THE "ATOMIC CANDLE:" Progress Towards a Smart Rubidium Atomic Clock

J. C. Camparo
The Aerospace Corporation, El Segundo, CA

Abstract

Just as it is possible to stabilize the *frequency* of an electromagnetic field to an atomic resonance between energy eigenstates, so it is possible to stabilize the *intensity* or brightness of a field to an atomic Rabi-resonance. For ease of reference, we term such a device an "atomic candle." Here, we describe the operation of a microwave atomic candle based on the 0-0 ground state hyperfine transition in Rb^{87}, and our experiments examining its stability and sensitivity to various experimental parameters. Specifically, we have measured the microwave power stability of our candle, relative to the peak of the Rabi-resonance, and obtained $\sigma_{\Delta P/P}(\tau) = 9\times10^{-7} + 10^{-7}\sqrt{\tau}$. Additionally, we examined the Rabi-resonance's shift as a function of various experimental parameters including microwave detuning from the 0-0 resonance and resonance-cell temperature. Our paper concludes with a discussion of a novel application of the atomic candle: the precision measurement of a material's complex dielectric constant.

Introduction

Studies have suggested that the long-term timekeeping behavior of gas-cell atomic clocks may be influenced by microwave field-strength variations within the clock's cavity [1,2]. Basically, in a gas-cell atomic clock microwave power variations or microwave cavity-Q variations are mapped onto the atomic standard's output frequency as a consequence of the "position-shift" effect [3,4]. Since most of the atomic signal comes from a small region of vapor within the cavity, the clock's output frequency is perturbed by *local* values of static magnetic field (i.e., Zeeman shift) and light intensity (i.e., light shift). When the microwave field-strength within the cavity changes, this small region shifts its position to a new location where the local perturbations may be significantly different [5]. The magnitude of this position-shift effect is not small, as a one decibel change of microwave power can yield a several parts in 10^{11} frequency change [6].

One method of eliminating this frequency shift mechanism is via "smart clock technology," in which the atoms giving rise to the atomic clock signal actually detect and control the microwave field-strength. Figure 1 is a schematic of how this smart clock technology might be implemented. Briefly, a microwave field would have its amplitude modulated with a voltage-controlled-attenuator (VCA). The field would then interact with an atomic system, presumably where there would be some kind of power-dependent atomic resonance. Employing phase sensitive detection in the familiar fashion, the atoms' resonant response to the amplitude-modulated field would produce an error signal that could then be fed back to the microwave source in order to stabilize the microwave field-strength (i.e., microwave brightness.) Given the clear analogy of this scheme to the generic, passive atomic clock, for ease of reference we refer to this particular smart-clock technology as an atomic *candle.*

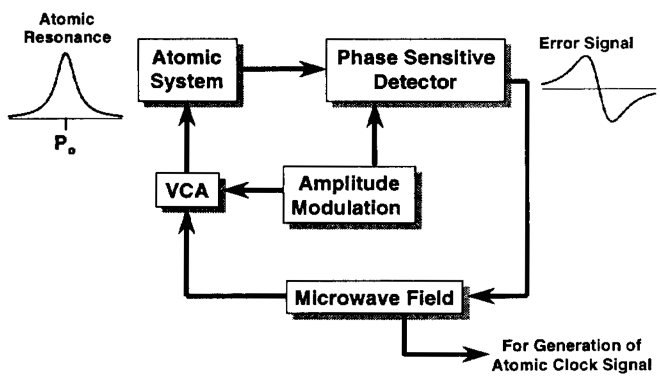

Figure 1: Schematic illustration of a generic "atomic candle."

