# Frequency Standard Using Single Indium Ions

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This paper will discuss the temperature stabilization of a Fabry-Perot cavity. This cavity will be used to frequency stabilize a laser that will be used to search for the $5s^2\ {}^1S_0 \rightarrow 5s5p\ {}^3P_0$ indium clock transition. The temperature stabilization process included insulating the cavity and building a temperature control circuit. The equilibrium stabilization was well within a milliKelvin deviation from the desired temperature if the cavity was undisturbed.

## I. INTRODUCTION

An accurate time and frequency standard is a requirement of many precise physical experiments. Although there are atomic clocks in use which are quite accurate, there is a need for more accuracy for some applications. The proposed indium atomic clock has the potential to be accurate to $10^{-17}$ seconds, which is an improvement over current atomic clocks. For the clock to be this accurate, it will need to be vibrationally isolated. This isolation would be easier to accomplish in space. Also many possible applications of such an accurate clock could be performed in space. These applications include extremely precise measurements of gravitational red shift and precise timing of pulses from binary and millisecond pulsars.

In order to implement an indium atomic clock, two stages must be completed. First, an indium ion must be trapped and cooled to eliminate its motion. Second, a "flywheel" (or intrinsically stable) oscillator (in this case a laser) must be locked to the clock transition of the ion. The first stage has been completed and my work this summer has been on the second stage, working to have an intrinsically stable clock laser. This stage has two parts as well. First, it is necessary to frequency stabilize the laser to a bandwidth of less than 25 kHz. The laser will then be used to probe the indium ion to find the clock transition. The bandwidth of the laser at this stage will be larger than it will be for the frequency standard and it will be much more powerful, which will facilitate finding the narrow clock transition. After the general area of the transition is found, the laser will be stabilized to a 1 Hz bandwidth. It will then be able to be used to find the exact clock transition.

## II. ATOMIC CLOCKS

In an atomic clock, an oscillating electric field is locked to a transition in an atom. This leads to long-term stability of the frequency of the oscillator, which can be a frequency standard. If this frequency is then counted, it can be used as a time standard, or a clock. The accuracy of the frequency standard, and therefore of the clock is determined by the width of the atomic transition to which the laser is locked: the narrower the transition, the more accurate the clock. The width of the band of frequencies emitted from a given transition is called the linewidth of the transition. Because of the Heisenburg uncertainty principle, the following relationship exists.

$$(\Delta\nu)(\tau) = \frac{1}{2\pi}$$

Here the natural linewidth is $\Delta\nu$ and the lifetime of the transition is $\tau$. From this we can see that the longer the lifetime, the smaller the natural linewidth.

However, if the atoms are in motion, there is a Doppler shift of the absorption and emission leading to a broadening of the linewidth. Because the Doppler width is proportional to the velocity of the atoms, reducing their motion narrows this width. Trapping and laser cooling can be used to eliminate the motion of the atoms so there is no first order Doppler broadening.

## III. TRAPPING

In this experiment, the indium ion is trapped in a Paul-Straubel trap, which is a variant of a Paul trap.

A Paul trap uses a radio frequency, ac voltage on a hyperboloid of revolution ring and two hyperbolic end caps, to create a quadrupole potential in the trap. Although a static electric field alone cannot create a potential well, the ac voltage creates an average force, pushing the ion to the center of the trap. The time average force is caused by what is called the pseudopotential. The pseudopotential has a well in the center of the trap in which an ion can be trapped.

In a Paul-Straubel trap, the endcaps are moved to infinity. This causes the trap to only approximate the quadrupole potential of a Paul trap, but the approximation at the center of the trap is very good, and the ion stays very near the center of the trap. In an ideal Paul-Straubel trap, the ring is still a hyperboloid of revolution, but in actuality, several ring geometries approximate a quadrupole potential. The trap that is used in this experiment is simply two wires twisted together to make a ring in the middle. The trap is not perfectly symmetric by design because this leads to oscillations of the atom being non-degenerate in the three directions, x, y, and z. In other words, the trapped ion will oscillate in the three degrees of freedom independently, while staying very close to the center of the trap.

## IV. LASER COOLING

Although the ion is trapped in the Paul-Straubel trap, it is still oscillating in all three dimensions. These oscillations are small, but in order to narrow the Doppler width of the clock transition, the atom must be cooled to essentially eliminate them. This is done by laser cooling the ion.

