PHYSICS ELEMENT DESIGN ASPECTS FOR A TACTICAL RUBIDIUM FREQUENCY STANDARD

Bruce Grover and Tae M. Kwon

Litton Industries
Guidance and Control Systems
5500 Canoga Avenue, Woodland Hills, California 91365

ABSTRACT

The rubidium frequency standard to be used in tactical applications must be capable of satisfying frequency stability specifications under severe environmental conditions which include a high ambient temperature. This has resulted in a physics element design of lamp, separated filter and resonance cell which operates above the highest ambient temperature, with a simple oven structure. This design differs from previous rubidium standards primarily in its smaller size and higher operating temperatures. The Litton tactical rubidium frequency standard physics element parameters and their effects on frequency stability are presented in this paper.

INTRODUCTION

Guidance and Control Systems Division of Litton Industries has developed a modular rubidium frequency standard for tactical military applications. Frequency standards for tactical applications demand small size, rapid warmup, low power consumption, and extreme ruggedness along with medium frequency stability. The frequency standard to be used in tactical applications must be capable of operating under severe environmental conditions which include extreme temperatures. Specifications call for a broad operating temperature range and for baseplate temperature as high as 80°C. Temperature stability of the physics package elements: lamp, filter cell and resonance cell can be maintained over the environmental range by operating these elements at temperatures above 80°C. This approach leads to a simpler oven design and compliance with the power budget. To date, rubidium standards have operated with resonance cells at temperatures below 70°C and an optical path length between 0.5 and 1.0 inches. As this temperature increases, the ideal balance between absorbed and transmitted light necessary for adequate signal to noise, and hence short term frequency stability, can best be maintained by decreasing the optical path length dimension of the cell. Since rubidium density increases by two for each 9°C increase in temperature, operation above 80°C might require a resonance cell with path length dimension below 0.25 inches. This is a region where signal loss mechanisms due to rubidium interaction with the cell walls becomes increasingly important. Regardless of the operating temperature, a practical rubidium standard must operate with low frequency sensitivity to temperature (temperature turning point) and rubidium light intensity (light turning point). For these reasons, a portion of our program has been devoted to a study of these physical processes, including a parameterization of the light and temperature turning points as a function of system variables. Much of this work may be found in a final technical report.[1] We wish here to examine the Litton tactical rubidium standard physics element parameters and their effect on frequency stability. Where possible a physical explanation for these dependencies will be given.

EXPERIMENTAL SET-UP

The experimental set-up is shown in Figure 1. The physics package is placed inside a large cylindrical mu-metal shield. A pair of helmholtz coils located inside of the shield provides the static dc magnetic field. 10 MHz signal from a Cs frequency standard provides the reference to the frequency synthesizer and the input to the frequency multiplier. Outputs of the multiplier, 120 MHz, and of the synthesizer, f_1 approximately 5.3 MHz, are mixed at a mixer to generate f_2 = 120 MHz $\pm f_1$.

In order to interrogate the atomic resonance at 6.8 GHz, the frequency f_2 is further multiplied by a step recovery diode in the microwave cavity. The cavity is tuned to select the lower sideband, f_3, of the 57th harmonics of f_2, i.e., f_3 = 57 x 120 MHz - f_1. For f_1 being 5,312,500 Hz, f_3 becomes 6,834,678,500 Hz. In this set-up, the interrogation frequency can be varied by varying the synthesized frequency f_1. Phase modulation of the interrogation frequence is accomplished by modulating f_1 at the frequency synthesizer. Both frequency f_m and depth of modulation are readily adjustable at the lock-in amplifier. The resonance signal detected in the photodiode contains both in-phase and quadrature-phase components with respect to the modulation. The quadrature signal is detected at the lock-in amplifier. The ^{87}Rb resonance dispersion curve is obtained in an x-y recorder by plotting the signal amplitude as a function of the interrogation frequency f_3.

The physics package consists of three physics elements: lamp, filter cell and resonance cell, and is shown in Figure 2. Later studies were made using a modification of this unit with both filter and resonance cell inside the microwave cavity. The entire physics package is assembled within two layers of magnetic shield, the outer dimension of which measures 1 1/4 x 1 1/4 x 3 inches.

The lamp consists of a 1720 glass blank, 1/2 mm wall, of cylindrical shape 9 mm diameter and 10 mm overall length with a slight convex exit window and pinchoff at the opposite end. About 100 micrograms of isotopically pure ^{87}Rb is filled with 2.5 torr of buffer gas. The lamp is excited in a helical resonator driven by a modified Colpitts oscillator at ~90 MHz. Lamp luminance for D_1 and D_2 rubidium radiation increases with lamp temperature over the range of interest, here 100°C to 120°C. Lamp temperature is monitored and controlled closely to maintain a constant spectral output. Filter cells used in this study are made from 12 mm diameter 1 mm wall glass tubing cut to length with 1 mm glass disks attached as end windows. The fill stem is attached on the side wall of the filter. Filter cells used in this work range from 7 mm to 9 mm overall length and are filled with isotopically pure ^{85}Rb and either Ar, N_2, or both gases. The filter cell temperature is controlled and monitored in the range 85°C to 92°C. The filter cell serves two primary functions. One is to establish enough preferential optical pumping of the F=1 hyperfine level over the F=2 level for sufficient signal to noise ratio. The second function is to establish a spectral condition for minimum dependence of rubidium resonance frequency on light intensity. Resonance cells used in this work are made of glass in a fashion identical to our filter cells. These cells range from 8 mm to 10.5 mm in length and are filled with isotopically pure ^{87}Rb and varying amounts of N_2 and Ar, approximately 10 torr N_2 and 14 torr Ar.