Of course, the problem with this atomic candle idea is its need for a power-dependent atomic resonance. While everyone knows that the transition probability between atomic states is a resonant function of field-frequency, resonances dependent on field-strength are generally thought to be nonexistent. Over the past decade, however, researchers have come to recognize that atomic systems can exhibit *dynamical* resonances, specifically the so-called "Rabi-resonances" [7,8]. These resonances arise when atoms interact with modulated fields. The modulated field induces atomic population oscillations, and the amplitude of these oscillations exhibits a resonance when the field's modulation frequency matches the atom's Rabi

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frequency (i.e., a parameter proportional to the field-strength sensed by the atoms). Thus, a Rabi-resonance represents a power-dependent resonance that can be employed in an atomic candle [9]. In particular, defining δ_Z as the amplitude of the population oscillations that are induced by a phase-modulated field, it is possible to show that [9]

$$\ddot{\delta}_Z + \gamma\dot{\delta}_Z + \Omega^2\delta_Z \cong A\sin[2\omega_m t]. \qquad (1)$$

Here, γ is the atomic relaxation rate; ω_m is the field's modulation frequency; A is a constant, and Ω is the Rabi frequency. As mentioned above, the Rabi frequency is a parameter that is proportional to the microwave field-strength, and its specific form is

$$\Omega = \frac{\mu_B B_{\mu wave}}{\hbar}, \qquad (2)$$

where μ_B is the Bohr magneton, $B_{\mu wave}$ is the microwave magnetic field strength and $\hbar$ is Planck's constant divided by 2π. Thus, according to Eq. (1), the amplitude of the atomic population oscillations responds to the phase-modulated field like a damped, driven harmonic oscillator, and when the Rabi frequency equals $2\omega_m$ there is a resonant enhancement in the atom's population oscillations.

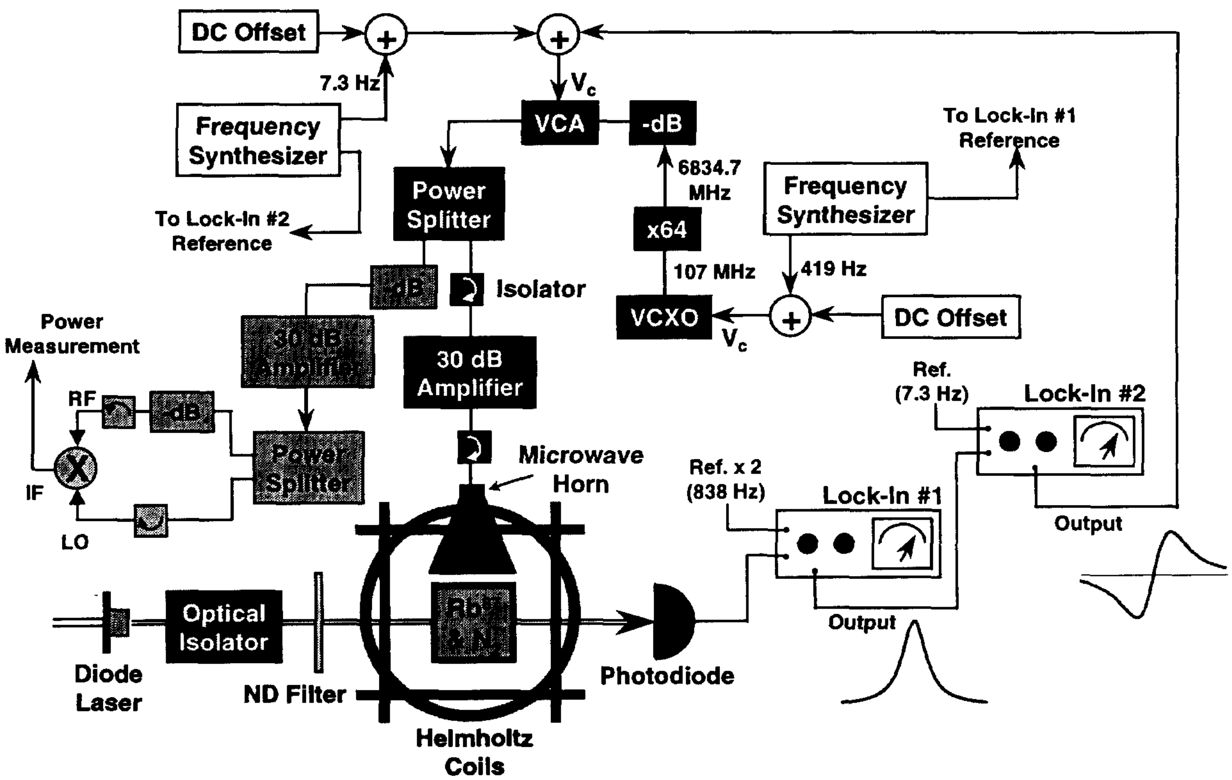


Figure 2: Block diagram of our microwave atomic candle's experimental realization as discussed in the text.