To cool an atom, a laser excites an atomic transition in the atom. The laser is red de-tuned so that the atom only sees the frequency necessary to excite the transition when it is moving toward the laser. After absorbing a photon, the atom re-emits one, but this emission is in random directions; therefore, it does not affect the net motion. The effect of the entire process is to slow down the atom.

Often several lasers are used to cool an atom, one for each degree of freedom. But, if the trap is designed so that the ion's oscillations in each dimension are different, then only one laser is needed. This laser must have a component of momentum in the direction of each degree of freedom. Then whichever way the ion is moving, it will see a portion of the laser beam traveling anti-parallel to its direction and this portion will slow down the ion. Since the oscillations of the atom are harmonic, only one direction of cooling will cause the entire oscillation in each degree of freedom to be decreased.

## V. WHY INDIUM?

There are several reasons why Indium is a good choice for an atom in an atomic clock. These reasons deal with the energy level structure of the valence electrons. The outer shell of Indium has two s electrons and one p electron. The p electron is stripped off leaving a positive ion with two electrons having the same quantum state with the exception of their spins. This configuration leads to an integral spin angular momentum, and therefore, an integral total angular momentum. When one of the 5s electrons is excited to the 5p level, there are two choices for the spin angular momentum (S). Either the spins will be in different directions, leading to an S value of zero, or they will be in the same direction, leading to an S value of one. These two states are called singlet and triplet states respectively. In the triplet state, the total angular momentum (J) can vary from $|L-S|$ to L+S. This will lead to J values of zero, one and two. Also, the ground state has zero total angular momentum. This means that there is a possible transition between two J=0 states, $5s^2\ {}^1S_0 \rightarrow 5s5p\ {}^3P_0$ (See Fig. 1). This type of transition is usually forbidden, but because of the coupling between the nuclear spin angular momentum and the total angular momentum of the electron, the transition is allowed. But, it has a lifetime of 140 ms. This transition is the proposed clock transition.

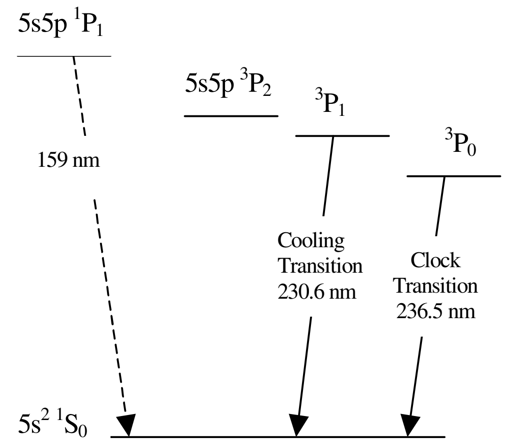


FIG.1. $In^+$ energy level diagram.

There are several advantages to having a J=0 to J=0 transition. First, there is no electronic Zeeman shift when the ion is placed in a magnetic field. Also, there is no quadrupole moment that would interact with the electric field gradients present in the Paul-Straubel trap. And, as mentioned above, the metastable nature of the transition leads to a long lifetime so the natural linewidth is very narrow, making it a perfect candidate for a clock transition.

It is also necessary to have a strong transition that can be used to cool the ion. The $5s^2\ {}^1S_0 \rightarrow 5s5p\ {}^3P_1$ is such a transition. It has a short lifetime ($\tau$=.44μs) and it is strong enough to be used for cooling.

In addition to having these transitions, it is necessary to have lasers that can excite them. The wavelengths are 236.5 nm for the clock transition and 230.6 nm for the cooling transition. Both of these wavelengths are available with current technology.

Finally, both the cooling transition and the clock transition have the same ground state, so the electron shelving technique can be used to detect when the clock transition has been excited. In the electron shelving technique, the florescence from the cooling transition is detected. Then, when an electron is excited to the metastable $^3P_0$ state, the florescence from the $^3P_1$ state stops. This is because with an electron excited to the metastable state, the atom cannot be excited to the $^3P_1$ state until the metastable state decays to the ground state. This technique causes almost all of the clock transitions to be detected, greatly amplifying the signal over conventional florescence detection methods.

## VI. LOCKING THE LASER

The ion is trapped and cooled so located at the center of the trap and is practically motionless. The clock laser is then pulsed twice. The probability of the atom being in the excited state then has a peak at $\omega=\omega_0$. Omega is the laser frequency and omega naught is the frequency of the atomic transition. If the frequency of the laser is shifted from one side of this peak to the other, an error signal will be generated which can then be fed back to the laser. This error signal can then be used to lock the laser to the frequency of the atomic transition.

