A Rotating Bias Field for Use in a BEC Interferometer

Kenneth Lawrence Baranowski

Tabernacle, New Jersey

Bachelor of Science in Physics,

The College of William & Mary in Virginia,

Williamsburg, Virginia, 2001

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I ask nothing more than to be able to grow in strength, and achieve the ultimate of my possibilities.

Edward Weston, *The Daybooks*

Acknowledgments

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Chapter 1

Interferometers: Their History and Uses

1.1 History

In the late 19th century Physics believed it had exhaustively explained everything in the universe. Physicists just had a few loose ends to tie up before everything was understood.

> ..and it came to be believed that the main lines of scientific theory had been laid down once for all, and that it only remained to carry measurements to the higher degree of accuracy represented by another decimal place, and to frame some reasonably credible theory of the structure of the luminiferous ether. [13]

Therefore, the big question of the day was the existence of the ether through which electromagnetic waves propagate and on which many physical theories were predicated. The ether transmits electromagnetic disturbances just as water propagates waves. In the ether frame, light moves through the vacuum at c, the speed of light [35]. Therefore, if you were moving through the ether, then you would notice a difference in the speed of light in your reference frame according to Galilean Relativity.

The Earth was understood to move through the ether, so Albert Michelson[1], later aided by E. W. Morley, developed an apparatus which would send light in two, perpendicular directions and then watch the interference pattern as the entire apparatus was rotated 90°. If the fringes moved then the speed of light was different in the two directions. This fringe movement would imply the existence of the ether and allow the Earth's velocity through the ether to be determined. Many physicists assumed the existence of the ether and were just waiting for someone to present the experimental proof. But Michelson and Morley found nothing. Michelson and Morley were unable to detect any deviation in the speed of light, as Ronald Clark explains:

> Designed to show the existence of the ether, at that time considered essential, it had yielded a null result, leaving science with the alternatives of tossing aside the key which had helped to explain the phenomena of electricity, magnetism, and light or of deciding that the earth was not in fact moving at all... [12]

This shock to Physics would inspire Einstein's Theory of Relativity.

General Relativity does an excellent job describing the interaction of massive particles with space and time and other massive particles, but gravitation has yet to be phrased satisfactorily as a field theory.[2] Gravity also has yet to be unified with the Electromagnetic, Weak and Strong Forces. Gravity still holds many secrets. An experimental verification of the Lense-Thirring effect of General Relativity would further verify the theory and increase our understanding of gravity [30].[3] The results of the same device that stimulated Einstein's imagination over a hundred years ago may again provide answers to gravity's most fundamental questions. An interferometer which can precisely measure phase differences will further unravel these questions allowing us to glean more information than any other interferometer has. It is this interferometer that we are building.

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[1] born in Strzelno, Poland (but under Prussian control)

[2] See for instance [8]

[3] While the interferometer we are constructing will not have the sensitivity needed to directly observe the Lense-Thirring effect later modifications to our apparatus may.

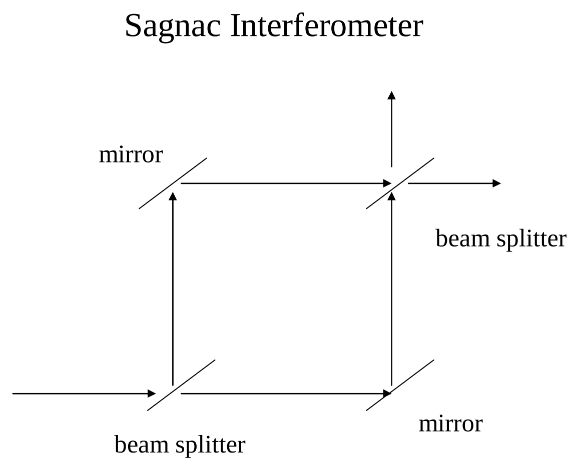

Figure 1.1: A Sagnac interferometer. When the beam is made of light the beam splitter can be a piece of glass. When the beam is made of massive particles the beam splitter and mirrors must be carefully crafted laser beams.

Above we have listed the fundamental questions. There are at least two other reasons for interest in BEC interferometers. The first is practical; an interferometer would be a great tool for navigation. An interferometer senses rotations because rotations shorten one of the arms of the interferometer while lengthening the other arm. Imagine Fig. 1.1 rotating. As a wave is split one part would travel up and the other right. By the time the wave reaches the recombining element the lower branch (for clockwise rotations) has traveled a shorter distance than the upper path. This difference in path length can be measured and connected with the rotation speed. The measurement of rotations is important not only for navigation but also for Geophysics where the composition of the Earth can be studied by knowing exactly how the Earth rotates [30]. So, though navigation is one use for a rotation sensitive interferometer, another is the study of the Earth's composition.

Another reason for interest in BEC interferometers is both fundamental and applied. An interferometer can measure differences in the gradient of the gravitational field. Investigating the gradient in the gravitational field is yet another piece in gravity's puzzle and so interesting fundamentally. Yet, there is an associated practical concern: oil.[4] Oil deposits have a different density than the earth that surrounds them, this density disparity can be sensed by measuring the gradient of the gravitational field.[5] We now see that the rotation sensing capabilities along with detecting gradients in the gravitational field make a precise interferometer a worthwhile goal and so justify our discussion of the intricacies associated with making a BEC Interferometer.