The resonance cell is placed in a small rectangular microwave cavity operating in the TE_{101} mode.[2] The cavity is partially loaded with a low loss dielectric slab. A 0.3" diameter in each end of the cavity allows light to pass through the resonance cell and be collected at a photo cell mounted on the outside of the cavity. Two 10 mm diameter plano-convex lenses are placed in the cavity to optimize the optical process. Table 1 lists some of the physics package parameters used in this work.

LIGHT SHIFT

To minimize dependence of clock frequency on rubidium light intensity, the physics package parameters are adjusted to allow unit operation at the so called light turning point where light shift, i.e., the change in clock frequency with light intensity, is zero. All physics package parameters that we have studied appear to influence the light turning point (LTP) to some extent, however the filter cell parameters: length, temperature and buffer pressure have the greatest effect. Figure 3 shows light shift as a function of filter length for several cavity temperatures and constant pressure. Light shift here is defined as the change in resonant frequency with a 15% change in light intensity. Figure 4 gives cavity temperature at the LTP as a function of filter cell length. Figure 5 shows light shift versus buffer pressure based on N_2 buffered filter cells and shows the trend in light shift over a wide pressure range. In general, we observe that light shift changes sign on passing thru a LTP indicating that the integrated light shift spectrum also changes sign. This is to be contrasted with light shift which asymptotically approaches zero from one side only. This behavior as a function of the filter pressure parameter is shown in Figure 6.

Since data for Figures 3 and 4 was taken from an integrated cavity configuration, the temperature dependence indicated could in general arise from both filter and resonance cells. However, separated measurements as in Figure 7 indicate that light shift is a weak function of resonance cell temperature in this range.

Light shift is also influenced by lamp temperature. Figures 8 and 9 show clock frequency and light shift versus lamp temperature, respectively, and indicate that both frequency and light shift increase positively with lamp temperature in the region of a light turning point. Figure 10 relates light shift to the RB87 lamp sprectrum filtered by a RB85 filter cell and provides a qualitative understanding of the light shift vs. filter pressure, length and temperature behavior shown here.

TEMPERATURE COEFFICIENT

We find that the temperature coefficient of the resonance cell, i.e., the change in clock frequency with resonance cell temperature is determined by several processes. The dominant process is the well known pressure shift arising from an increase or decrease in hyperfine level spacing due to Rb-N_2 and Rb-Ar atom collisions respectively. In practice, the Ar/N_2 ratio is adjusted to minimize the temperature coefficient at the LTP. Figure 11 shows frequency vs. cavity temperature for several resonance cells of differing buffer ratio (N_2/Ar) as measured in the integrated cavity. It should be mentioned that the filter cell contributes a negative temperature coefficient to this data. The negative filter cell coefficient appears to be an unavoidable consequence in this range of increased filtering of the positive light shift, F=2, component with increasing filter temperature. This contribution to the temperature coefficient of the integrated cavity scales with the total light intensity. The cavity temperature coefficient should then be a strong function of light level as Figure 12 indicates.

MAGNETIC FIELD GRADIENT

When a magnetic field gradient is present across the resonance cell, inhomogeneous effects cause light shift, resonance cell temperature coefficient and microwave sensitivity values to be altered. Figures 13 and 14 illustrate microwave sensitivity and light shift as a function of c-field when the c-field produces approximately a 30% gradient across the resonance cell.

SUMMARY

Due to the influence of the many parameters involved it is not suggested that data presented here should be exactly reproducible in rubidium frequency standards of others. However, the more general qualitative behavior of the physics package elements discussed here should apply to the tactical rubidium standards of others in this higher temperature and smaller cell size regime.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support by the USAF RADC/ESD. Contributions to this work have been made by all members of our group. Particular thanks go to W. Debley for cell fabrication.

