# INVESTIGATIONS OF LASER PUMPED GAS CELL ATOMIC FREQUENCY STANDARD

C. H. Volk, J. C. Camparo and R. P. Frueholz
The Aerospace Corporation, P.O. Box 92957, Los Angeles, CA 90009

## ABSTRACT

Recently it has been suggested that the performance characteristics of a rubidium gas cell atomic frequency standard might be improved by replacing the standard rubidium discharge lamp with a single mode laser diode. Since the short term stability of the rubidium frequency standard is limited by the shot noise of the photodetector,[1] an increased signal to noise ratio, from the more efficient laser diode pumping, might significantly improve the short term performance. Because the emission wavelength of the laser diode can be tuned, improved long term performance could be attained through the control of the light shift effect. However, work done by Lewis et al[2] at NBS Boulder indicates that a new source of instability is present in the laser pumped clock; the frequency instability of the laser induces instability in the frequency standard.

We have been investigating various aspects of the laser pumped gas cell atomic clock. Our investigations include effects due to laser intensity, laser detuning and the choice of the particular atomic absorption line. Our studies indicate that the performance of the gas cell clock may be improved by judicious choice of the operating parameters of the laser diode.

The laser diode has also proved to be a valuable tool in investigating the operation of the conventional gas cell clock. Our results concerning linewidths, the light shift effect and the effect of isotopic spin exchange in the conventional gas cell clock are reported here.

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## INTRODUCTION

The recent advances that have been made in the semiconductor laser diode technology have been followed very closely by numerous applications for this type of laser in practical devices. The laser diode is extremely attractive because it possesses the features of high light intensity in a small package requiring only moderate to low power for operation.

The rubidium gas cell atomic clock is one such device, among others, that could possibly be improved by the incorporation of a laser diode which would be used in place of the conventional rubidium discharge lamp. Figure 1 is a schematic representation of the rubidium gas cell clock. In the 'classic' design of the clock,[1] the physics package consists of an optical absorption cell contained within a microwave cavity, a hyperfine filter cell and a rubidium lamp providing the optical pumping radiation. The absorption cell and the lamp usually contain $^{87}$Rb while the hyperfine filter employs the $^{85}$Rb isotope. A simplification of this design uses an 'integrated' absorption cell in order to avoid the necessity of the hyperfine filter cell.[2] From Figure 1, it is readily apparent that the use of a laser diode as the optical pumping source in the rubidium clock could be quite beneficial. The laser would provide a much more intense beam of light with better collimation and a spectral linewidth sufficiently narrow to allow for the elimination of the filter cell. Additionally, because of the tuneability of the laser diode, frequency offsets due to the light shift effect could be readily controlled.

Although the idea of using laser diodes in place of discharge lamps is not a new idea, it has only been very recently that single mode laser diodes of sufficiently long life have become commercially available at prices that make their use somewhat reasonable. In addition to our effort in this area at The Aerospace Corporation, there is a very active effort at NBS Boulder to investigate the possible uses of laser diodes in atomic clocks.[3]

However, as is normally the case, no simple substitution of one component in a device for some other, although much better, component is ever possible. The new component itself, in this case the laser diode, must be made to conform to the constraints of the device; the clock. Additionally, new aspects of the device normally appear upon the incorporation of the improved component. We report here on our observations of new characteristics of the rubidium clock when operated using a laser diode pump source.

## DISCUSSION

Our experimental apparatus is shown schematically in Figure 2. The emission from a Mitsubishi ML 4001 GaAlAs laser diode was collimated and used to illuminate the absorption cell of an Efratom FRK-L rubidium frequency standard. This particular standard employs the integrated absorption cell. The laser diode linewidth was measured to be approximately 400 MHz and the laser provided output power of up to 6 mW/cm$^2$. The rubidium lamp from the frequency standard was removed to allow access for the laser light. Since the laser diode electronics were sufficient to keep the wavelength of the laser from drifting for about an hour, no further wavelength stabilization of the diode was used for these particular experiments. The laser diode was tuned to the proper hyperfine absorption line of the $^{87}$Rb by observing the transmitted light through the absorption cell, and due to the particular diode used we tuned to the D$_1$ ($5S_{1/2}$-$5P_{1/2}$) resonance of rubidium at 794.7 nm. The 10 MHz clock frequency was monitored with an HP-5345A frequency counter and a gate output indicated locking of the crystal frequency to the rubidium hyperfine transition.

