Ion-Acoustic Plasma Waves in rf-Discharge Lamps: Light-Shift Stabilization for Atomic Clocks

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Abstract— **In vapor-cell atomic clocks, long-term stability can be significantly influenced by temporal variations in a discharge lamp's output via the light-shift. In order to stabilize the light-shift effect it is necessary to stabilize both the lamp's brightness and its spectral output; and this in turn requires one to stabilize the lamp's temperature and the rf-power driving the lamp. Though the lamp's output intensity can be used as a control parameter for lamp stabilization (e.g. for lamp temperature), another is required. Here, we consider the resonant frequency of ion-acoustic plasma waves as a second control parameter for the stabilization of rf-discharge lamps.**

I. INTRODUCTION

As illustrated in Fig. 1, the atomic-system portion of the generic vapor-phase atomic clock consists of a rubidium (Rb) discharge lamp, a filter cell containing Rb^{85} vapor, a resonance cell containing Rb^{87} vapor, and a photodetector. The Rb lamp emits spectral lines in the near-IR (i.e., two closely spaced lines at 780 nm and two closely spaced lines at 795 nm, with only one pair of lines shown in the figure). After passing through the filter cell's Rb^{85} vapor, the spectrum of this light is altered slightly so that it can efficiently generate an atomic-clock signal in the resonance cell via Rb^{87} optical pumping [1,2].[1] The lamplight monitors the Rb^{87} atoms' interaction with a microwave field, which is the essential atomic-clock signal: the atomic clock's output frequency derives from this microwave field. If the microwaves are tuned to the ground state hyperfine energy level spacing, ν_{hfs}, at ~ 6834.7 MHz, the Rb^{87} atoms will strongly absorb the microwaves and the intensity of lamplight transmitted by the resonance cell will decrease (i.e., the vapor state created by optical pumping will, to some extent, be destroyed). If the microwave frequency is not tuned appropriately, the Rb^{87} atoms will not absorb the microwaves and the transmitted lamplight will remain unaffected. In this way a feedback loop is created that locks the microwave frequency to ν_{hfs}. In order to affect the lamplight's transmission, the microwave frequency must be within about one part in 10^7 of ν_{hfs}; and any atomic perturbation that causes ν_{hfs} to change in time will result in a temporal variation in the clock's output frequency.

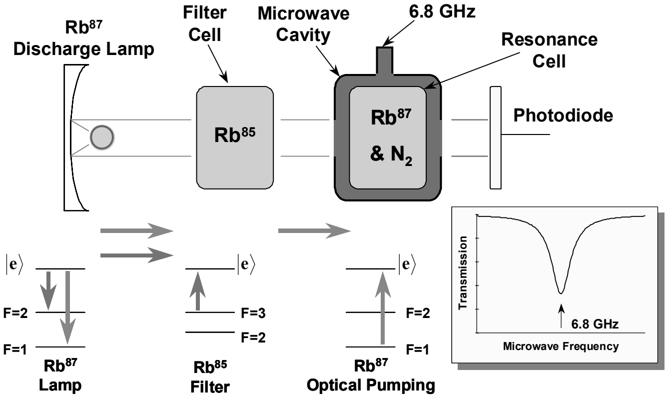

Figure 1: Schematic of generic vapor-cell clock's physics package

One of the more important perturbations affecting the atomic ensemble's energy level structure is the light shift, also known as the ac-Stark shift [3,4]. Briefly, a spectral component of the lamplight's electric field, $E(\omega)$, induces a dipole moment in the atom, $p(\omega)$: $p(\omega) = \alpha(\omega)E(\omega)$, where $\alpha(\omega)$ is the polarizability of the atom at the frequency ω.[2] This dipole moment in turn interacts with the electric field of the light, setting up a second-order perturbation that alters the atom's energy level structure. The interaction potential, V, between the light and the atom has the form

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[1] As a result of optical pumping, the atoms are placed in a state where their interaction with the lamplight is minimal; hence, the amount of light transmitted by the vapor is maximized.

[2] For a discussion of the atomic polarizability in classical dispersion theory see [5].

$$V = -\tfrac{1}{2}\int p(\omega)\cdot E(\omega)\,d\omega = -\tfrac{1}{2}\int \alpha(\omega)\left|E(\omega)\right|^2 d\omega \cdot \qquad (1)$$

Notice that in evaluating the interaction potential, the influence of all spectral components of the lamplight must be considered, and so the integral implies that it is the full lamp spectrum that is important in determining V. Consequently, if the light shift is to be controlled and stabilized in a vapor-cell clock, it is not enough to think in terms of stabilizing the lamp's intensity; one must also stabilize the *spectrum* of the lamp's output. Clearly, in order to stabilize the rf-discharge lamp's brightness and spectrum, the lamp temperature and rf-power must both be controlled. The problem, of course, is that while there are two lamp parameters to control, one typically thinks only in terms of the lamp's brightness as a readily monitored quantity.