1.2 Massive Interferometric Particles

An ideal laser interferometer has mirrors and beam splitters that are fixed relative to each other.[6] Vibrating mirrors or beamsplitters introduce a phase shift into one of the beams obfuscating any interferometric measurements. Manipulation of laser light is simple, but using massive particles will require their splitting, diversion and recombination. We will need to use lasers for these tasks. With massive particles we must separate the localized collection carefully into two groups. An individual particle's wavefunction must be represented by:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}[|\Psi(r_1)\rangle + |\Psi(r_2)\rangle]. \tag{1.1}$$

Notice that every single particle is in a superposition of being in each of the two arms of the interferometer.

To actually split the beam we will use laser light. By applying counter-propagating beams with wave-vectors **k** and -**k** you can split the beam into three pieces: one that did not interact with the laser beams, and two with equal magnitude of their momentum, but in opposite directions ($\pm\, 2\hbar$k). This is exactly what would happen if you applied a laser beam to a diffraction grating. The beamsplitter will deflect the atoms which absorbed momentum from the laser beam. Therefore, we can use a magnetic field and dressed atomic states to put the atoms in superpositions of internal states so that we get the Ψ given in Eq. 1.1.

[4]Not just oil, but mineral deposits, water deposits, or other large deposits with a different densities than the surrounding material can be sensed.

[5]This is how divining rods were supposed to work.

[6]Currently the world's most precise interferometer is a ring laser interferometer.

To manipulate our atoms we will transfer the momentum of the photons in the laser beam to the atoms.[7] Lastly, we will use another atomic beamsplitter to spatially overlap the two beams for imaging.

1.3 Good Interferometers

For Michelson and Morley a good interferometer meant isolating their apparatus from vibrational sources. Today's optics tables which sit on cushions of air practically alleviate that concern. However, we must still worry about relative changes in the location of optics, which are due mostly to temperature drifts. Further, as the TOP section will explain, the frequency of the rotating bias field can be chosen in a range of frequencies. Vibrations at the chosen frequency will not be cancelled by the rotation of the bias field, and so it will be important to choose a frequency for the bias field in which the background is small.

[7] analogous to Michelson and Morley's mirrors

Chapter 2

Bose-Einstein Condensates as Beam Particles

Interferometric beams can be made of massive particles as well as photons. Both atomic and BEC interferometric experiments have been documented, for instance by Wolfgang Ketterle [5], [31]. BEC has a rich history and its experimental realization in dilute atomic gasses was very challenging due to the extremely cold temperatures necessary. Furthermore, confinement of atomic gasses in order to cool them is non-trivial and resulted in both the Magneto-Optical Trap (MOT) and the Time-Orbiting Potential (TOP) trap. Let's explore BEC in order to understand what advantages it may yield.

2.1 Historical Background of Bose Einstein Condensation

To begin, what is Bose-Einstein Condensation?

> BEC is a common phenomenon occurring in physics on all scales, from condensed matter to nuclear, elementary particle[1], and astrophysics[2], with ideas flowing

[1]Quark antiquark operator pairs have non-vanishing expectation values related to spontaneous chiral symmetry breaking of the strong interaction [26].

[2]BEC is suggested to exist in neutron stars where kaons replace electrons. This implies that to become a black hole a less massive star is necessary than was otherwise expected [10].

across boundaries between fields [32].

Ideally, BEC exists when a finite number of bosons ($\gg 1$) occupy the lowest single particle energy state [25]. For years the only experimental example of BEC was superfluid ^{4}He [32], but that would change.

In 1924 an Indian physicist, Satyendra Nath Bose, developed a theory for photons in which all photons could condense into the ground state [9]. Bose had a difficult time getting his work published and so sent it to the very influential Albert Einstein for his comments. Einstein saw the article's importance and so translated and submitted the article for Bose to Z. Phys. [12]. Einstein then continued Bose's work with massive particles whose number was conserved.[3]

Einstein found that below a certain temperature a finite fraction of the particles would be in the lowest energy single particle state [16]. This began a 70 year quest for experimental verification of Bose-Einstein Condensation. With almost eighty years between today and Einstein's paper there are five systems in which BEC has been realized: liquid ^{4}He, spin-polarized atomic alkali gases, atomic Hydrogen, metastable He atoms [29] and excitons [27].

BEC in dilute gases was first realized in 1995 by Cornell's group in ^{87}Rb [4], Li by Hulet's group[10] and in Na by Ketterle's group[14]. In a non-ideal dilute atomic gas the atoms have a non-zero interaction energy. Therefore, the ideal definition of BEC, where all of the atoms are in the single particle lowest energy state, is less than satisfactory. Certainly, the interatomic interaction energy will prohibit all of the atoms from being in the single particle ground state; instead, the atoms will have slightly different energies. BEC really occurs when bosons are in the multiparticle ground state. A complementary definition of BEC says that when the interatomic spacing becomes smaller than the thermal de Broglie wavelength one has a BEC [4]. So the individual atomic wavefunctions, which are exactly the same, overlap. The realization of such a situation would prove to be technically challenging. Not only is spatial confinement necessary, but the constituent particles need

[3] unlike Bose's theory in which photon number isn't conserved.

to be colder than anywhere in Nature.