Figure 3 shows the absorption spectrum of the gas cell as the laser was tuned across the D$_1$ resonance. The two central peaks at a tuning of 2 and 5 GHz correspond to the F = 3 and F = 2 hyperfine absorption lines of the $^{85}$Rb present in the cell for the normal operation of this clock. The shoulder that appears on the F = 3 hyperfine line of the $^{85}$Rb near 0.5 GHz corresponds to the F = 2 hyperfine line of $^{87}$Rb, and the peak at 7.3 GHz corresponds to the F =1 hyperfine line of $^{87}$Rb. This line appears to be asymmetric because of the unequal contributions from the two hyperfine states of the first excited state.

Figure 3 also shows those regions of laser tuning where the clock locked, and it should be remembered that the clock will only lock when there is a population imbalance between the two $^{87}$Rb hyperfine states. Not surprisingly, the figure clearly shows that the clock locked when the laser was tuned to either of the $^{87}$Rb hyperfine absorption lines. However, when the laser was tuned to the F = 3 absorption line of $^{85}$Rb, the clock locked to the $^{87}$Rb microwave resonance. This effect shows that hyperfine polarization is being shared between the $^{85}$Rb and $^{87}$Rb populations. The most obvious mechanism to account for this sharing of polarization is spin-exchange between the two isotopes.[4] The presence of spin exchange between the $^{85}$Rb and $^{87}$Rb may result in a frequency shift in the clock that is proportional to the rubidium density. Whether this proposed frequency shift has any deleterious effect on the operation of the clock is not presently known.

Our preliminary investigation of the light shift effect in the gas cell clock involved its dependence on laser intensity and wavelength. The laser diode emission was first centered on the F = 1 $^{87}$Rb absorption line and then subsequently tuned to the high and low side of this line. The laser intensity was 6 mW/cm$^2$. Since the 10 MHz output and the Rb hyperfine transition frequency are directly proportional, it is a straightforward procedure to relate a change in the clock's output to a shift in the Rb hyperfine transition frequency. The results of this light shift measurement are displayed in Figure 4.

From top to bottom the four curves of Figure 4 represent laser detuning from the $5S\frac{1}{2}$ (F = 1) - $5P\frac{1}{2}$ (F = 2) resonance of approximately -700 MHz, -200 MHz, 0, and +200 MHz respectively. All of these curves show the same general behavior: they are linear at low laser intensity, reach an extremum, and finally saturate to a light shift value dependent only on the laser detuning from the atomic resonance. The linearity of these curves at low light intensity and their symmetry about zero frequency detuning are consistent with the standard theory of light shifts first developed by Barrat and Cohen-Tannoudji[5] and treated semi-classically by Happer and Mathur.[6] We believe that the new features of the light shift curve, the extrema and saturation regions, are due to an Autler-Townes type splitting[7,8] of the microwave resonance. This splitting would occur because the microwaves are no longer probing a nearly unperturbed Rb atom; they are probing a Rb atom while it is interacting with the intense laser emission. Arditi and Picque proposed a similar mechanism for distortions that they observed in the microwave signals from a Cs vapor optically pumped with a GaAs laser diode[9], and we have seen similar distortions in our microwave lineshapes.

As evidenced by Figure 4, the light shift is a sensitive function of laser frequency detuning. In fact, even when the laser is tuned on resonance there is a very small light shift effect which we believe is due to the overlap of the $^{87}$Rb ($5S\frac{1}{2}$ (F = 1) - $5P\frac{1}{2}$ (F = 1 and 2) ) absorption lines. In order to more fully understand the effect of laser detuning, we measured the light shift as the laser was tuned across the F = 1 hyperfine resonance for a fixed laser intensity. Figure 5 shows the results of one such experiment where the relative laser intensity was held fixed at about 0.3 mW/cm$^2$ and the zero of frequency detuning corresponds to the $5S\frac{1}{2}$ (F = 1) - $5P\frac{1}{2}$ (F = 2) atomic resonance. The solid curve is a calculation of the light shift as a function of detuning based on the theory of Happer and Mathur. The discrepancy between theory and experiment in the region of large negative detuning may be due to spin exchange shifts resulting from the pumping of $^{85}$Rb by the wing of the laser line. We presently do not have enough data to definitively determine the origin of this discrepancy.