Realization of an Atomic Candle

Our present realization of a microwave atomic candle is shown in Fig. 2 [10]. A Pyrex glass resonance cell containing isotopically pure Rb^{87} and 100 torr of N_2 is placed in the near field of a microwave horn with 15 dB gain. The microwaves are resonant (or near resonant) with the 0-0 hyperfine transition of Rb^{87} at 6834.7 MHz. The cylindrical cell has a diameter of 2.5 cm and a length of 3.9 cm, and is contained within a phenolic box with Pyrex windows. Braided windings wrapped around the cell heat it to approximately 35 °C, and the temperature is actively controlled to a few tenths of a degree. The entire assembly (cell and enclosure) is centrally located in a set of three perpendicular Helmholtz coil pairs: two coil pairs zero out the Earth's magnetic field while the third pair (~ 300 mG) provides a quantization axis for the atoms parallel to the microwave field's magnetic field direction.

Light from a DBR AlGaAs diode laser is tuned to the Rb $5^2P_{3/2}$ – $5^2S_{1/2}(F=2)$ transition at 780.2 nm, and is attenuated by neutral density filters before passing through the resonance cell. The laser intensity entering the resonance cell is nominally ~ 60 $\mu W/cm^2$ in a 0.8 cm diameter beam, and the laser linewidth is less than one megahertz. The laser light intensity is chosen so as to mitigate against light shift effects [11], yet produce a good amount of optical pumping. The transmission of the laser light through the vapor is monitored with a photodiode, and the propagation direction of the laser is parallel to the atoms' quantization axis.

In the absence of resonant microwaves, optical pumping reduces the density of atoms in the absorbing state, and consequently increases the amount of light transmitted through the vapor. However, when the microwave frequency is resonant with the Rb^{87} 0-0 hyperfine transition atoms return to the absorbing state, thereby reducing the amount of transmitted light. The transmitted laser light therefore acts as a measure of atomic population, so that any microwave induced oscillation of the atomic population may be readily observed.

The microwaves are derived from a voltage-controlled-crystal-oscillator (VCXO) which has a modulation bandwidth of 10 kHz, and its output frequency at ~ 107 MHz is multiplied up into the gigahertz regime. The microwaves are attenuated by the combination of a voltage-controlled-attenuator (VCA) and a fixed attenuator (labeled as -dB in the figure) before being amplified by a +30 dB solid state amplifier. The output from a frequency synthesizer at approximately 419 Hz is added to a DC voltage in order to provide the VCXO's control voltage, V_c. The DC level of V_c tunes the average microwave frequency to the 0-0 hyperfine resonance, and the sine wave provides microwave frequency (i.e., phase) modulation. The *amplitude* of the microwave frequency modulation is 750 Hz.

Following the VCA, the microwave signal is split in two. One half of the signal goes to the horn and the experiment, the other half is used to directly monitor the microwave power supplied to the horn. For the power measurement, the signal is attenuated prior to amplification by a second +30 dB amplifier, and following amplification is again split in two. These two signals are then mixed, creating a DC signal whose amplitude is proportional to the power of the original microwave signal.

As intimated above, the Rabi-resonance is manifested in the atoms' second harmonic response to the phase-modulated microwave field. The output of the photodiode is thus sent to a lock-in amplifier (labeled as #1 in the figure) referenced to the microwave phase-modulation's second harmonic (i.e., 838 Hz). The photodiode/lock-in combination essentially acts as a low-pass detector for the atoms' second harmonic signal. (The time constant of this lock-in is set to its minimum value of 3 msec.)