2.2 Techniques for Low Temperatures

A major impediment to creating BEC in the lab in dilute gases was the extremely cold temperatures necessary to slow the atoms down enough to move the atoms close enough to allow their de Broglie wavelengths to overlap for an extended period of time. The coldest recesses of space have a temperature of about 2.7 Kelvin. To put in perspective, in the first BEC in a dilute atomic gas, Cornell's group [4] cooled their sample of ^{87}Rb atoms to an amazing 170 nK. That's more than a million times colder than the coldest parts of the universe! This is quite a challenge and so we'll begin our discussion of the techniques we'll use in our experiments.

2.2.1 An Overview of the Cooling and Trapping Sequence

The atoms are first dispensed as atomic ^{87}Rb. They are then collected in a Magneto-Optical Trap (MOT 1). At this point there are around 10^9 atoms in the trap and they're at about 200 μK. Next, the magnetic and optical fields confining the atoms in the first MOT are switched off so the atoms can be pushed with the push beam into the second MOT (MOT 2). The atoms are further cooled in MOT 2. Next, we optically pump the atoms while they're in a uniform **B** field to put the outermost electron into the desired Zeeman state. A magnetic trap is then applied. Next, the trap is compressed and we engage the Time-Orbiting Potential on which this thesis focuses. Finally, we evaporatively cool the sample to the Bose-Einstein Condensation Temperature and voilà BEC!

2.2.2 Doppler Shift Cooling

^{87}Rb is vaporized by getters within the vacuum system. In order to slow the atoms down we use light detuned from the atomic resonance. According to Special Relativity an observer moving at any speed relative to a light beam will see a Doppler shift in the frequency of that light:

$$f' = \sqrt{\frac{1+v/c}{1-v/c}} f_0 \tag{2.1}$$

if the observer is moving toward the emitter, while if the observer is moving away from the emitter replace v with -v. Consequently, if an atom is moving toward a laser source of a resonant frequency, that beam will appear blue detuned. Therefore, red detuned light will appear resonant. So Doppler shift cooling is when red detuned light is shined on a beam of atoms which in turn absorbs the momentum from those photons in order to slow the atoms down. In order to fully take advantage of laser cooling we also need to have present a magnetic trap.

2.2.3 Magnetic Trapping

Any particle (fundamental or composite) with a magnetic moment can be spatially confined by using an inhomogeneous magnetic field. The interaction energy of a magnetic moment in a **B** field is given by:

$$E = -\vec{\mu} \cdot \vec{B}. \tag{2.2}$$

Where

$$\mu = -g_f m_f \mu_B \tag{2.3}$$

and μ_B is the Bohr magneton.

We see in Eq. 2.2 that the location of lowest energy is where **B** = 0. Therefore, a magnetic moment will be drawn to the location of the minimum in the magnetic field just as a marble is drawn to the lowest point in a bowl. The presence of the magnetic field splits the F=2 energy level into five levels ranging from m_f = -2...+2.[4] As can also be seen in Eq. 2.2 the levels with positive m_f will have a negative energy and be trapped, while those states with a positive m_f relative to the **B** will have a positive energy and thus be ejected from the trap. Doppler shift cooling and magnetic trapping will cool and confine our atoms,

[4]F = I + S, where I is the nuclear spin. I = 3/2 for Rb, therefore the two's are because for Rb F = 2.

but in order to get colder we will need to use weaker fields and more cleverly engineered laser light.

2.2.4 Magneto-Optical Traps

Magneto-Optical Traps (MOTs) use magnetic fields similar to magnetic traps, however MOT magnetic fields are weaker because the confining force comes from the lasers. A standard MOT uses a quadrupole magnetic field with a zero of the field in the center of the trap (z = 0). As the atoms move away from the zero point of the field the m states are Zeeman shifted. For instance, let's say states with $m > 0$ are shifted to higher energies on the right of the zero point (z > 0), while $m < 0$ states are shifted down in energy on the right (and therefore up on the left, z < 0) [29]. We can take advantage of these shifts by using two beams of light, both red shifted, of equal intensity and circularly polarized. If we shine σ_- light to the left and σ_+ light to the right, then on the right atoms will absorb more σ_- light than σ_+ light because the inhomogeneous field will shift the $m < 0$ states to the red while $m > 0$ states will shift to the blue becoming even more non-resonant. This results in radiation pressure pushing the atom back to the zero point of the field. The converse occurs on the left, where more σ_+ light is absorbed, which pushes the atoms back to the center. By using six laser beams, oriented as mentioned above, it is possible to create a 3-D trap.

2.2.5 Push Beam

Once the first MOT has trapped the atoms there is still a background of very hot ^{87}Rb atoms with pressure of 10^{-8} Torr. In order to lower the trapped atoms to the critical temperature and, certainly, to do our interferometric experiments, we need a quieter background. We will accomplish this by moving the atoms several feet to a second Magneto Optical Trap. We will move them by shining a pulse sequence of photons, which will transmit their momentum to the atoms. This trap won't be mired by having a flow of hot ^{87}Rb atoms constantly bumping into the trapped atoms. In fact, MOT 2's pressure is 10^{-11} Torr. Here, we will be