Two important factors which effect the shape of Figure 5 are the excited state hyperfine splitting and the broad laser line. It is the combination of these two factors which produces the nearly flat region at a laser detuning of $\sim -.015\,\text{cm}^{-1}$ (-450 MHz), and indicates that the atomic hyperfine frequency is relatively insensitive to slight changes in the laser frequency. We refer to this flat region as the "decoupling" region, since the clock frequency could be considered as decoupled from laser frequency noise if the laser was tuned into this region.

The two curves of Figures 4 and 5 suggest a novel technique for operating a laser diode gas cell clock which might result in improved performance. The laser diode would be operated at high intensity so as to be in the saturation region of Figure 4, and detuned into the decoupling region of Figure 5. In this way the atomic response to the optical pumping conditions would decouple laser intensity and frequency noise from the clock output. We are in the process of performing Allan Variance measurements on a gas cell clock operated with this optical pumping scheme, and the results will determine if any improvement occurs.

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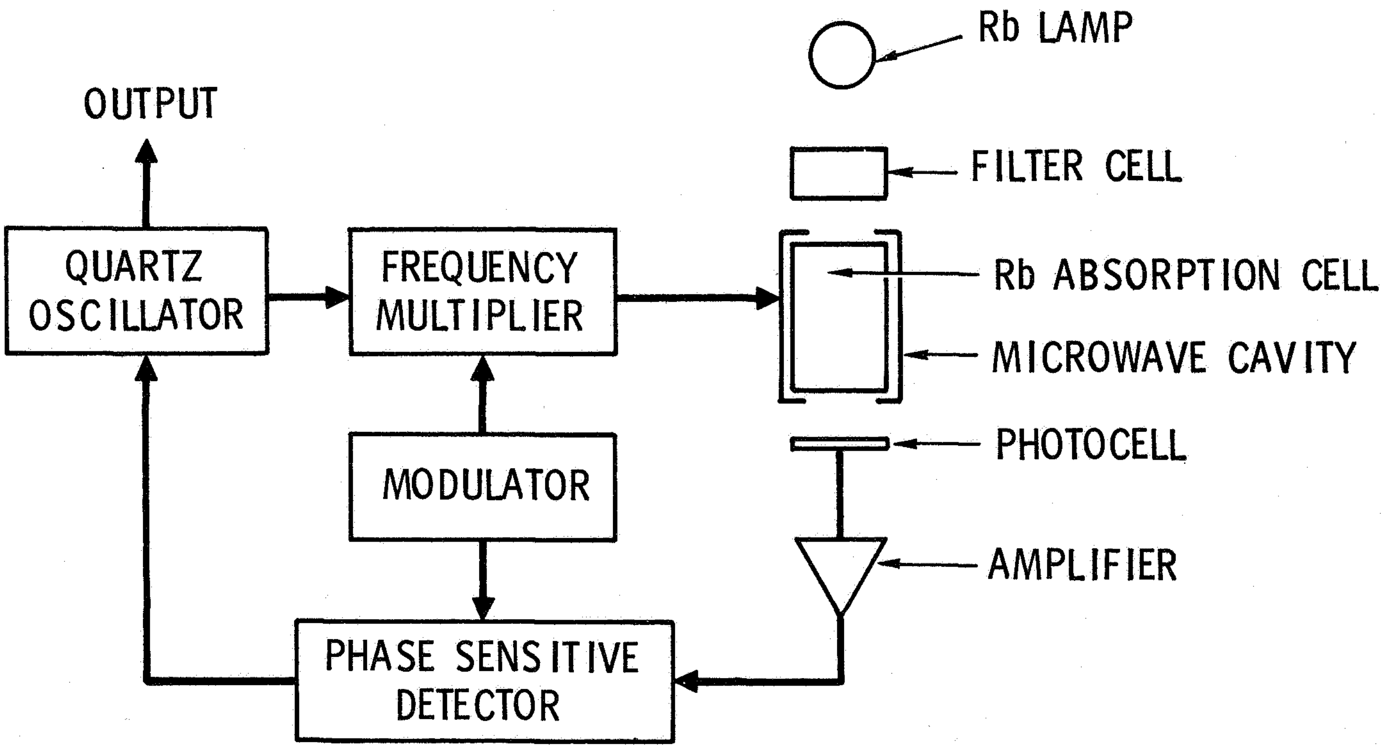