## VII. "FLYWHEEL" LASER

The indium clock transition has a very narrow linewidth because of its long lifetime. The lifetime of the transition is 140 ms and this leads to a natural linewidth of about 1Hz. Because of the narrow transition, the laser that excites it must be tunable and very stable. The laser can only interrogate the ion about once a lifetime, so the laser must have short-term intrinsic frequency stability so it does not wander away from the transition between interrogations. This is often called a “flywheel” laser.

## VIII. FREQUENCY STABILIZATION

One common method of frequency stabilization is locking an oscillator to a resonator. The Pound-Drever method is one way of doing this; it involves locking the laser to a Fabry-Perot cavity.

A Fabry-Perot cavity consists of two mirrors. Usually these are spherical mirrors separated by a distance L (See Fig. 2). We used a cavity with one spherical mirror and one flat mirror. This type of cavity has the same transverse mode properties as a spherical cavity with mirror separation 2L. In a Fabry-Perot cavity, the outer faces of the mirrors are mostly transmitting and the inner faces are mostly reflecting. If a half-integer number of wavelengths of the incident light fit inside the cavity, the cavity is said to be in resonance and light builds up inside

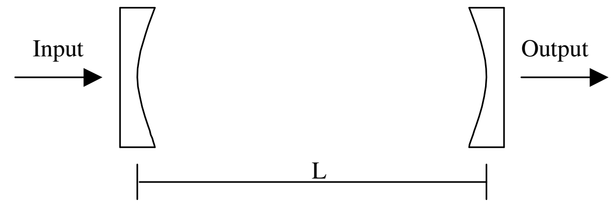


FIG. 2. Fabry-Perot Cavity.

it. When the cavity is in resonance, there are transmission peaks at frequencies of $\nu = mc/2n\mathrm{L}$. Here, $m$ is an integer, $n$ is the index of refraction inside the cavity, and $c$ is the speed of light. The peaks are separated by $\Delta\nu_{FSR} = c/2n\mathrm{L}$ which is called the free-spectral range of the cavity. The finesse of the cavity is $\mathrm{F} = \pi\sqrt{R}/(1-R)$, where R is the reflectivity of the mirrors. The higher the finesse, the narrower the resonance peaks. The width of the peaks (full width at half maximum) is

$$\Delta\nu_{\mathrm{FWHM}} = \Delta\nu_{\mathrm{FSR}} / \mathrm{F}.$$

In the Pound-Drever method, the laser light is locked to the resonance of the Fabry-Perot so that a half integer number of wavelengths fit into the length of the cavity. For this to be a good method of frequency stabilization, the length of the cavity must be constant. Otherwise, length changes will translate to frequency changes in the laser. To prevent changes in length, the mirrors of the cavity in this experiment are separated by a spacer made of Invar steel with a change in length per unit length of:

$$\frac{\Delta l}{l} = \frac{10^{-6}}{^{\circ}\mathrm{C}}.$$

Still, the temperature of the cavity must be regulated to within a milliKelvin to prevent almost all thermal expansion. A milliKelvin temperature change corresponds to a change in frequency per unit frequency ($\Delta f/f$) of $10^{-9}$. Also, the cavity must be isolated from vibrations in the lab.

## IX. TEMPERATURE STABILIZATION

My part of the project was to help design and build a temperature regulating circuit and to insulate the Fabry-Perot cavity. The circuit I built is shown in Figure 5. The part on the far left of the circuit is a bridge. The 23kΩ thermistor labeled THERM is attached with thermal epoxy to the heater, which is around the cavity. The 20kΩ reference resistor labeled R10 is insulated so its resistance does not change when the temperature of the room changes. When the resistance of both branches of the bridge is identical, the voltage at the two nodes is also the same.  This causes the output of op-amp U1 to be zero, and the heater's output is not changed.  But, if the reference resistor has a lower resistance than the thermistor, the heater output is increased.  At room temperature the thermistor has a higher resistance than the reference resistor, so at equilibrium the heater is turned on, and the cavity is kept slightly above room temperature.

The .01 μF capacitor (C1) and the 1MΩ resistor (R2) cause the gain to roll off at the angular frequency ω=1/RC.  This corresponds to a frequency of 15.9 Hz.  This filters out fast signals which is beneficial because they are likely to be caused by noise as opposed to actual temperature changes in the cavity.