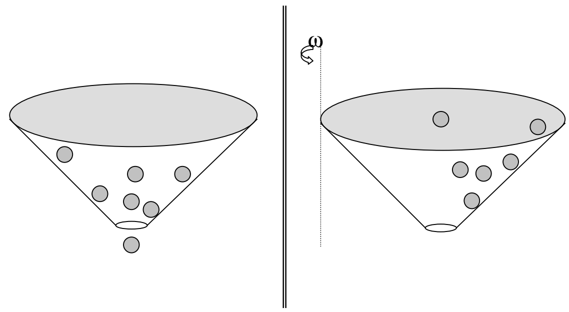

Figure 2.1: On the left is a funnel filled with marbles which will reach the hole in the funnel and escape from the funnel. On the right we have a funnel spun by its edge. If the frequency is chosen properly the marbles won't be able to roll out of the hole, but will be stuck up a height on the walls of the funnel. Our TOP trap works analogously with atoms replacing marbles and our trapping fields replacing the funnel.

able to further cool the trapped atoms to the critical BEC temperature and also accomplish highly sensitive phase measurements.

2.2.6 Time Orbiting Potential (TOP) Trap

Atoms will be confined in our trap and pulled toward the minimum in the magnetic field. In our trap, the minimum is a zero of the field. This will cause confined atoms, which have $m_f > 0$ and pass through the zero, to then have $m_f < 0$ relative to the applied magnetic field. This happens because as the atoms pass through the zero point of the field, the direction of the magnetic field changes. Therefore, the previously trapped atom is ejected from the trap because of its positive energy.[5] The ejection of once confined atoms is a leak in our trap. Short of using a trap without a hole, there have been at least two proposed ways to remedy this problem. Ketterle suggested plugging the hole with laser light in order to dissuade atoms from getting too near the hole [14]. The approach we take is based on Cornell's solution [4]. We propose to apply a rotating **B** field superposed with the already present quadrupole field. The zero point rotation circulates the hole much like marbles in

[5] See Eq. 2.2

a funnel spun by its edge, see Fig. 2.1.

The frequency of the rotating field is constrained both from above and below. First, the rotation must be slow enough that atoms' spins can adiabatically respond to the change in the zero point of the field. This will ensure that atoms once confined will remain confined. If the field is rotated too quickly then atoms whose magnetic moment was once aligned with the magnetic field would find themselves antialigned and would be ejected from the trap. Stated a different way, the trap must rotate below the Larmor frequency [6]. Second, the rotation must be fast enough that the confined atoms are unable to reach the zero point. Otherwise, the atoms would still leak out of the trap. Between these limits we will have very cold atoms confined in what is fondly termed the "circle of death" which will be evaporatively cooled.

2.2.7 Evaporative Cooling

The atoms in the TOP trap are at about 200 μK. But to reach BEC in ^{87}Rb we need our sample at about 200 nK. Evaporative cooling is a process whereby the more energetic, trapped atoms are allowed to escape thus lowering the average temperature of the sample. We will accomplish this by using rf waves to cut off the top of our parabolic trapping potential. Atoms whose energies are above this level portion of the trap will be able to escape. While we will lose atoms in this process, it will bring us below the critical temperature and leave us with a BEC.

2.3 A BEC Interferometer

Just forming a BEC is very challenging. However, that is just our first step. BEC is merely the means by which we will be able to accomplish our interferometer. In order to appreciate the uniqueness of our interferometer, let's explore how other groups are using atoms and BEC to make interferometers.

[6]Recall, the Larmor frequency is the frequency a magnetic moment rotates in a magnetic field.

2.3.1 Techniques and current state of Atom and BEC Interferometers

Recently Shin et al. [31] have split a BEC in a single well potential in two by dividing the single well into a double well. They then held the separated condensates for up to 5 ms until they dropped the two condensates letting them overlap through ballistic expansion. The condensates were allowed to overlap during 30 ms of ballistic expansion and were not confined to any path. Therefore, the enclosed area of the interferometer was very small. Shin et al. do report that this matter wave interference pattern was highly reproducible (standard deviation of $< 40\,^{\circ}$). While this experiment showed an interference pattern, this apparatus can not measure rotation nor could long times (on the order of seconds) be realized.

The best matter-wave interferometer is that of Gustavson et al. [17]. This group uses an atomic beam Sagnac interferometer employing Raman transitions to coherently divide atoms. With this device they have recorded a sensitivity of 6 x 10^{-10} $\frac{rad}{sec}\frac{1}{\sqrt{Hz}}$. While their results are impressive there are advantages to be exploited by using a BEC. Their sensitivity is a factor of two less sensitive than our proposed interferometer which should have a sensitivity of at least 10^{-11} $\frac{rad}{sec}\frac{1}{\sqrt{Hz}}$.

There are three main advantages with BEC interferometers [30]. First, since our BEC will be moving slowly it will require a very small force to manipulate it. This will allow us to enclose a large area, in order to sense rotations, by using weak laser beams. Second, BEC has atoms all of which are in a definite wave function, unlike thermal atoms. Therefore, not only will our patterns be reproducible from condensate packet to condensate packet, but rather each atom should pass through the interferometer in exactly the same manner. Third, condensates have atoms with the same energy, therefore any atomic differences must be motional. This allows us to split and recombine our atoms based only on their motion and not the superposition of internal states on which Gustavson, et al. [17] relies. While [17] have evolved their current design from several previous generations to reach their current level of sensitivity, the three advantages BEC offers should allow us to begin with an interferometer whose sensitivity already surpasses the current state of the art.

