DIODE LASER 87Rb OPTICAL PUMPING IN AN EVACUATED WALL-COATED CELL

Wah-Ke[illegible] and H.G. Robinson
Physics Department, Duke University
Durham, North Carolina 27706

C.E. Johnson
Physics Department, North Carolina State University
Raleigh, North Carolina 27650

ABSTRACT

The evacuated wall-coated sealed cell coupled with diode laser optical pumping offers a number of attractive potential advantages for use in Rb or Cs atomic frequency standards. An investigation of systematic effects is required to explore possible limitations of the technique. We report on the use of diode laser optical pumping of ^{87}Rb in an evacuated wall-coated sealed cell. Experimental results/discussion to be presented include the signal strength and line broadening of the 0 – 0 hyperfine resonance as a function of light intensity for the D1 optical transitions (F -> F') = (2 -> 1') and (2 -> 2') : shift of the 0 – 0 hyperfine frequency as a function of laser intensity and detuning from optical resonance ; and diode laser frequency stabilization techniques.

INTRODUCTION

Previously we have observed ^{87}Rb and ^{133}Cs $\Delta m = 0, \pm 1$ hyperfine transitions in an evacuated wall-coated sealed cell (EWSC) of 200cc volume using conventional Rb or Cs rf-excited plasma lamps.[1-3] The use of diode lasers in optical pumping has been reported by other researchers for both Cs and Rb using gas cell or atomic beam apparatus.[4-9] High efficiency optical pumping with diode lasers has been studied theoretically for the EWSC.[10] In this paper, we report on the use of diode lasers in hyperfine pumping an evacuated wall-coated sealed cell of ~ 30cc volume. The frequency of the ground state hyperfine transition $(F, m_F) = (2,0) \leftrightarrow (1,0)$ was monitored permitting a determination of a number of parameters useful in criticizing such wall-coated cells coupled with diode laser signal acquisition as a candidate for use in atomic frequency standards.

APPARATUS

The basic apparatus is shown in Fig. 1. It consists of a diode laser, objective lens, attenuator, evacuated wall-coated cell inside a thermal enclosure, and a photodetector which monitors transmitted light intensity. A Rb side-arm on the cell was maintained at a temperature below that of the enclosure to control the Rb density in the cell. The diode laser is tuned to one of the four resolved D1 (F -> F') optical hyperfine transitions at 794.7 nm. Figure 2 shows the optical transitions available. We report here only on simple pumping with either the (2 <-> 2') or the (2 <-> 1') optical transition using linearly polarized light propagated along the direction of the applied magnetic field.

Light intensity was monitored by measuring the photocurrent resulting from light transmitted through the cell. The conversion factor between current and power is ~ 640μA/mw (or 1.67μw/μA) at 795 nm for unit quantum efficiency at the detector. Typical photocurrents used are 10 μA which implies < 17 μw. The estimated intensity incident on the cell for a 10μA detected current is ~ $100\mu w/cm^2$.

Instead of an inhomogeneous lineshape characteristic of the gas cell, the homogeneous lineshape which results from use of an EWSC is one of its chief advantages. Thus even though light intensity does not uniformly illuminate the EWSC, all atoms interact in the same way with the light due to the averaging which a given atom performs in bouncing against the cell walls. Indeed, it is this averaging which generates the homogeneous Lorentzian lineshape.

RESULTS

The EWSC was maintained at $40^{o}C$ while the Rb side-arm was kept at ~ $22^{o}C$. With the Rb density attained under these conditions and using 10 μA on the (2 <-> 1') transition, the fractional absorption of light with no microwave power was ~ 7.5×10^{-2}. This was determined by a rapid sweep of the laser through the optical resonance - optical pumping effects were present to some degree. The fractional 0-0 signal under a high saturation condition by microwave power was 1.5×10^{-2}. This is taken as evidence of good optical pumping/detection efficiency even at the low light levels used. The long T1 relaxation time available in wall-coated cells implies relatively low light intensity will produce significant level population differences.