REFERENCES

1. Rubidium Frequency Standard Study, Feb. 1982 to March 1983, USAF, Electronic Systems Division. F19628-83-C-0046.

2. H.E. Williams, T.M. Kwon, T. McClelland, 1983 Frequency Contr. Symp. p.12.

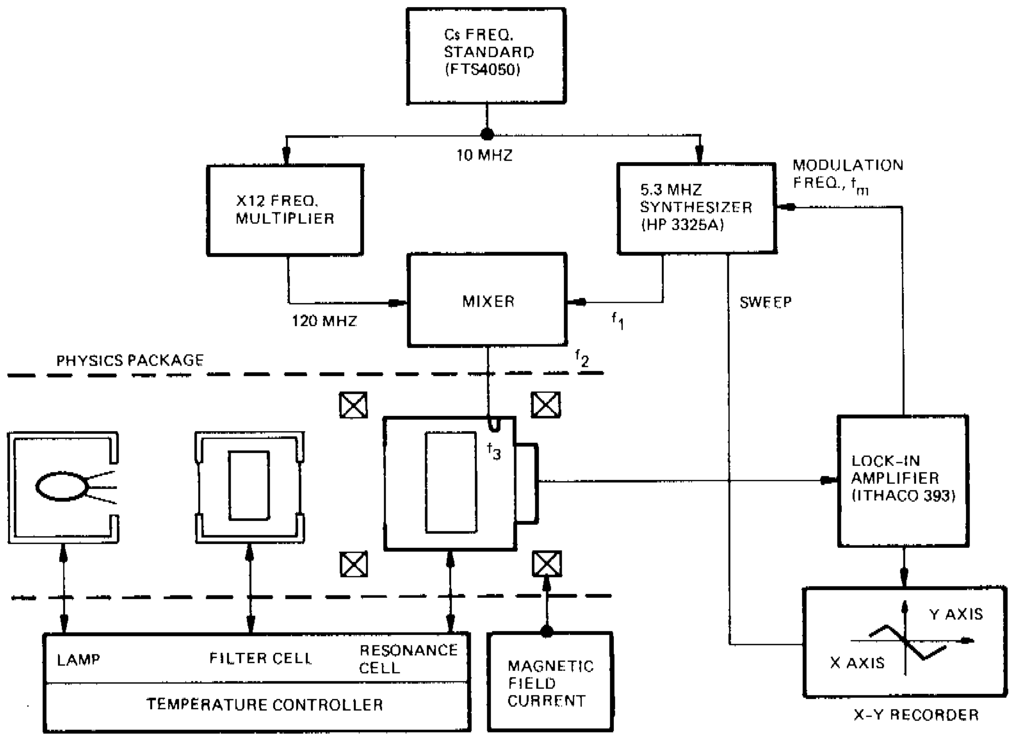

Fig. 1-Experimental Apparatus

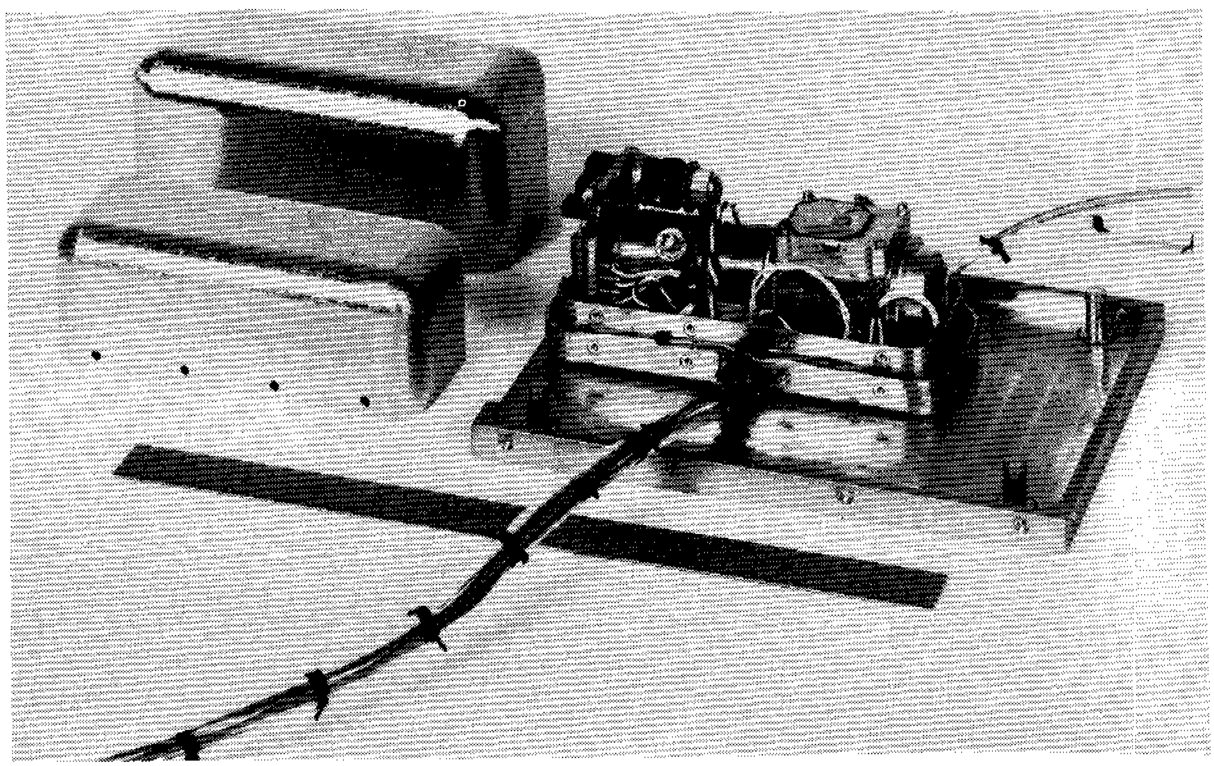

Fig. 2-Litton Engineering Model FSU Physics Package

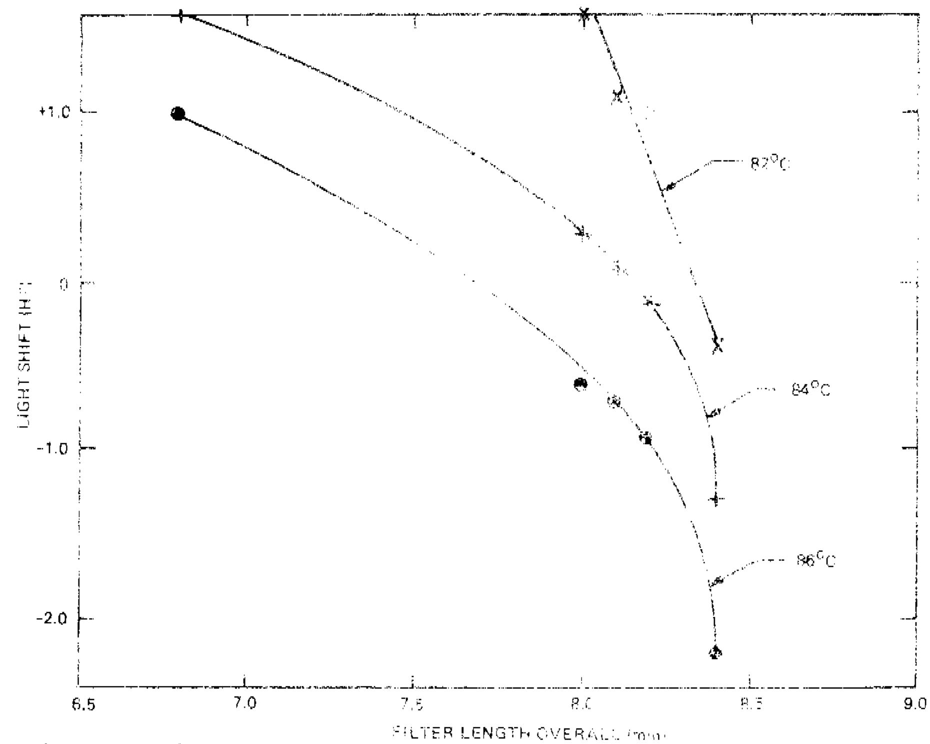

Fig. 3-Light Shift Vs. Filter Length for Several Cavity Temperatures
Filter Pressure = 120 TORR Ar, Lamp Temperature = 118°C