Chapter 3

Our Trap

Our trap is composed of four rods and two coils as can be seen in Fig. 3.1. First, we have two anti-helmholtz coils which set up the quadrupole field establishing axial confinement. Each of the rods is actually two rods, one imbedded within the other. The outer rods create a quadrupole field which provides radial confinement. Finally, two pairs of the inner rods carry current produced by Ch. 4's circuit to establish two dipole fields which will be phase locked to create a rotating magnetic bias field which is the focus of this work. So, our trap has two z-coils for axial confinement, four rods for radial confinement and two dipole circuits for the rotating bias field.

Recall that this trap has a hole which needs to be circulated by the rotating bias field produced by two current sources. The sources are 90° out of phase with one another. The rotating field configuration creates a magnetic field that is constant in magnitude at the center of the trap and rotates in space and time, which will move the zero point of the net magnetic field. [1]

3.1 Bias Field: Electronic Overview

An Agilent 33120A 15MHz/Arbitrary waveform generator provides the input current to a current amplifying circuit. Fig. 3.2 shows a simplified version of how we propose to amplify

[1]see the TOP trap section for details regarding the rotation frequency

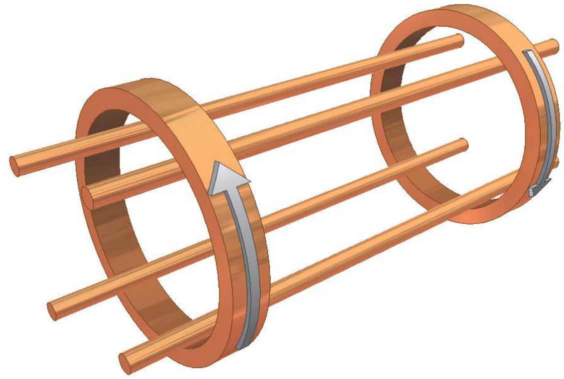

Figure 3.1: A drawing of our trap. The anti-helmholtz coils will create a quadrupole field for axial confinement. The four rods will create a quadrupole field for radial confinement. The four rods will also carry 50 kHz currents in pairs, where the two rods furthest from one another are a pair. The two pairs will be 90° out of phase with each other, creating a rotating bias field. This trap will provide weak confinement, $(\bar{\omega_x}\bar{\omega_y})^{1/2} = 2\ \pi$ x 2 Hz [30]. Drawn by Jeramy Hughes.

the current. The signal first enters an operational amplifier and then passes through the power amplifying circuit described in Chapter 4. This output goes through a transformer which amplifies the current by a factor between[2] 7.9 and 9.2 and diminishes the voltage by the same factor.[3]

After the transformer the signal passes through the trap. Lastly, there are two 0.22 μF capacitors connected in parallel with each other and in parallel with four 50 Ω 2 Watt resistors connected in series (effectively 200 Ω) with each other. The capacitors are present to cancel the inductance of the trap. Since

$$Z = R + \frac{1}{i\omega C} + i\omega L \tag{3.1}$$

Then if a capacitor and an inductor are connected in series the inductance can be cancelled

[2]See the Transformer section in this Chapter for details

[3]Remember transformers do not have any power connection, and therefore an ideal transformer must conserve power (P = I V).

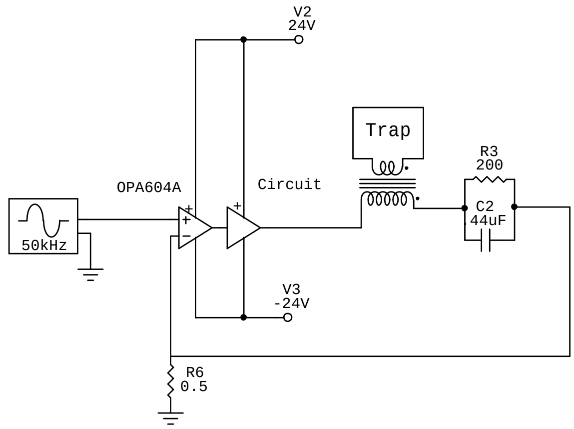

Figure 3.2: Simplified circuit diagram with the power amplifying circuit of Chapter 4 marked as a unitary gain amplifier (which it is).

by choosing a particular capacitance value

$$C = \frac{1}{\omega^2 L} \tag{3.2}$$

Therefore the net impedance of the R, L, C circuit is R.

Fig 3.2's 200 Ω resistor is present to allow a negative feedback path for DC currents. Without this resistor a DC difference between the + and - pins of the op-amp couldn't be compensated for. Without this compensation the op-amp output would remain at either the high or low rail since it would be unable to alter the output's DC level. The negative feedback to the operational amplifier is also connected to one side of the 0.5 Ω sense resistor. The other side of the sense resistor is connected to ground.

3.2 Signal Generator

The Agilent 33120A Waveform Generator can output a 10 V_{pp}[4] signal with an output impedance of 50 Ω. Therefore, the peak to peak Current is 0.2 $Amps_{pp}$. Agilent lists their

[4] Vpp indicates Volts, peak to peak. The amplitude, therefore, is the peak to peak voltage divided by 2: $V_{amp} = V_{pp}/2$.

signal generator as having an amplitude accuracy of 1%, total harmonic distortion from DC to 20 kHz[5] of $< 0.04\%$, and phase noise being less than -55dBc in a 30 kHz band [1].