The optical hyperfine pumping light which establishes population differences between the F = 2 and 1 levels in the ground electronic state and which provides the means for detecting the 0-0 hyperfine transition in the presence of a resonant microwave field also causes a broadening of the 0-0 resonance. The intrinsic linewidth attained in this cell at ~ 1.5 μA light intensity was ~ 20 Hz. The following increases in the 0-0 width due to light intensity were determined:

(2 <-> 2') => ~ 4 Hz/μA

(2 <-> 1') => ~ 2 Hz/μA .

The 0-0 signal amplitude vs. light intensity is shown in Fig. 3. The Hitachi laser was used in this case. The microwave power was kept at an arbitrary but constant level and was weakly saturating. The klystron signal source was locked to the 0-0 resonance. Note the relatively low light intensities used. The data for the (2 <-> 2') and (2 <-> 1') transitions were taken individually. Both sets of data are plotted on Fig. 3 for convenience.

Two parameters are used for the light-induced frequency shift.[11] The parameter $\alpha(I)$ gives the shift of the 0-0 frequency per unit optical intensity when the optical frequency is tuned to resonance.

$$\alpha(I) = \partial\nu_{o-o}/\partial I$$

Thus the 0-0 frequency shift $\delta\nu_{o-o}$ caused by the resonant light intensity I is given by

$$\delta\nu_{o-o} = \alpha(I) \times I \ .$$

Another parameter β describes the shift of the 0-0 frequency when the optical radiation is de-tuned from resonance,

$$\beta(I) = \partial\nu_{o-o}/\partial\nu_{opt}.$$

The frequency shift due to this effect for a small de-tuning is

$$\delta\nu_{o-o} = \beta \times \Delta\nu_{opt}.$$

A discriminator-like frequency shift of the 0-0 transition is produced for larger de-tuning of the optical resonance.

In Fig. 4 are shown the results of the measurement of the 0-0 frequency vs. light intensity for both Hitachi and Mitsubishi lasers. The slope of this data gives the light shift parameter $\alpha(I)$. Here the klystron was locked to the 0-0 resonance and the laser was locked to the optical absorption resonance in the EWSC itself. Using on-resonance (2 <-> 1') light at ~ 10 µA intensity, a 0-0 shift of ~ - 4.5 Hz was found. Thus a fractional intensity stability of 1.5×10^{-3} will produce a 0-0 fractional shift of 1×10^{-12} at 6.8 GHz under conditions used. The Hitachi laser linewidth was ~ 30 MHZ whereas the Mitsubishi laser linewidth was ~ 100 MHz. Both of these widths were determined for free-running lasers (not locked to an atomic resonance). In spite of the factor of three difference in linewidths, both lasers have almost identical α coefficients, as seen from Fig. 4. Because the lasers were locked to the atomic absorption, narrowing of the spectral width occurs. We have not yet measured the laser linewidths in the locked condition.

Measurements on the second light-shift parameter β were more difficult. In this case neither the laser nor the klystron was locked to the 0-0 transition. The laser was detuned from optical resonance typically by ~ 150 MHz. This is small compared to the optical Doppler width and therefore implies remaining in the linear region of the discriminator shaped 0-0 shift curve. Figure 5 shows results for the (2 <-> 2') and (2 <-> 1') transitions where β is found at a given light intensity by dividing the observed 0-0 frequency shift by the laser detuning from optical resonance. The β-coefficient has also been reported for Rb gas cell devices.[5,7] Table I compares data obtained from the indicated sources.

Table I. Comparison of β-coefficient for gas cells and the EWSC.

Reference	Cell Type	Optical Transition F -> F'	Incident Intensity µw/cm^2	$\lvert\beta\rvert$ Hz/MHz	$\lvert\beta\rvert/I$ mHz-cm^2/MHz-µw
5	gas	2->1',D2	280	0.63	2.25
7	gas	1->2',D1	300	0.41	1.37
This paper	EWSC	2->1',D1	100	0.025	0.25

Using this data a comparison between the gas cell and the EWSC is difficult since different conditions were used in each case. Nevertheless, a β normalized to unit intensity is calculated in the last column. In this Table, our transmitted intensity of ~ 85µw/cm^2 (as inferred by ~ 10µA photocurrent) was taken to imply ~ 100µw/cm^2 intensity incident on the glass cell.