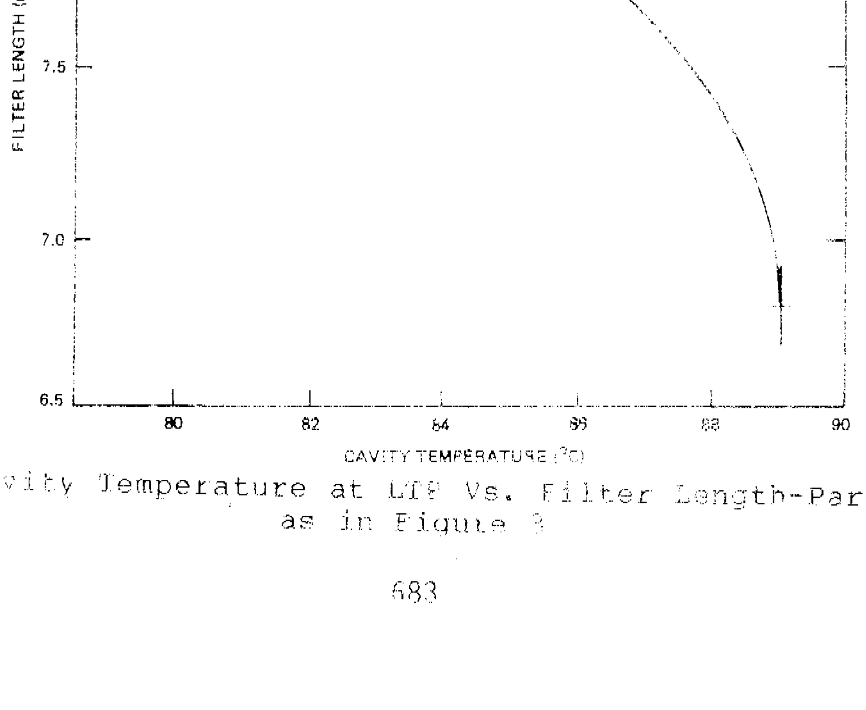

Fig. 4-Cavity Temperature at LTP Vs. Filter Length-Parameters as in Figure 3

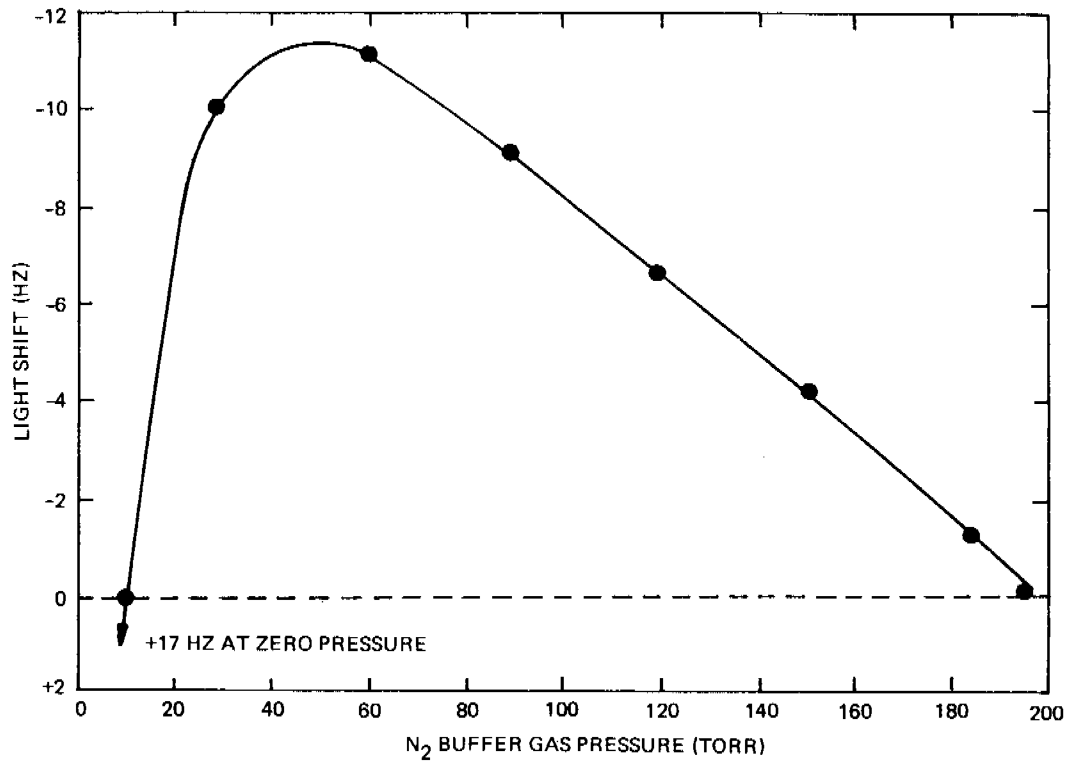

Fig. 5-Light Shift Vs. Filter Buffer Gas Pressure (N_2)
Lamp - 116.5C, Filter - 88C, Resonance Cell - 9.2 mm, 83C
Filter Length Nominal 8.4 mm