3.3 Transformer

The Transformer is a West Coast Magnets WCM406 E28[6]. The transformer has a power efficiency[7] of 74.6%. We were able to measure the current on the input side of the transformer by monitoring the voltage drop across a 1 Ω resistor. On the trap side of the trasformer we calibrated a 6 ft length of wire wrapped around a toroid to measure the current.[8] The current ratio depends on the load as Table 3.1 reflects:

Pathway	Magnitude of Current Ratio	Phase of Current Ratio
Quadrupole	9.2 ± 0.3	$2.7^\circ \pm 3.2^\circ$
Z coils	8.0 ± 0.1	$2^\circ \pm 0^\circ$
Bias 2	7.9 ± 0.1	$1.3^\circ \pm 0.6^\circ$
Bias 1	8.6 ± 0.2	$5.3^\circ \pm 6.4^\circ$

Table 3.1: Complex Current Ratio of the WCM406 E28 transformer.

We now understand the transformer to behave as shown in Figure 3.3.

3.4 Current Meter

We use a current meter for three pieces of information. First, we need to measure the magnitude of the current flowing into the trap. Second and third, we need to measure both the magnitude and phase of the impedance of the trap. We wrapped a small gauge wire around three metal washers to give a toroidal shaped current meter. By using the current

[5] which hopefully also applies at 50 kHz where we will be performing our experiments
[6] see http://www.wcmagnets.com/images/pdf/wcm406.pdf for more details
[7] Power efficiency is P_{in}/P_{out}.
[8] see the next section for details

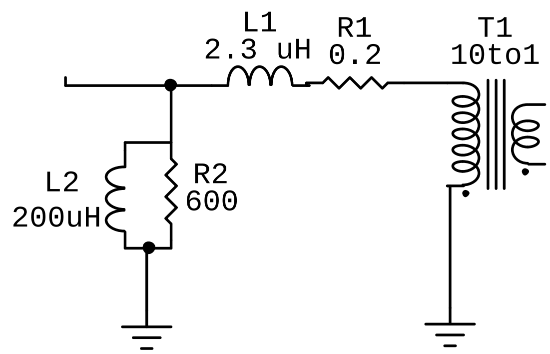

Figure 3.3: Schematic of the actual electrical characteristics of the transformer.

flowing through a 0.1 Ω precision resistor, we found that the Voltage drop across the ends of the wire coil was related to both the current and the frequency by the following equation:

$$V = I(\sqrt{f})(0.72\frac{m\Omega}{\sqrt{Hz}})e^{i44^\circ} \tag{3.3}$$

Where I is the current being measured and f is the frequency of the signal. Once we know the complex current[9] we can measure the phase and magnitude of the impedance of any device which are given by:

$$\frac{V}{I} = Ze^{i(\Phi_{voltage} - \Phi_{current})} \tag{3.4}$$

which is the complex Ohm's Law.

3.5 Electrical Characteristics of Our Trap

There are four electrical paths current will take through the trap each with a pair of connections. One pair is for the two coils[10] which can be seen in Fig. 3.4. Another pair is for the quadrupole field generated by the four rods.[11] The remaining two pairs are for the rotating bias fields which are accomplished by running a current through the pairs of rods

[9]both magnitude and phase relative to the voltage
[10]the Z coils
[11]labeled Quadrupole

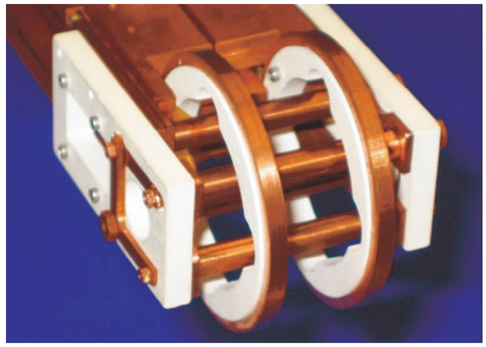

Figure 3.4: An image of our trap.

Path	Impedance (Z)
Quadrupole	69 mΩ e^{i53°
Z Coils	87 mΩ e^{i71°
Bias 2	67 mΩ e^{i67°
Bias 1	72 mΩ e^{i71°

Table 3.2: The impedance of the four pathways generating: the axial confinement (Z Coils), the radial confinement(Quadrupole), and the two bias fields (Bias 1 and 2) which rotate the zero point of the field.

that are furthest from each other.[12] This gives us two loops which create dipole fields. The two loops' relative phase will be locked at 90°.[13]

Each of these paths has its own complex impedance value and phase which is summarized in Table 3.2.

[12] labeled Bias 1 and Bias 2

[13] see TOP trap section in Ch. 2

Chapter 4

The Circuit

A rotating magnetic field is needed to shift the zero in the magnetic field. This zero would otherwise be statically located at a point near the center of the trap due to the axially and radially confining quadrupole fields. Without this rotating magnetic field, trapped atoms would move toward the zero point in the field and be ejected from the trap. We have chosen Cornell's solution to this problem [4] which is to move the zero point in the field in a circle slowly enough to be adiabatic, but fast enough so the atoms won't be able to catch up to the zero and escape from the trap. The zero point will be rotated by phase locking and superposing two magnetic dipole fields whose magnitude and direction sinusoidally oscillate. The current provided by a commercial signal generator is too small to create the field strength we need. Therefore, we need to build a power amplifying circuit to deliver the necessary current.