DIODE LASER STABILIZATION

A description has been given by Lewis and Feldman[5] on the use of diode lasers in atomic frequency standards. They reported long-term locking of the laser to an atomic absorption line. Other researchers have also reported locking diode lasers.[12,13] For the initial determinations reported in this paper of various parameters characterizing the 0-0 hyperfine transition in the EWSC, it was convenient to stabilize the diode laser to the Rb optical absorption of interest. Methods useful for this purpose are presented briefly.

Two diode laser stabilization schemes have been implemented. For apparatus simplicity, the first scheme uses the normal Doppler broadened optical absorption in the EWSC itself. (A separate non-wall-coated cell could have been used.) The other scheme uses Doppler free saturated absorption in a separate cell. Both of these methods require that the laser be frequency modulated in order to interrogate the optical line center.[14] Long-term drift is tuned out by a temperature servo and short-term noise is removed by feedback to the laser current.

The block diagram for the basic scheme to observe saturated absorption[15] is shown in Fig. 6. To suppress the non saturation features, the saturating beam can be chopped. This selectively modulates the saturation effect. Subsequent lock-in detection produces the sub-Doppler features shown in Fig. 7c. Also shown is the normal Doppler broadened absorption signature (Fig. 7a) and the absorption-saturation signature without suppression of background (Fig. 7b). All of these traces are shown using wide-band (5 kHz) signal recovery channels. Either the 7b or 7c signature can be used to lock the laser. With the β-coefficient measured for the 2 -> 1' optical transition at 10 μA intensity, a signal-to-noise ratio of ~ 145 would be required to stabilize the laser so that the 0-0 frequency would be stable to 1 part in 10^{-12}. Adequate S/N appears to be present.

Figure 8a shows the block diagram of the system used in acquiring most of the data presented in this report. Both the laser and the klystron were locked to the Rb atoms. Figure 8b shows the saturated absorption laser lock diagram.

CONCLUSIONS

Several parameters have been determined relating to the potential for use of the evacuated wall-coated sealed cell coupled with diode laser signal acquisition in an atomic frequency standard. This work may be regarded as preliminary -- measurements need to be repeated, refined, and expanded. The encouraging results on the 30cc cell provide excellent motivation for continued research.

ACKNOWLEDGEMENTS

Work supported in part by Frequency and Time Systems, Inc. and by the Duke University Research Council.

REFERENCES

1. H.G. Robinson and C.E. Johnson, Appl. Phys. Lett. 40, 771(1982).
2. H.G. Robinson and C.E. Johnson, Proc. 14th PTTI, 307(1982).
3. H.G. Robinson and C.E. Johnson, IEEE Trans. Instr. Meas., IM-32, 198(1983).
4. M. Arditi and J.L. Picque, J. de Phys. Lett. 41, L370(1980).

5. L.L. Lewis and M. Feldman, Proc. 35th Annual Freq. Control Symposium, 612(1981).

6. M. Feldman, J.C. Bergquist, L.L. Lewis, and F. Walls, Proc. 35th Annual Freq. Control Symposium, 625(1981).

7. C.H. Volk, J.C. Camparo, and R.P. Frueholz, Proc. 13th PTTI, 631(1981).

8. J.C. Camparo, R.P. Frueholz, and C.H. Volk, Proc. 14th PTTI, 113(1982).

9. J.C. Camparo and C.M. Klimcak, Am. J. Phys. 51, 1077(1983).

10. C.L.J. Newton and H.G. Robinson, Proc. 14th PTTI, 133(1982).

11. These parameters are defined for continuous optical pumping. Detection by pulsed optical pumping would apparently eliminate light shifts.

11. H. Tsuchida, M. Ohtsu, T. Tako, N. Kuramochi, and N. Oura, Jap. J. Appl. Phys. 21, L561(1982).
These authors locked the laser to a normal absorption in ^{85}Rb on a D_2 line. They reported an abnormal saturation absorption signature.

13. T. Yabuzaki, A. Ibaragi, H. Hori, M. Kitano, and T. Ogawa, Jap. J. Appl. Phys. 20, L451(1981).
Authors used a saturated absorption feature in Cs to lock to a D_2 line.