The output of op-amp U1 is then connected directly to the error monitor op amp labeled U6.  This is used to see the output of the first op amp without changing the voltage at that output.  The error signal was calibrated to give a 3 Volt signal for every degree Kelvin of temperature change of the thermistor.

The second thermistor (REF THERM), shown below the bridge, is placed on the end of the cavity, a more exposed part than the first.  The output of the op-amp U5 then is a measure of the lower bound of the temperature stabilization.  From it, it is possible to tell the maximum that the temperature is changing in the cavity.

The rest of the circuit is the output stage.  The two 10kΩ resistors drop the voltage from the output of  U1 to half, which causes an immediate change at the output of U2.  The 2.2 μF capacitor (C2) and the 2.2 MΩ resistor (R6) act as an integrator.  This causes the output of the op amp to change at frequencies under ω=1/RC, leading to a high gain for DC and very low frequency signals.  The 20kΩ resistor and the 10μF capacitor add in some gain at higher frequencies.

Next, the transistors are in a Darlington configuration because op-amp U2 cannot provide enough current to turn on transistor Q2, a power transistor.  Therefore, the first transistor (Q1) amplifies the current at the output of the op-amp so the power transistor can be turned on.  The output of the Darlington is then attached to the heater.  The diode is connected between the input to the heater and ground to prevent burning out the power transistor by not allowing the emitter to drop significantly below ground as it could for an inductive load.

Finally, op-amp U7 monitors the output to the heater.

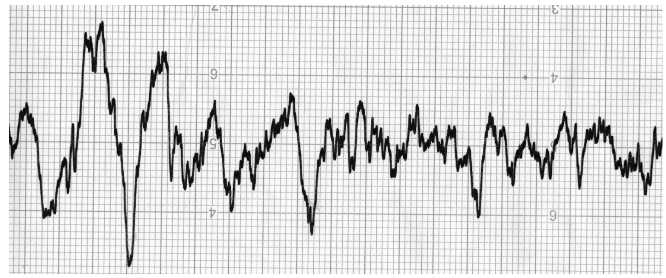

FIG. 3.  Error signal from a test run of  the temperature control circuit.  Each major vertical division represents a 1.4 milliKelvin temperature deviation. Each major horizontal division represents 6 minutes.

The circuit was tested using a metal bar wrapped in heater wire and placed in a box of foam peanuts.  The results from this test are shown in Figure 3.

After the circuit was tested, the next step was to insulate the cavity.  To do this I used the lathe to machine foam insulation into a cylindrical tube with one end closed.  The cavity then fit inside this tube.  A 50 Ω heater, made of heater wire attached with thermal epoxy to a thin sheet of copper, surrounded the cavity.  The insulation and cavity were then placed inside a PVC pipe, and nylon end caps were placed on the ends of the pipe.  This provided added insulation and protection for the foam.  The insulation led to a temperature stabilization of the cavity to about 1/5 of a milliKelvin if the PVC pipe was not touched.  Touching the PVC caused the temperature to rise a few milliKelvin.  Figure 4 shows the error data from the stabilized cavity.  The peaks are when the PVC was touched.

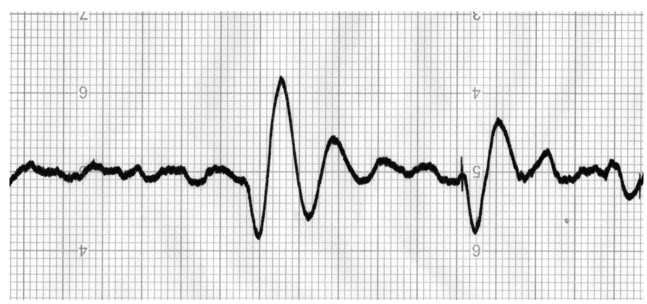

FIG. 4.  Error signal vs. time, with the temperature control circuit attached to the insulated Fabry-Perot.  The peaks are when the cavity was touched.  Each major vertical division represents 1.4 milliKelvin of temperature deviation.  Each major horizontal division represents 6 minutes.

## X. VIBRATION ISOLATION

It is also necessary for the cavity to be isolated as much as possible from the vibrations in the lab.  To accomplish this, the cavity will be built on an aluminum breadboard and then suspended by weak springs. The breadboard can be suspended from the ceiling or from posts standing on the floor or table.

Because the cavity will be suspended, it is necessary to couple the light into the cavity using an optical fiber. Otherwise, as the table vibrated and the cavity did not, the laser would lose lock to the cavity. Also, the fiber and all the wires connected to the cavity are required to be limp to decrease vibrational coupling.