In order to generate a correction signal that can be used to stabilize the field-strength, we modulate the microwave power at 7.3 Hz by applying a sinusoidal signal to the VCA's control voltage. The peak-to-peak amplitude of the attenuation modulation is 7.7 dB. Though flicker noise can be a problem at such low modulation frequencies, our experience indicates that optimum atomic candle conditions require this modulation frequency to be much lower than the phase modulation frequency. Our choice of modulation amplitude for the VCA was limited by the preamplifier, which is indicated in Fig. 2 by a "+" signal operator; ideally this would have been closer to 10 dB given the width of our Rabi resonance (i.e., FWHM ~ 13 dB [10]). The atoms' Rabi-resonance response to the modulated microwave power is monitored in a heterodyne fashion with the aid of Lock-In #2, whose output is thus a "field-strength discriminator." Adding the field-strength discriminator voltage to the VCA control voltage, Vc, closes the field-strength feedback control loop.

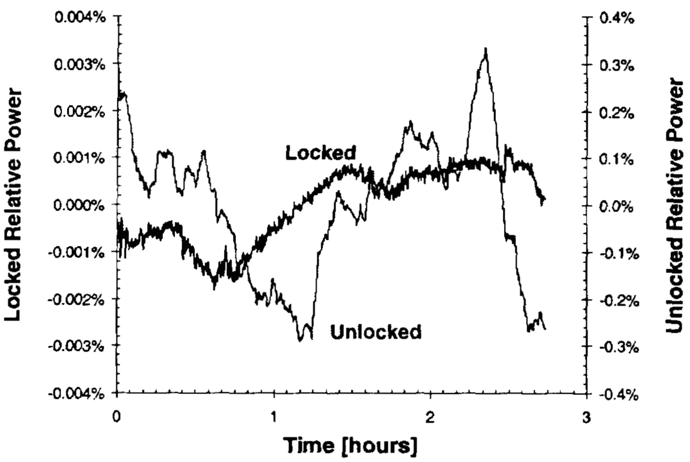
Atomic Candle Stability

Figure 3a shows the correction signal obtained from lock-in #2 as a function of time with the feedback loop closed and open. This signal is basically a measure of the match between the field strength sensed by the atoms and the peak of the atoms' Rabi-resonance. Though the lock-in's output signal cannot be taken as a measure of the field-strength stability produced by the candle itself, it may be regarded as a measure of how well the field-strength is locked to the atomic Rabi-resonance. With this caveat in mind, Fig. 3b shows the Allan variance, $\sigma_{\Delta P/P}(\tau)$, for the lock-in signal with the feedback loop open and closed. For averaging times between 10 and 100 seconds, the Allan variance of the locked microwave power fluctuations appears to be dominated by flicker noise; while in the long-term, for averaging times greater than 100 seconds, the Allan variance is dominated by random-walk noise:

$$\sigma_{\Delta P/P}(\tau) = 9\times10^{-7} + 10^{-7}\sqrt{\tau}. \qquad (3)$$

At the present time, we are still trying to uncover the source of these noise processes.

Figure 3b and Eq. (3) clearly demonstrate a tight lock between the microwave field strength and the peak of the Rabi-resonance. Consequently, physical processes that shift the atomic Rabi-resonance must necessarily cause the candle's output intensity to vary. Unfortunately, similar to the situation in the early days of gas-cell atomic clocks, when little was known about hyperfine resonance shifts [12], little is presently known about the origin and magnitude of Rabi-resonance shifts.



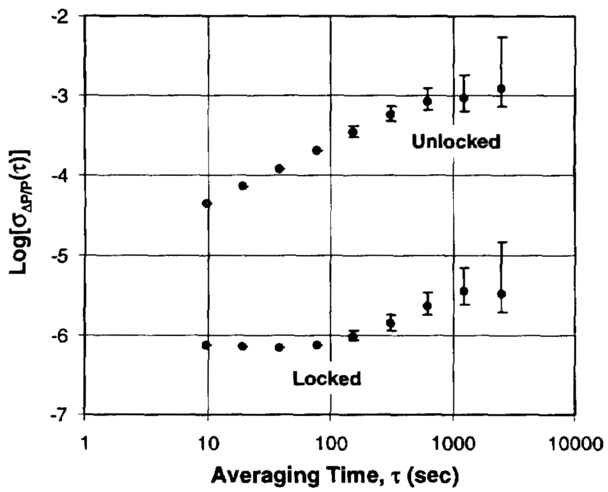


Figure 3: (a) Correction signal from lock-in #2 as a function of time. (b) Allan standard deviation of the time series shown in (a).