14. Optical heterodyne saturation is another method available if FM on the laser is objectionable. Unmodulated laser output is produced. See for example J.L. Hall, L. Hollberg, Ma Long-sheng, T. Baer, and H.G. Robinson, J. de Phys., Colloque C8, 59(1981).

15. For example see F.T. Arecchi, F. Strumia, and H. Walther, Advances in Laser Spectroscopy, Plenum Press (1983);
or Wolfgang Demtroder, Laser Spectroscopy, Springer-Verlag (1981).

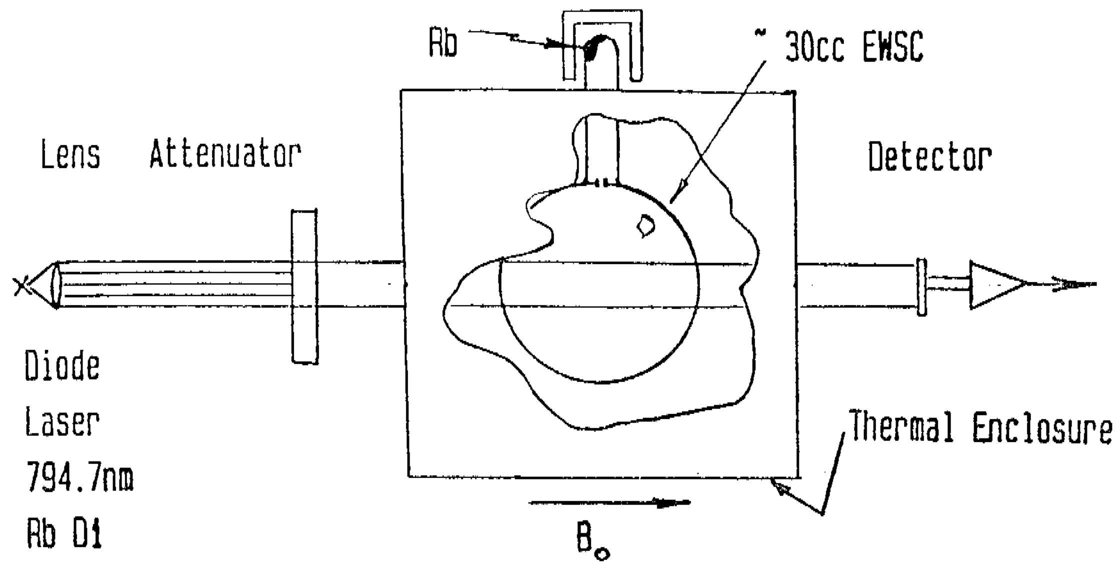

Figure 1. Schematic of basic optical pumping apparatus used with the EWSC. The thermal enclosure was operated at 40C while the Rb was maintained at 22C.

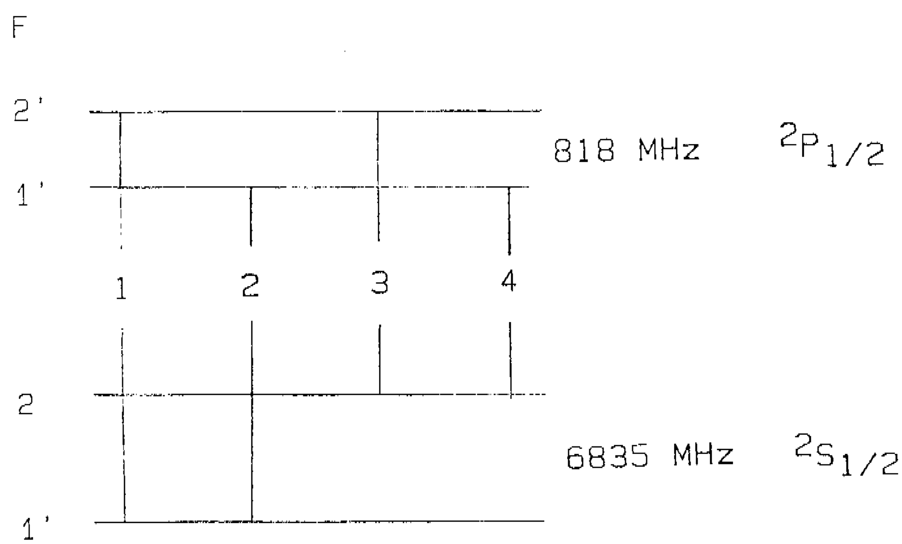

Figure 2. Rb D1 optical transitions available. The (F - F') = (2 - 2') and (2 - 1') transitions were used for this work.