We begin this chapter with some background on the push-pull design and components that we'll use in our circuit design. Then we'll step through how the circuit works, on paper. By troubleshooting the easy stuff first and then following the signal through the circuit you'll most quickly find any problems in the circuit that arise. Finally, we'll look at the fabrication process and the circuit's remarkable performance in the real world.

4.1 An Overview of the Circuit

The power amplifying circuit has three main parts. First, a current source provides a DC bias current to the Push-Pull section of the circuit. Second, an operational amplifier regulates the output waveform. Third, a push-pull sequence amplifies the current. A push-pull is a transistor configuration in which current magnitude can be increased for a bipolar signal. These three pieces allow us to produce a 4.8 Amp output signal that's almost as clean as the 0.1 Amp input signal.

4.1.1 A Brief Introduction to Transistors

Transistors are three pin semiconductor devices in which each pin is connected to either an n or a p layer. P type semiconductors have fixed electron acceptor atoms with free holes and N type semiconductors have fixed donor atoms and free electrons [2]. An internal potential barrier occurs when an n type semiconductor has an interface with a p type semiconductor. There are, as always, impurities in both semiconductor regions which feel the electromagnetic pull to cross the barrier between the regions. In so doing they make the p region positive and the n region negative. This two region situation is known as a diode. Once the neutrality of both regions is again established electron current will flow from the n junction into the p junction. The neutrality is attained when the voltage difference between the n and p regions equals the diode's drop, V_D.

Transistors come in two flavors, npn or pnp. They are comprised of three regions and so two interfaces where each interface looks to a voltmeter like a diode. The collector and emitter of the transistor attach to the two similar semiconductor regions[1] while the base connects to the dissimilar layer. What distinguishes transistors from diodes, however, is that the current into the base dictates the current that flows into the collector and therefore out of the emitter:

$$I_C = \beta I_B, \tag{4.1}$$

[1] n for an npn and p for a pnp transistor

where

$$I_E = I_B + I_C \tag{4.2}$$

So we get:

$$I_E \simeq \beta I_B, \tag{4.3}$$

since β is usually between 50 and 200 we can neglect the one less factor of I_B and thus arrive at Eq. 4.3. In order for Eq.s 4.1 through 4.3 to apply the collector voltage must be more positive than the emitter voltage (for an npn[2]). Also, the current at the collector depends on both temperature and the difference in voltage between the base and the emitter.[3]

4.1.2 Operational Amplifier

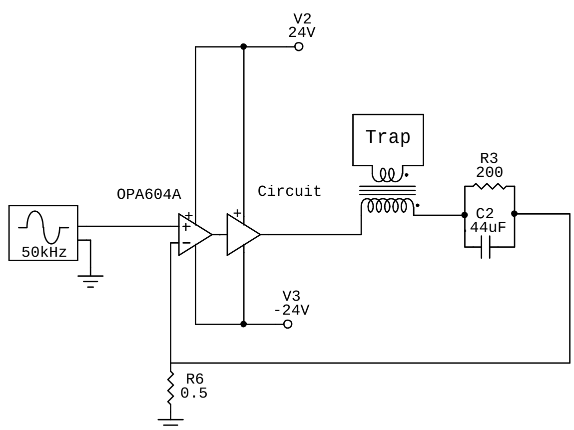

Figure 4.1: Schematic of entire circuit with the power amplifying circuit marked as a unitary gain amplifier.

The power amplifying circuit is a push-pull configuration with a built in current source. There is also an OPA604A operational amplifier (op-amp) before the push-pull circuit which matches the output signal to the input signal. This is accomplished by using negative feedback from the 0.5 Ω sense resistor. The op-amp's mission is to make the positive signal

[2] reverse this statement for a pnp

[3] Ebers-Moll and Early effects

input (pin 3) match the negative feedback (pin 2) it receives by adjusting its output (pin 6). Therefore, the current flowing through the load is the voltage at the negative feedback pin divided by the sense resistor.[4] The output of the op-amp is constrained to be between the lower rail (-24 VDC) and the upper rail (+24 VDC). The output of the op-amp is connected to the push-pull circuit which has unity voltage gain, but a tremendous current gain.

4.1.3 Crossover Distortion

Only the transistor attached to the positive (negative for a pnp) power supply can produce a positive (negative) voltage at its collector. Therefore, when dealing with bipolar input signals you need two transistors working together to output a bipolar, current amplified signal. This is the essence of the push-pull configuration [19].

As was previously mentioned, when a voltmeter “looks” at a transistor it “sees” diodes pointing towards (away from) the base of a(n) PNP (NPN) [19]. Therefore, there is a voltage drop between the base of a transistor and its collector. Because the push-pull configuration has two transistors that means the base voltage of each transistor needs to be one diode drop above zero before the transistor will begin conducting. Since there are two transistors this means that a sine wave on the input of the push-pull will result in a sine wave with flat spots where the sine wave is within V_D of zero. This is called crossover distortion and arises because the two transistors are not switching from conducting to non-conducting at the same instant. Crossover distortion can be corrected by forward biasing the transistors.