For our realization of an atomic candle, Table I is a collection of the Rabi-resonance shift parameters that we have measured. Basically, all of these shift parameters with the exception of temperature are very small. As with the standard gas-cell atomic clock [13], temperature fluctuations appear to have an important long-term effect on the atomic candle's power stability. Though we are still investigating the origin of this temperature effect, preliminary experiments suggest that it may be related to a temperature-dependent shift in the 0-0 hyperfine transition frequency. Nevertheless, the data of Table I suggests that long-term power stabilities on the order of milli-dB are certainly achievable; and if the temperature sensitivity can be reduced, that tens of micro-dB stability may not be unreasonable.

Table I: Atomic candle sensitivities

Shift Parameter	Magnitude
Microwave detuning	3.5×10^{-4} dB/Hz
Laser Intensity	5.2×10^{-4} dB/%
Laser Frequency	1.3×10^{-4} dB/MHz
Cell Temperature	0.15 dB/°C

Precision Dielectric Measurements Using an Atomic Candle

As indicated above, our primary motivation in developing the atomic candle has been to ameliorate a problem with the long-term stability of gas-cell atomic clocks. In order to achieve the tight lock on field-strength indicated by Figs. 3 and Eq. (3), it is clearly necessary for the atomic candle to detect and respond to very small changes in field intensity. With regard to the atomic candle's primary purpose, these changes are random in nature. However, they could just as well be deterministic and under experimental control, in which case the candle would provide a sensitive detector of subtle field-strength changes. To illustrate this potential, we have used the field of our microwave atomic candle to measure the absorption coefficient and refractive index of acetone at 6.8 GHz.

Regarding Fig. 2, if an attenuating material (in our case acetone) is placed between the horn and the resonance cell, the microwave intensity reaching the Rb atoms will be reduced. As a consequence, the atomic candle will feed a correction signal back to the VCA that just compensates for this attenuation. The magnitude of the attenuated power is therefore detected as an *increase* in the microwave power supplied to the horn.

Ideally we would have used the correction signal itself to measure the microwave attenuation, as microwave power changes than appear on a near-zero signal background, limits in the dynamic range of the electronics associated with the VCA made this approach in our experiment problematic. Additionally, however, we felt that measuring the power supplied to the horn directly would provide a cleaner demonstration of the atomic candle's application.

The acetone was 99.6 % pure research grade, and was contained in a 14.5 cm diameter open Pyrex dish placed between the horn and the resonance cell. The dish rested on a 1.8 cm thick sheet of polyurethane microwave absorber, which had an attenuation coefficient greater than -20 dB. The sheet was large enough to ensure that sidelobes from the horn were attenuated. A small ~ 3 cm^2 hole was cut in the sheet directly under the center of the horn, so that only microwaves incident normally to the liquid would pass into the resonance cell. The power measurement signal was chopped at 0.1 Hz prior to amplification by the second +30 dB amplifier in order to discriminate against a slow baseline drift in the mixer signal. During the course of the experiment, the acetone temperature remained at 21 °C with no observed rise in due to microwave absorption. The liquid's depth, d, was determined by adding known volumes of acetone to the dish, and then correcting these depth-values for any loss of acetone due to evaporation.

In a separate experiment, we measured the rate-of-change of power supplied to the horn, dP/dt, resulting from evaporation alone. At fixed temperature and pressure, the rate of acetone evaporation is constant, since this primarily depends on the acetone vapor pressure just above the liquid surface. Thus, by noting the times that acetone was added to the dish, we could use these separate experimental results to correct the power measurements for the evaporative loss of acetone. (Note that it should be possible to use the atomic candle to measure dP/dt due to evaporation as a function of liquid temperature, and thereby access the liquid's latent heat of vaporization.)