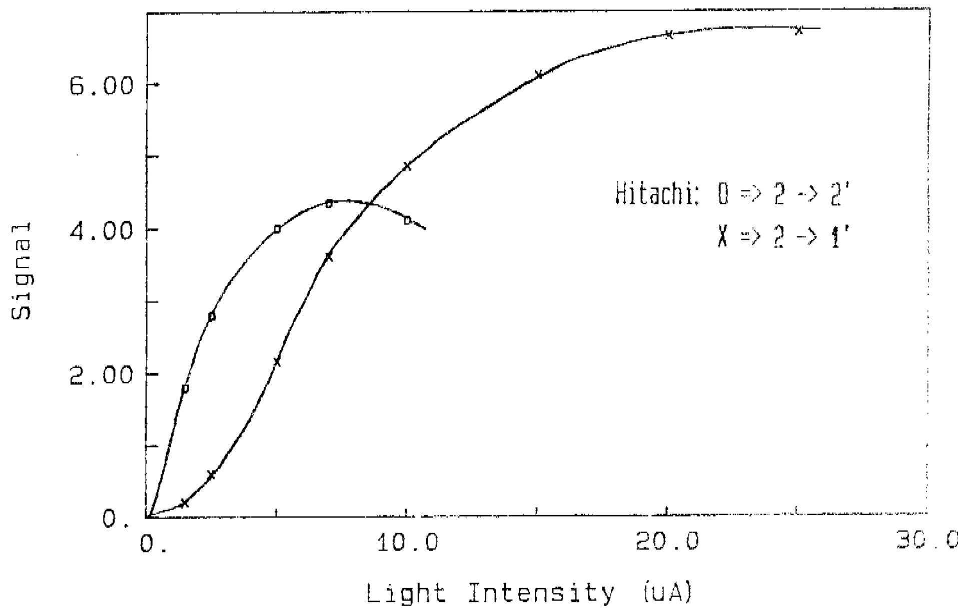

Figure 3. The 0-0 hyperfine signal vs. light intensity at a weakly saturating microwave power.

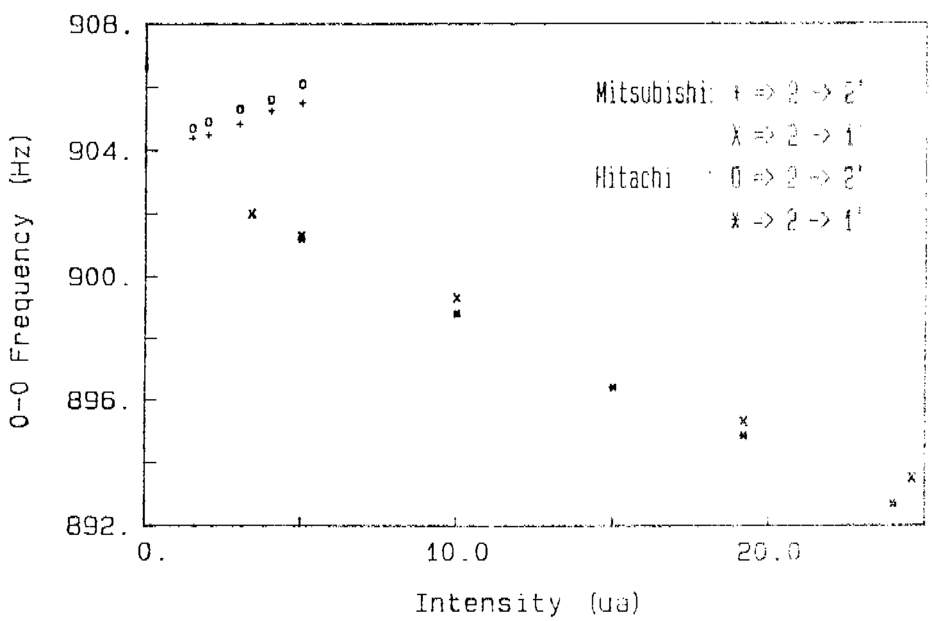

Figure 4. The 0-0 frequency vs. light intensity as a function of optical transition and type of laser used. The slope of this data gives the light shift parameter $\alpha(I)$. This data was taken with the laser locked to the Rb optical absorption and the klystron locked to the 0-0 hyperfine transition.