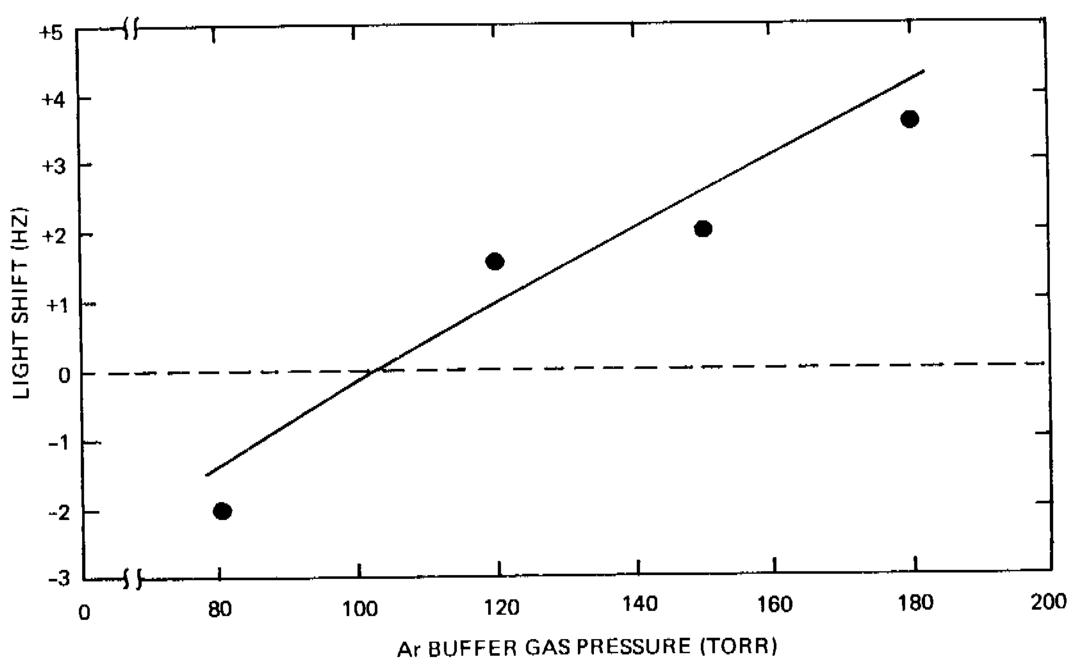

Fig. 6-Light Shift Vs. Ar Buffer Gas Pressure of Filter Cell

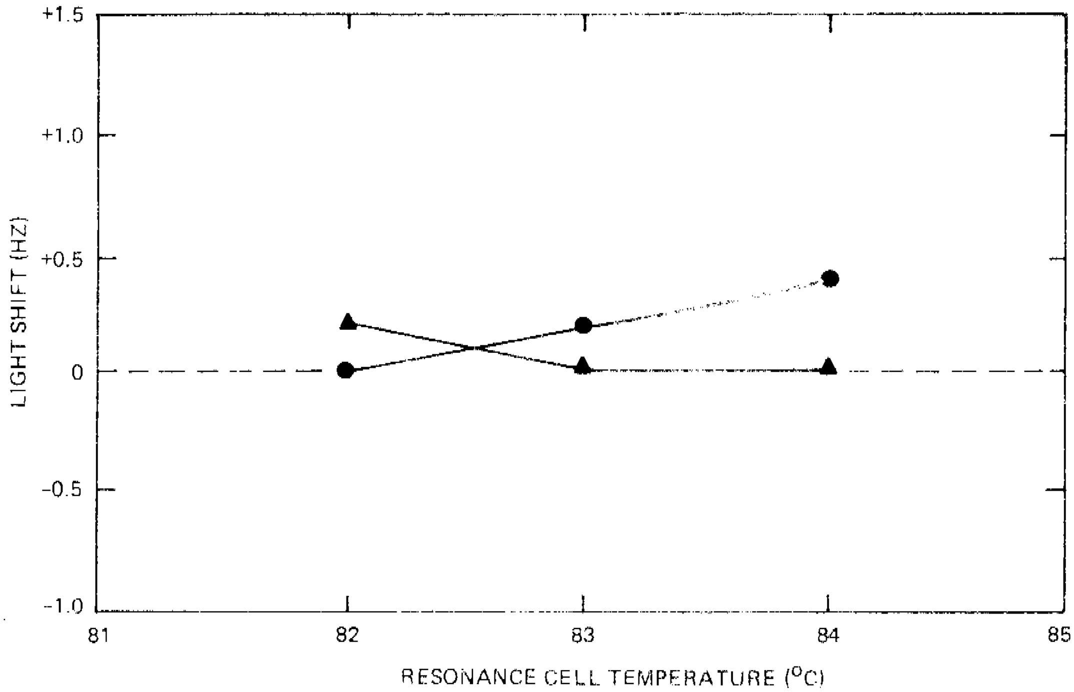

Fig. 7-Light Shift Vs. Resonance Cell Temperature
Lamp - 116.8C, ●90C Filter, ▲91C Filter