At our wavelength, macroscopic depths of acetone act as a thin film. Hence, the power reaching the resonance cell, P_{lock} (i.e., the locked power of our atomic candle), is given by [14]

$$\frac{P_o}{P_{lock}} = \frac{e^{\alpha d}}{|T|^2}\left\{1 + 2|R|e^{-\alpha d}\cos[4\pi n d/\lambda + \theta] + |R|^2 e^{-2\alpha d}\right\}. \tag{4}$$

Here, P_o is the measured power supplied to the horn, R and T are parameters associated with the transmission and reflection of the liquid at its boundaries and θ is a phase angle. The absorption coefficient of acetone is denoted by α, while n is its index of refraction. Figure 4 shows our measurements of P_o/P_{lock} as a function of d. From the exponential increase in P_o/P_{lock} at large depths, we infer α, while the wavelength of the sinusoidal variations in P_o/P_{lock} yields n. The results are given in Table II, which also presents estimates of α and n based on the empirical Cole-Cole equation, a modified version of the familiar Debye equation [15]. (The table provides the standard error for the present measurements, while it gives the standard deviation associated with the different predictions obtained from the Cole-Cole equation.)

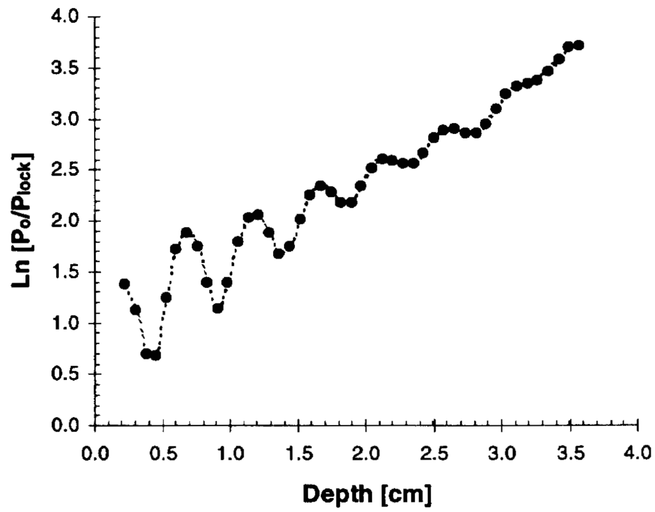


Figure 4: Logarithm of the relative power supplied to the horn as a function of acetone depth. The dashed curve is simply an aid to guide the eye.

Table II: Absorption coefficient, α, and refractive index, n, of 21 °C liquid acetone at 6.8 GHz. The agreement between the atomic candle and Cole-Cole equation mean values indicates the atomic candle's accuracy, while a comparison of the uncertainties indicates the atomic candle's capability for precise measurements.

	α	n
Atomic Candle	0.817 ± 0.026	4.623 ± 0.026
Cole-Cole Equation	0.817 ± 0.013	4.591 ± 0.023

Clearly, in its crudest realization for this type of measurement (i.e., an open dish of evaporating liquid that attenuates a non-plane wave microwave signal) the atomic candle has achieved excellent accuracy and precision in the determination of a complex dielectric constant. In particular, with little real care in the absorption-measurement portion of the experiment we have achieved a level of precision that is competitive with "state-of-the-art" measurements.

Conclusions

In this work we have described our construction of a microwave atomic candle based on the ground state 0-0 hyperfine transition in Rb^{87}. While our primary interest in the device is in terms of smart-clock technology, we believe that the ability of the atomic candle to detect subtle variations in electromagnetic field-strength may have much broader applications. To this end, we employed our atomic candle to measure the complex dielectric constant of liquid acetone to high precision.

Finally, though we have considered a microwave atomic candle in the present work, it should be noted that nothing precludes the construction of an optical atomic candle, since Rabi-resonances have been observed in the optical regime [16]. Specifically, in order to generate an optical atomic candle signal, the laser intensity must be large enough to saturate the atomic transition and the laser frequency must be modulated at the corresponding Rabi frequency. For a homogeneous, strongly allowed transition, saturation intensities are on the order of 10 to 100 mW/cm^2. Moreover, at the saturation intensity the Rabi frequency is approximately equal to the natural decay rate. This suggests that laser frequency modulation rates for an optical atomic candle will be on the order of 10 to 100 MHz. These laser intensities and modulation rates are easily attained, and argue for the viability of an optical atomic candle. However, it should be noted that in the case of a gas-cell candle, Doppler broadening may have important implications.

Acknowledgments

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