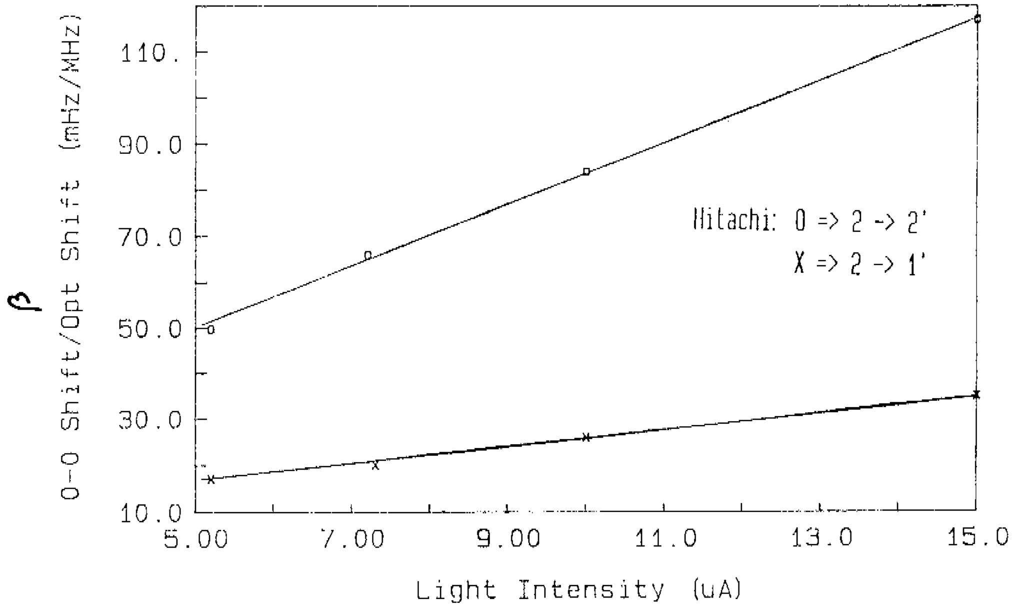

Figure 5. Light shift parameter $\beta = \partial\nu_{00}/\partial\nu_{opt}$ as a function of light intensity. Data used optical detuning of ~150MHz, small relative to the optical Doppler width.

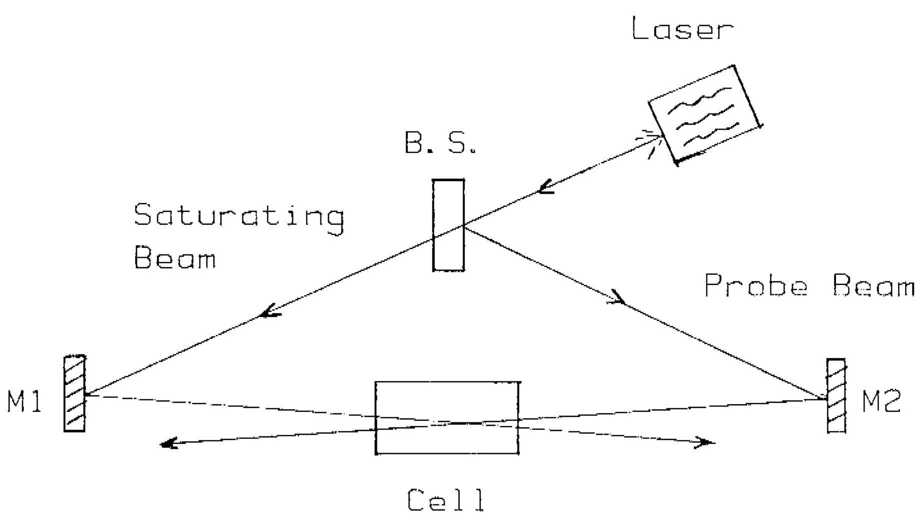

Figure 6. Block diagram for observation of saturated absorption features.