Figure 1. Schematic Diagram of a Passive Rubidium Gas Cell Frequency Standard

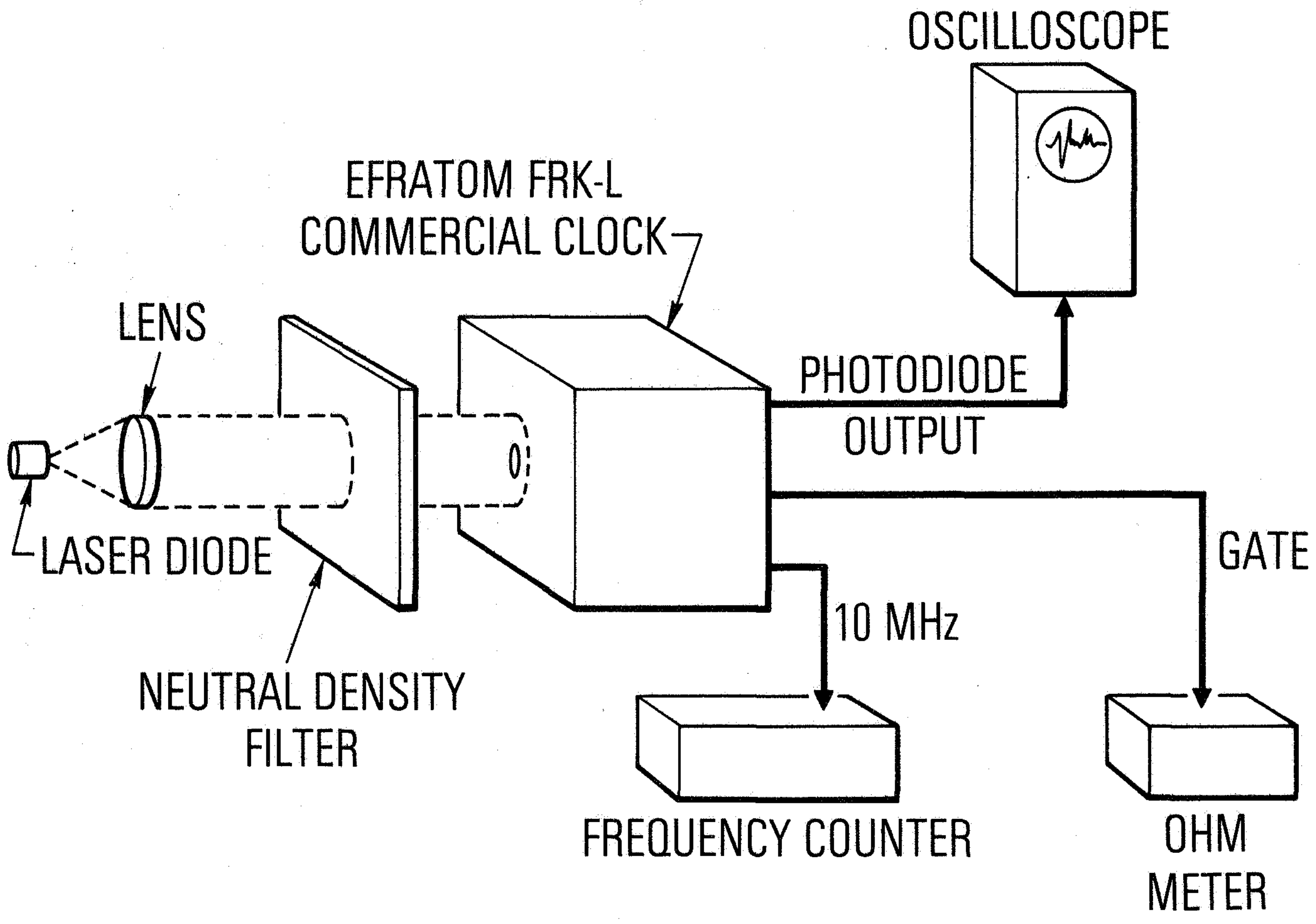

Figure 2. Schematic Diagram of the Experimental Apparatus

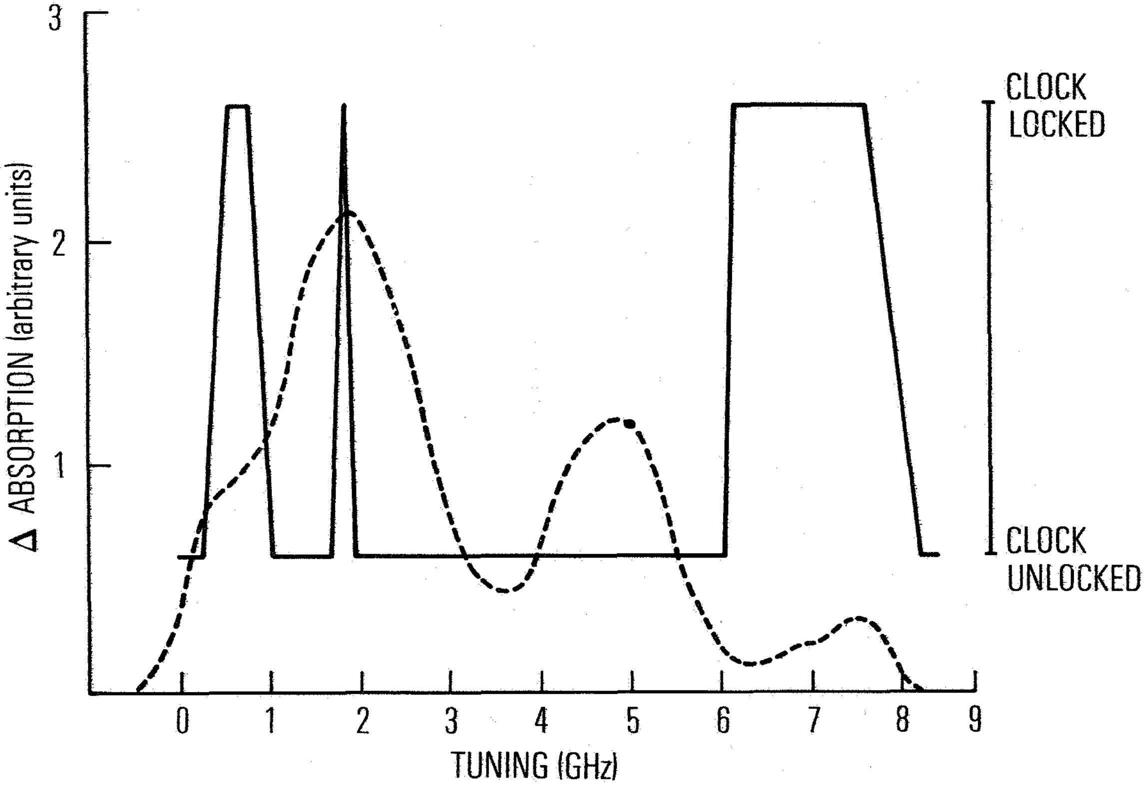

Figure 3: Rb absorption spectrum in the integrated cell showing the hyperfine structure of both $^{87}$Rb and $^{85}$Rb. The solid line represents the locked condition of the clock. This was determined by observing the current flow in the phase lock indicator. We observed conditions between unlocked and full-lock of the feedback loop, and thus this plot essentially maps potential operating points of the clock.