II. ION-ACOUSTIC PLASMA WAVES

During the course of investigations into vapor-cell clock frequency equilibration [6], we "re-discovered" the phenomenon of ion-acoustic plasma waves in rf-discharge lamps. Briefly, if the positive ions in a discharge are set in motion, they will oscillate at a resonant frequency, f_{ion}. This resonant frequency depends on a characteristic length of the discharge, L, and the electron temperature, T_e. Typically, with L ~ 1 cm and $T_e \sim 10^4$ K, f_{ion} is on the order of tens of kilohertz, which is the acoustic range of frequency. Concomitant with the bulk ion oscillations, the discharge's rf-power coupling varies, and hence the light output oscillates at f_{ion}.

Tonks and Langmuir are credited with the first discussion of these waves, which they encountered during their pioneering investigations into ionized gases [7]. In the 1960s, Robert Shaw found that these waves could develop spontaneously in rf-discharge lamps used for optical pumping [8]. During our studies into the mechanisms of frequency equilibration, we too observed the spontaneous generation of these waves in an rf-discharge lamp. However, whereas Shaw postulated that his waves were generated by a nonlinear mechanism occurring within the discharge, we found evidence that our waves were forced. Under certain conditions, we found that the Hartley oscillator, which generated the rf power for the discharge, could oscillate simultaneously in two closely spaced modes [9]. The beat signal between these modes was at ~ 12 kHz and forced the ions' motion.

In follow-up studies, we found that we could generate the waves more directly by placing a loop of wire around the glass bulb of the rf-discharge lamp as illustrated in Fig. 2a. We then used this loop as an antenna to directly inject acoustic frequency signals into the plasma. Figure 2b shows the results of one of our studies, where the amplitude of lamp intensity oscillations, relative to the dc light level, is plotted as a function of the frequency of the injected signal, f_{inj}. The curves clearly display a resonance shape, the peak of which corresponds to f_{ion}. Note also that these are likely small amplitude waves, since the relative change in light intensity is only a few percent.

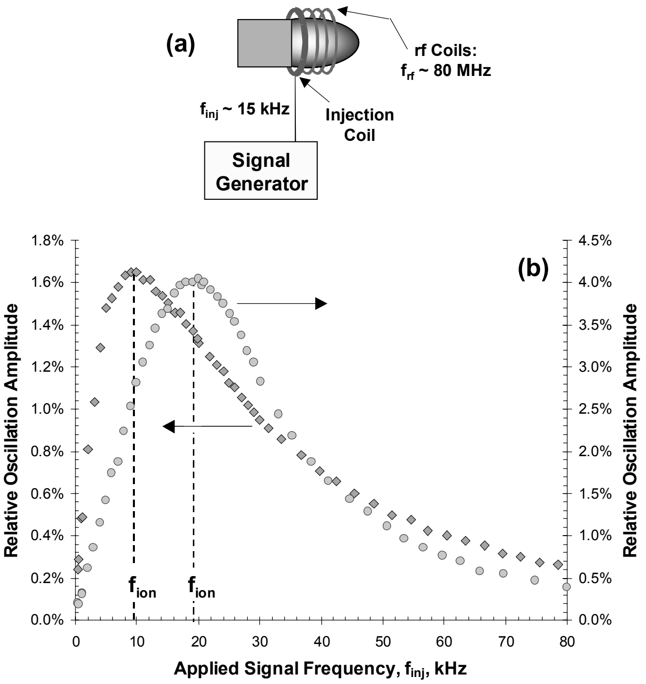

Figure 2: (a) Illustration of our method for injecting an acoustic frequency signal into the plasma. (b) Amplitude of light intensity oscillations as a function of the injected signal's frequency. With our Hartley oscillator, we were able to change the rf-frequency driving the lamp, f_{rf}, and consequently couple more or less rf-power into the discharge, P_{rf},. The shift in f_{ion} for the two curves is one piece of evidence demonstrating a sensitivity of f_{ion} to P_{rf}. (Diamonds correspond to f_{rf} = 70 MHz, while circles correspond to f_{rf} = 79 MHz.)