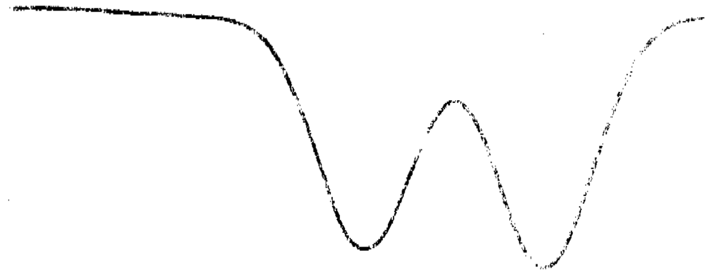

Figure 7a. Normal Doppler broadened absorption.

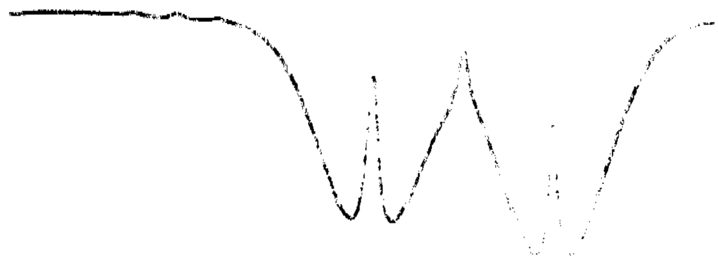

Figure 7b. Absorption-saturation signal.

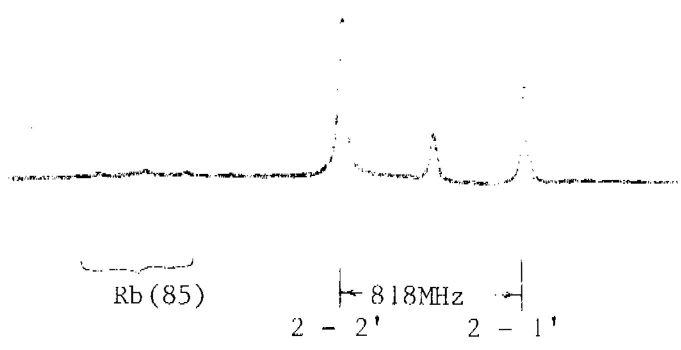

Figure 7c. Saturation feature observed with 5kHz bandwidth.

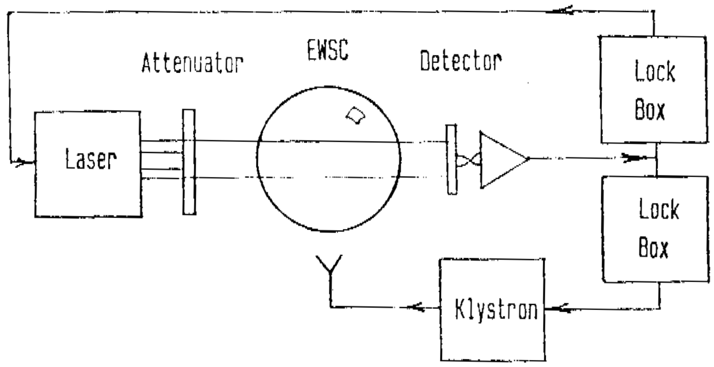

Figure 8a. Block diagram of system used to lock both laser and klystron to Rb.