## XI. THE FUTURE

In the near future, the laser will be locked to the Fabry-Perot cavity and the cavity will be suspended for vibration isolation.

After this occurs, the search for the frequency of the clock transition will begin. After the general location is found, the laser will be locked to a higher finesse cavity that will cause the laser to have a stability of about 1Hz. The laser can then be locked to the clock transition in Indium leading to a frequency standard.

After the frequency standard is realized, it will be necessary to implement a method for counting the oscillations to create a clock. The technology needed to count ultraviolet oscillations directly is not currently available, so this will be another goal of future research. However, a frequency standard of this unprecedented accuracy could find use in many sensitive measurements.


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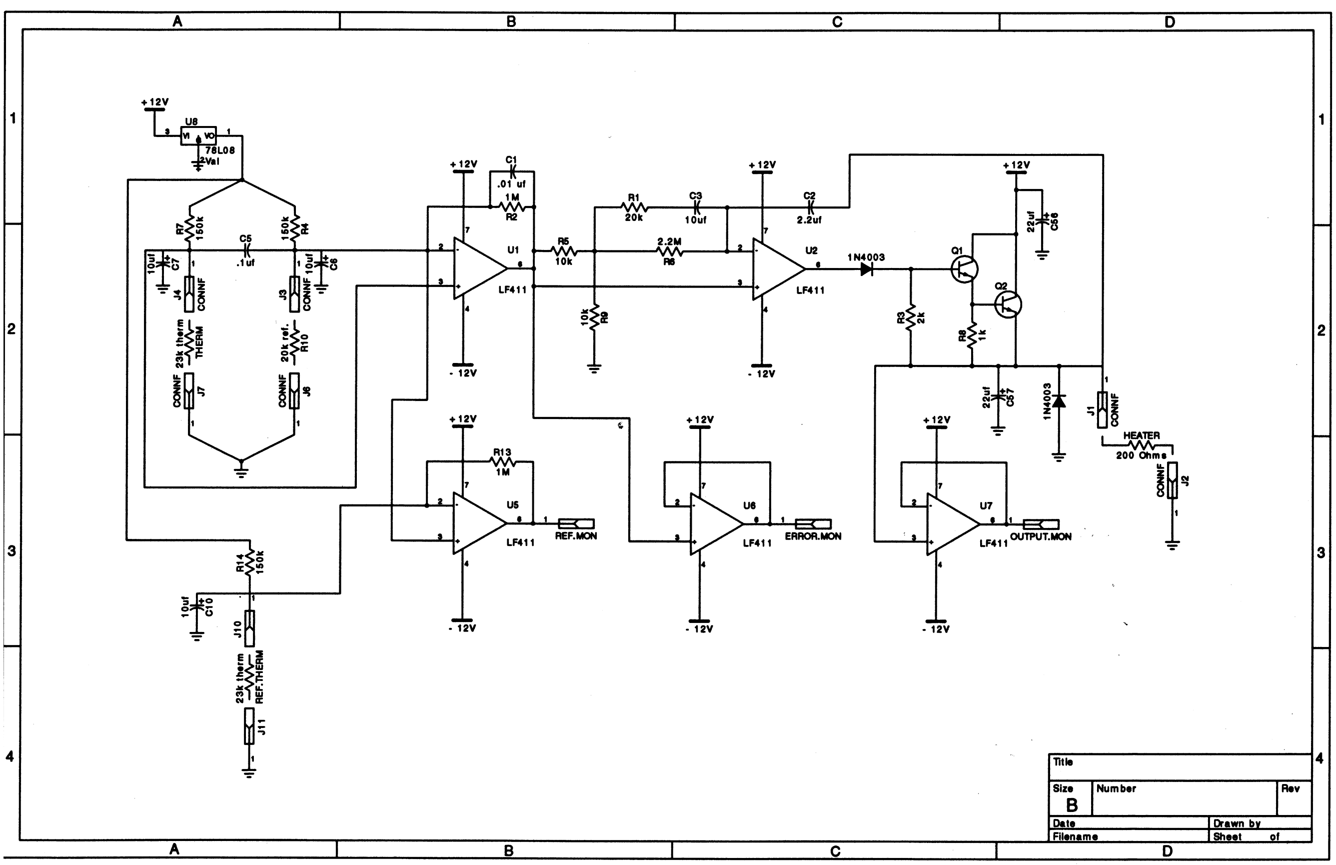


FIG. 5. Schematic of the temperature control circuit.

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