electric polarization is parallel to the C-field in Curve A and rotated by 6 degrees from parallel in Curve B.