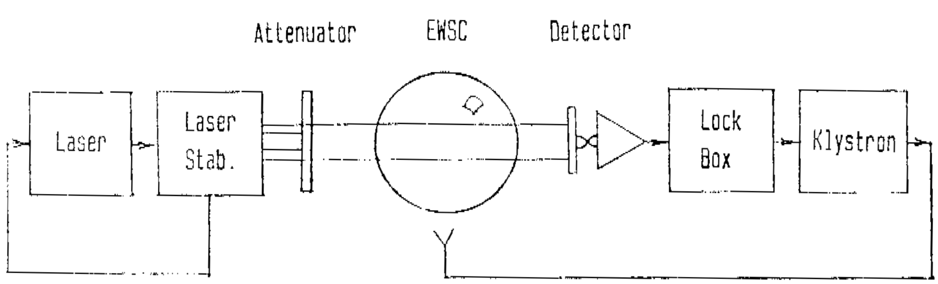

Figure 8b. Block diagram showing saturated absorption laser lock.

QUESTIONS AND ANSWERS

JACQUES VANIER, NATIONAL RESEARCH COUNCIL: Your alpha coefficient, could it be due to distortion of the spectrum of the laser diode?

MR. ROBINSON: I would have to go back to Will Happer who has worked out the theory for light shifts. He has worked out a theory using operator formalism which is an easier thing to grab hold of, and they are relatively complicated. The thing that Happer actually worked out was for light that was very broad compared to the hyperfine separation, and here we have exactly the opposite case. We have light that's narrow compared to the hyperfine separation. The theory is right. There is no question that the theory is going to work if you actually try and calculate it, I think.

There are several different effects that shift the thing. One is a second order Stark effect. You actually have applied an AC field to this ground, and you are actually tickling levels up and down, and you see then the average result of that. That's one of the ways you can get a light shift. There are virtual transitions, there are tensor shifts, there are all sorts of shifts that come in. Usually the tensor shifts have been neglected, but apparently in this case they may not be able to be.

The point is that you can get around them if you need to by using pulsed light, but they certainly are in all of these other systems. The gas cell has these things in there. It's just that you don't see them. They are masked by other things.

It just explores an explicit parameter that needs to be looked at in an evacuated wall-coated cell.

CARROLL ALLEY, UNIVERSITY OF MARYLAND: Did I hear you say a twenty Hertz linewidth?

MR. ROBINSON: Yes.

MR. ALLEY: That's for 6835?

MR. ROBINSON: That's for the 6835 line. You heard right.

MR. ALLEY: That sounded very good.

MR. ROBINSON: This stuff works.

MR. ALLEY: Oh yes, we know. What wall coating were you using?

MR. ROBINSON: This is still the same old wall-coating, Tetracontane, and I don't have any idea that that is the best wall-coating. It's just that we are moving relatively slowly, doing one thing at a time, and we had gotten that to work before, so that's what we tried again.

So this is the first one -- we had a 200 cubic centimeter cell that's about fifteen years old that is sealed off. These cells are absolutely sealed. There is no vacuum system associated with them. You can carry them around in your fingers. That's the cell that we have talked about here.

So they apparently have longevity. There are a lot of questions -- Harry Peters asked one today about what happens in the time history of these things. We don't know that yet. We haven't gotten there yet. That's still to come, clearly. But everything we do seems to be very attractive so far in getting the system to work.

MR. ALLEY: I will give you a thirty year old cell and see if it will work.

MR. ROBINSON: I should say that Carrol Alley tried pumping with lasers, diode lasers, and what we have done here is certainly not unique. There are several Japanese authors that have locked lasers to saturated absorption things. I know people at N. B. S. have done that. Lyndon Louis has done that, we are just following in the track.

I think that we may have some really gorgeous curves. I am not sure that anybody else has anything comparable to this sort of beautiful saturated absorption curve. I haven't seen it anyway. But the stuff just works. It's just gorgeous.

MR AUDOIN: There is a third resonant feature on your curve. Is that a level crossing?

MR. ROBINSON: The third resonant feature? Oh, in the saturated absorption curve. That's called a cross-over resonance, and it's nothing particularly unusual. I would like to explain that to you. The saturated feature, or curves are only for certain atoms. Since the two beams are shot through in opposite directions, the only atoms they both talk to are those which are moving perpendicular to both beams. In other words, the non-doppler shifted thing. That's the reason you get the main saturated absorption feature, which doesn't have any Doppler width to speak of.

The other resonance occurs when two opposite curves cross over, and those tails can be made to do the same thing. That's an artifact, it's not really a resonance. You don't want to lock on that, you want to lock on the two central ones.