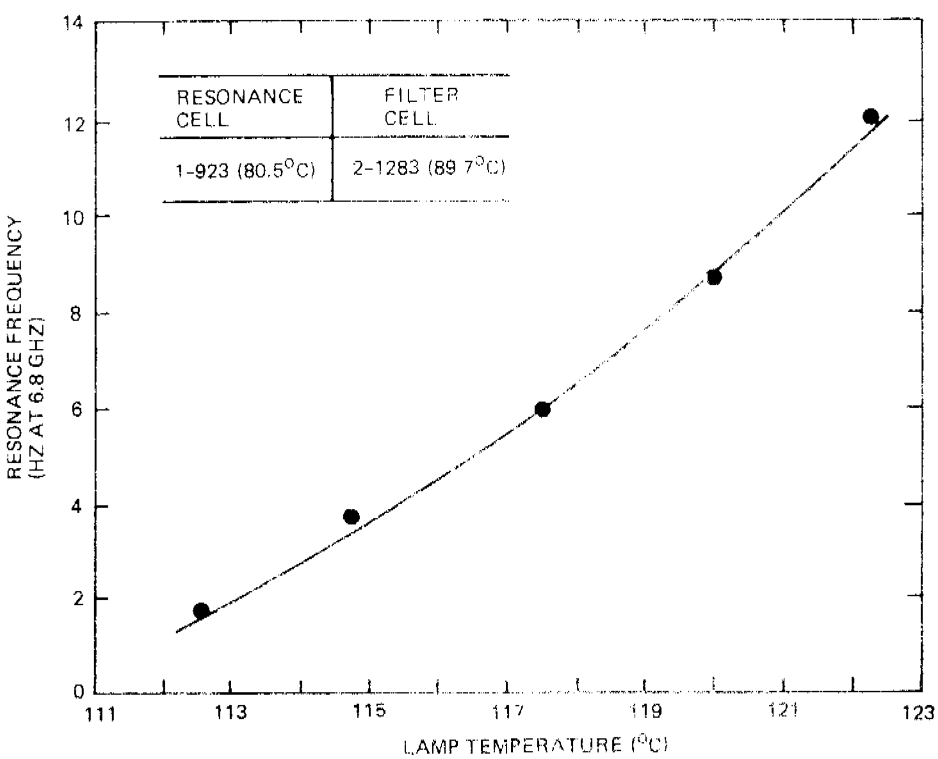

Fig. 8-Rb87 Resonance Frequency Vs Lamp Temperature

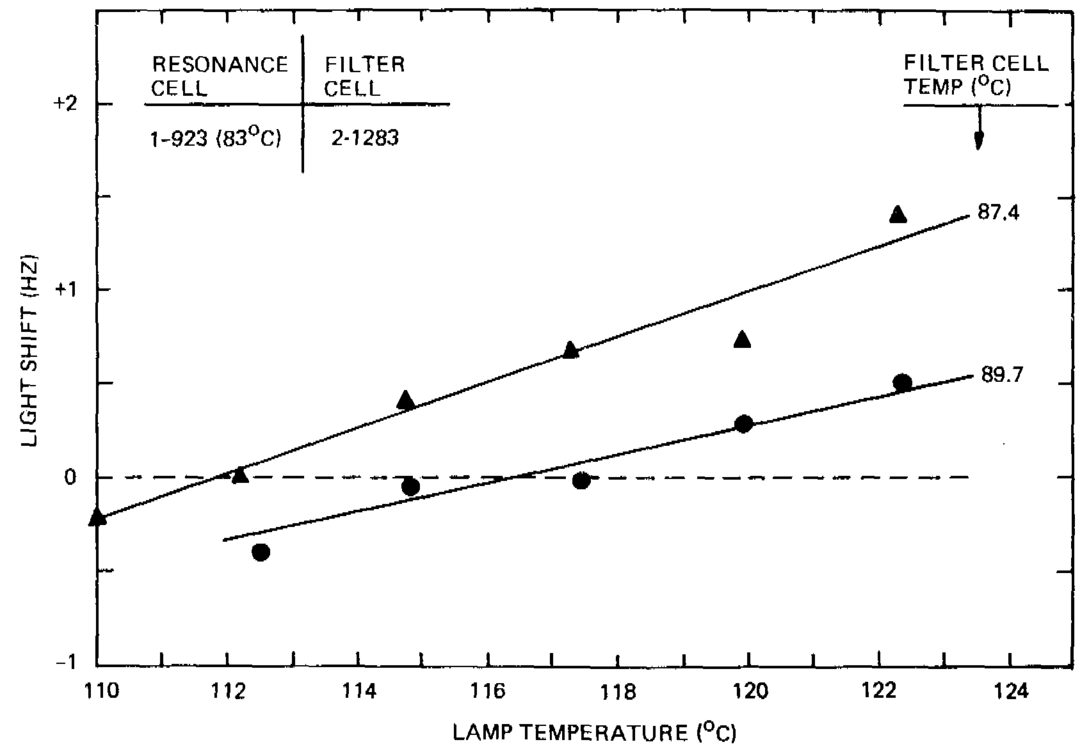

Fig. 9-Light Shift Vs. Lamp Temperature

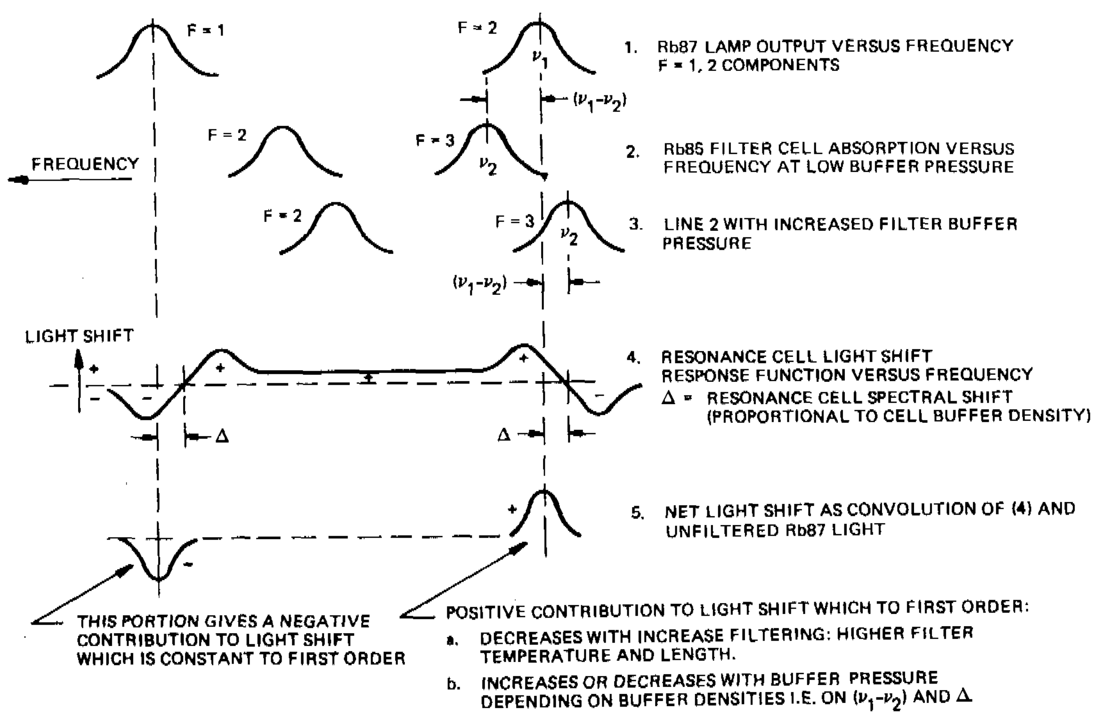

Fig. 10-Light Shift Model