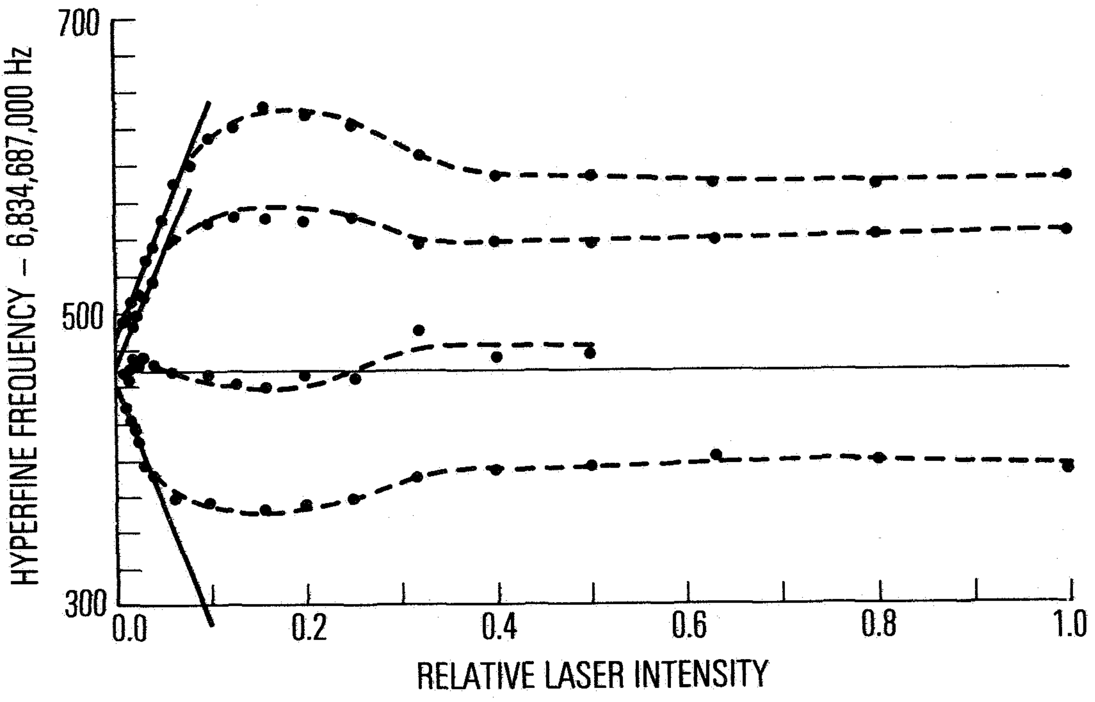

Figure 4: Microwave resonance frequency as a function of light intensity for various laser detunings from the $5S\frac{1}{2}$ (F = 1) - $5P\frac{1}{2}$ (F = 2) optical resonance. The detunings from top to bottom are = -700 MHz, -200 MHz, O, and 200 MHz. Maximum laser intensity is 6 $mW/cm^2$. The solid lines are linear fits of the low intensity light shift points. This linear relationship is expected from the classic theory of the light shift effect. The dashed lines are for the convenience of the reader to follow the light shift along a particular laser detuning.

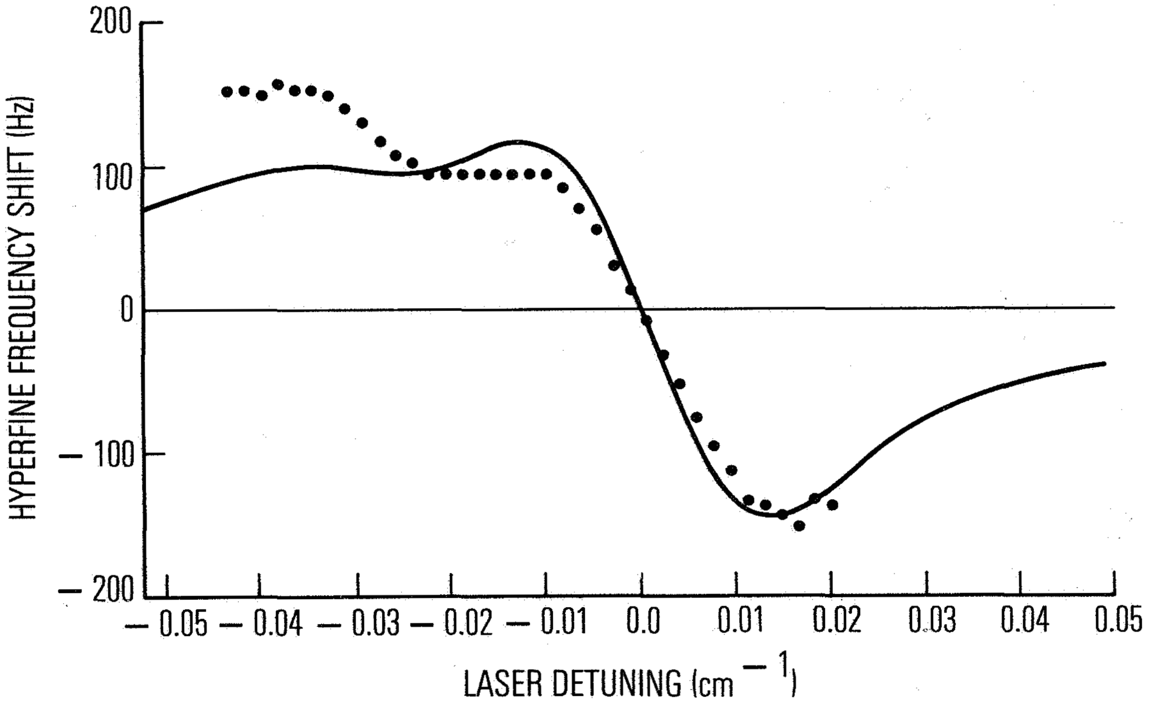

Figure 5: Microwave resonance frequency shift as a function of laser detuning for a fixed relative intensity of about 0.3 mW/cm$^2$. The zero of detuning corresponds to the 5S $\frac{1}{2}$ (F = 1) - 5P $\frac{1}{2}$ (F = 2) optical resonance, and the solid curve is a theoretical estimate of the light shift.