In the case of forced oscillations, the ion wave's resonant frequency is given by

$$f_{ion} = \sqrt{\frac{kT_e}{M_i L^2}\left(1 - \frac{E_a}{E_p}\right)} \cdot \qquad (2)$$

Here, M_i is the ion mass, E_a is the magnitude of the injected field, and E_p is the magnitude of the plasma field resulting from charge rearrangement in response to E_a. In the case of small injected signals, E_p should be slightly larger than E_a due to the resonant nature of the ion wave's motion. For the work of Fig. 2, we estimated that $E_a/E_p \sim 0.8$ [9].

Since f_{ion} depends on electron temperature, and since T_e will depend on the amount of rf-power coupled into the plasma, P_{rf}, it should be possible to use f_{ion} to sense and control variations in P_{rf}. As evidence of this capability, we performed an experiment to investigate the relationship between f_{ion} and P_{rf}. The results of this experiment are shown in Fig. 3a, and consistent with Eq. (2) yield $f_{ion}^2 \sim P_{rf}$ [9]. Fig. 3b shows the temperature dependence of f_{ion}, which appears to have an extremum at a nominal lamp operating temperature of 65 ^{o}C.[3] Note that this temperature dependence could arise from thermal variations in the discharge's characteristic length, L, the electron temperature, or the ratio E_a/E_p.

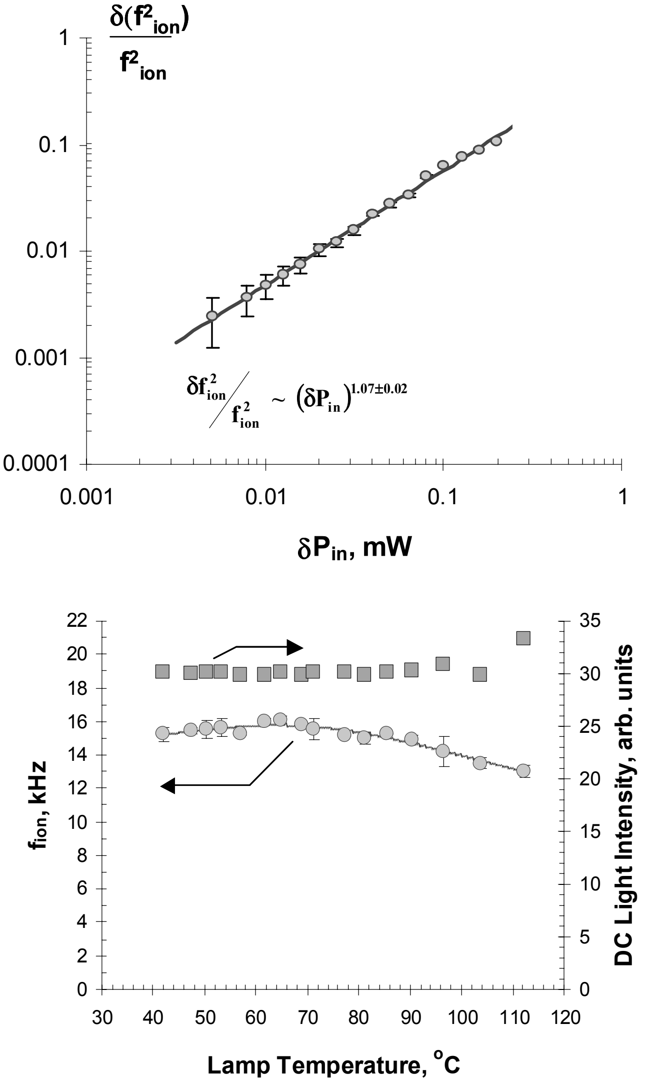

Figure 3: (a) In these experiments we used the lamp and Hartley oscillator that showed spontaneous ion-wave oscillations. Using the loop antenna to couple additional rf-power into the discharge, we measured the frequency of the spontaneous oscillations as a function of the added rf-power. (b) For these experiments we used our antenna to launch an acoustic frequency signal into the discharge, and measured f_{ion} as a function of the lamp's temperature, T_L. We also measured the total light from the central region of the lamp. At T_L = 65 °C, there is no real change in the light provided by the lamp. For a discussion of the light emerging from different regions of the lamp's bulb see [10].