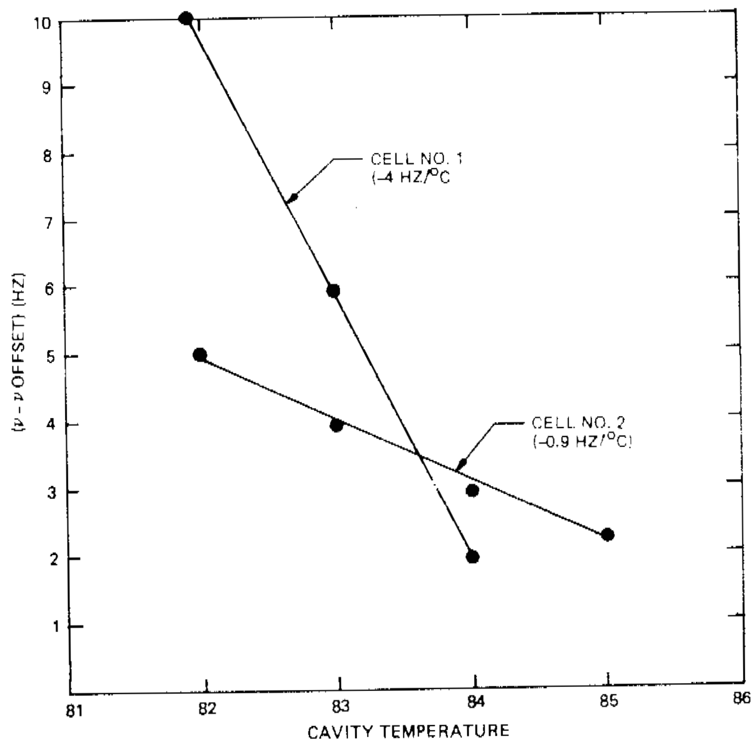

Fig. 11-Frequency Vs. Cavity Temperature for Resonance Cells of Differing Buffer Ratio (N_2/Ar)

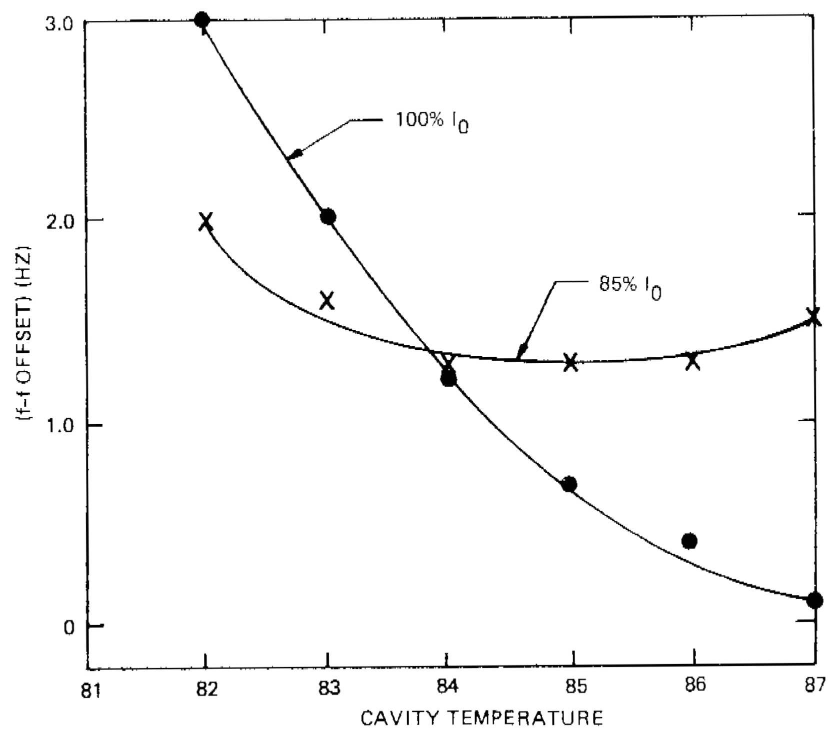

Fig. 12-Frequency Vs. Cavity Temperature as a Function of Light Intensity (I_O)

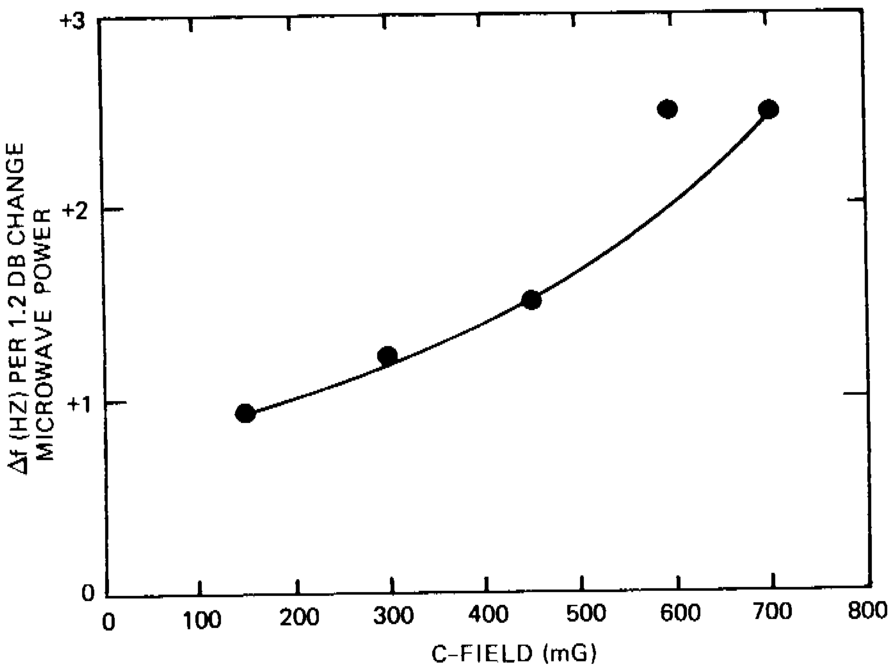

Fig. 13-Microwave Sensitivity Vs. C-Field With Gradient

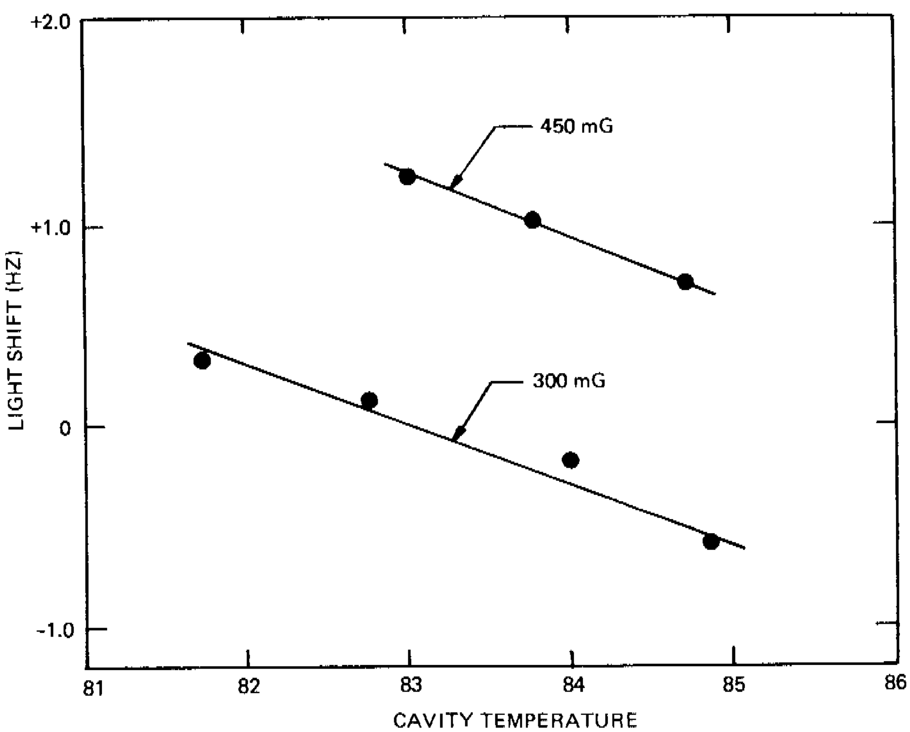

Fig. 14-Light Shift Vs. Cavity Temperature as a Function of C-Field with Gradient

TABLE I. PHYSICS PACKAGE PARAMETERS USED IN THIS STUDY

LAMP SIZE	9mm DIAMETER X 10mm LONG
LAMP FILL	Rb87 + 3 TORR Xe
LAMP TEMPERATURE	115 – 120^{o}C
FILTER CELL SIZE*	12mm DIA X 7-9mm LONG
FILTER CELL FILL	Rb85 + N_2 OR Ar
FILTER CELL TEMPERATURE	85C – 92C
RESONANCE CELL SIZE*	12mm DIA X 8-11mm LONG
RESONANCE CELL FILL	Rb87 + 10 TORR N_2 + 14 TORR Ar
RESONANCE CELL TEMPERATURE	80C – 85C
DC PHOTODETECTOR CURRENT	$\approx$ 75 μA
LINEWIDTH BETWEEN INFLECTION POINTS	800 – 1200 Hz
DISCRIMINATOR SLOPE AT PHOTODETECTOR	210 – 36 PA RMS PER 1 X 10^{-10}
FREQUENCY STABILITY IN SHOT NOISE LIMIT	5 X 10^{-12} $\tau^{-1/2}$ – 3 X 10^{-11} $\tau^{-1/2}$

*INCLUDES 1mm END WINDOWS

QUESTIONS AND ANSWERS

None for Paper #35.