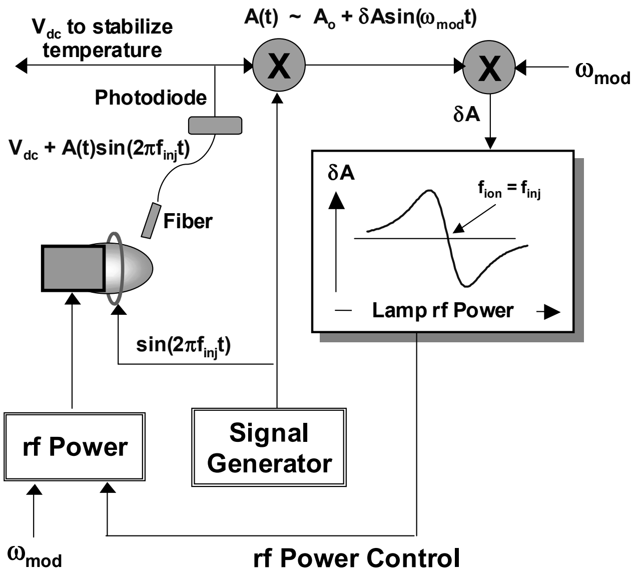

Figure 4: Block diagram of a feedback loop for stabilizing an rf-discharge lamp's temperature and rf-power as discussed in the text. Note that the lamplight is detected using a fiber/photodiode combination that is close to the lamp. The photodetector shown in Fig. 1 should not be used in a feedback loop for lamp stabilization, as the dc light level will depend on the filter and resonance cell temperatures, as well as the microwave power associated with the atomic clock signal.

III. POWER STABILIZATION OF AN RF-DISCHARGE LAMP

Based on the data presented in Figs. 2 and 3, the scheme for stabilizing an rf-discharge lamp's power using ion-acoustic waves is relatively straightforward, at least on paper. One first chooses an injected acoustic frequency, f_{inj}. Driving the discharge at this frequency, ion waves are created. One adjusts the rf power so that the amplitude of the ion waves is maximized (i.e., $f_{ion} = f_{inj}$). The choice of f_{inj} therefore determines the lamp's rf-power level. A feedback loop is then designed to keep the amplitude of the ion waves maximized (locking f_{ion} to f_{inj}), and in this way keeps the rf-power fixed at a pre-determined level.

A block diagram illustrating one possible realization of ion-wave lamp stabilization is shown in Fig. 4. Briefly, the rf-power is modulated at a low frequency ω_{mod} (e.g., $\omega_{mod}/2\pi \sim 10^2$ Hz). Simultaneously, a signal generator injects an acoustic frequency signal at f_{inj} into the discharge. The light output is detected with a fiber and photodiode. The dc portion of the light output is used to stabilize the lamp temperature. The oscillating portion of the signal is first down-converted to generate a signal that is proportional to the amplitude of the ion waves. Since the rf power is modulated, so too is the ion wave's resonant frequency, f_{ion}. Thus, if $f_{ion} \neq f_{inj}$, the amplitude of the ion waves will oscillate at ω_{mod}, while if $f_{ion} = f_{inj}$ the amplitude of the waves will oscillate at $2\omega_{mod}$. Using phase-sensitive detection, an error-signal can be created to correct changes in the rf power.

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[3] This temperature should not be taken as the actual temperature of the liquid Rb metal in the lamp, as it was measured by placing a thermocouple on the lamp's metal base. Nevertheless, it should be proportional to the liquid metal's temperature.

Of course, one could reasonably raise an objection with the feedback loop illustrated in Fig. 4. Specifically, as indicated in Fig. 2 the ion-waves generate intensity oscillations of a few percent. These, in turn, must produce a time varying light-shift of ν_{hfs} on a time scale of roughly 0.1 msec. However, since the light-shift coefficient of well-designed vapor-cell clocks is approximately $10^{-12}/\%$ [6], these ion-wave induced variations in ν_{hfs} will be relatively small. Moreover, since the time constant of the atomic clock's feedback loop is 0.1 to 3 seconds, averaging will further reduce the influence of rapid ν_{hfs} temporal variations on the clock's output frequency. At worst, we should expect the residual ion-wave induced variations in ν_{hfs} to give rise to a small offset in the clock's frequency. This, however, is not problematic so long as it is a stabile offset.

We are presently beginning construction of the Fig. 4 feedback loop, and should soon know its viability. It is worth noting though that regardless of the success or failure of ion-wave stabilization, the phenomenon clearly provides a valuable means of accessing an rf-discharge lamp's plasma character. In this regard, f_{ion} may prove useful as a parameter for studying subtle and slow (i.e., ~ months to years) variations in rf-discharge lamps and the electrical circuits that drive them. Such studies can be expected to lead to improvements in atomic clock discharge lamps, and therefore improvements in vapor-cell clock performance.

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