4.1.4 Classes of Push-Pull Circuits

There are several classes of push-pulls indicating the varying forward biasing of the transistors. Three of these are the most useful for the production of a large amplitude output signal, the Class A, B and AB. All three configurations are possible using an NPN and a PNP transistor as shown in the generic push-pull circuit schematic, Fig 4.2. The differences between the classes are simply for what portion of the signal cycle the transistors are

[4] according to Ohm’s Law

conducting, which offers advantages and drawbacks to each class [2].

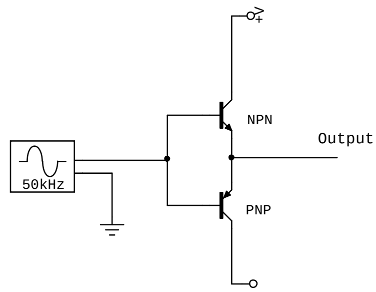

Figure 4.2: The schematic of a generic push-pull circuit. A bipolar signal output will drop to zero any time the input voltage is within V_D of zero.

Class A push-pulls have both of the bases biased so that current flows into both transistors during the entire input signal cycle.[5] The benefit is that you will get out an undistorted signal; the drawback is that since you have to float your signal on an offset. So you're closer to your rail than you otherwise would have been and therefore won't get very much current amplification.

The second type of push-pull is a Class B. Here, exactly when one transistor goes out of conduction the other goes into conduction. This is very hard to time in practice without getting some amount of crossover distortion. If you could make it work you would get much more current gain than either of the other two methods because the signal would be further away from the rails leaving lots of room for amplification.

The third useful type of push-pull circuit for us to consider is a Class AB. Here neither transistor is in conduction for the full cycle of the input wave, nor do they go out of conduction exactly when the other goes into conduction. Instead, there is an overlap of conduction. This results in less current gain than Class B, but doesn't require the fine tuning necessary to synchronize the instantaneous conduction handoff between the two transistors. The power amplifying circuit we employ is a class AB amplifier. The biasing necessary to put the two transistors into conduction is made possible by the two diodes, D3

[5] that is the transistor is always in conduction

and D4, which separate the two bases by a diode drop, and also the current source.

4.1.5 Current Source

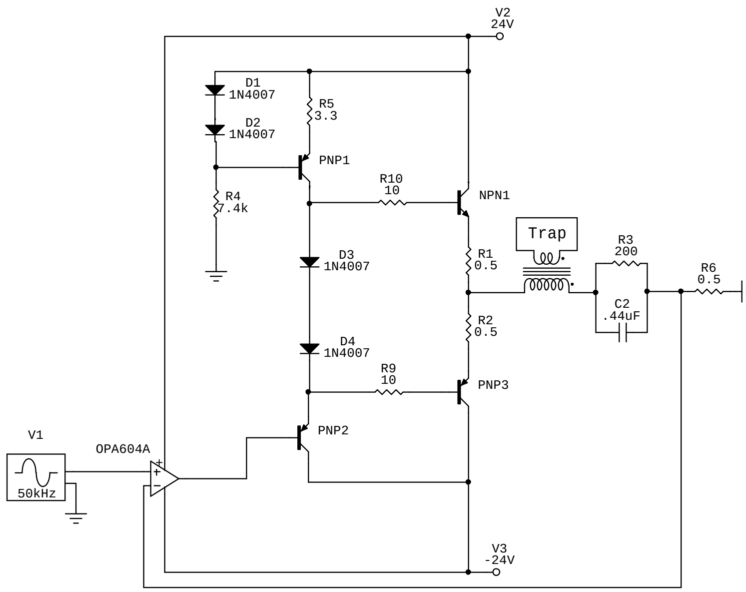

Figure 4.3: Schematic for our current amplifying circuit.

The current source is made up of D1, D2, R4, R5 and PNP1. The current source is needed to put the push-pull transistors in forward conduction. It puts out a constant DC current which dictates the current at PNP1's emitter by Eq. 4.3. The two diodes in combination with the transistor's own diode drop establish a single diode drop across the 3.3 Ω resistor. This draws about 180 mADC into the emitter of the NTE378 PNP transistor. Recall that the current at the collector (I_c) is related to the current at the base (I_b) by Eq. 4.1.

Since the resistor between D2 and ground is 7.4 kΩ all of the current passing through the diodes flows into the 7.4 kΩ resistor since current only flows out of the base of a PNP. Remember, a PNP transistor appears to a Voltmeter as two diodes conducting toward the base from both the emitter and the collector. Therefore, some of the current into the emitter will flow out of the base. This current needs a way to get to ground and the 7.4 kΩ resistor is the path. The value of this resistor is set in order to ensure that the 1/4 W power rating of the resistor will not be exceeded, as is demonstrated in Eq. 4.4:

$$P = \frac{V^2}{R} = \frac{(24V - 2(0.7V))^2}{7.4k\Omega} = 0.069W. \tag{4.4}$$

Therefore, the power dissipated by the 7.4 kΩ resistor is below the 1/4 Watt power threshold.

On the emitter side of the current source is a 3.3 Ω resistor. This value sets the current into the emitter because the voltage drop between the base and the power supply is determined by the diode's voltage drop. So, we know that the current flowing through the 3.3 Ω resistor is V_D divided by the resistor. The current flowing out of the collector is related to the current flowing into the emitter by Eq. 4.2. This current is capable of keeping both transistors in conduction for more than 180° of the signal which is necessary for Class AB function.

4.1.6 Remaining Circuit Odds and Ends

The power amplifying circuit is a Class AB push-pull using an op-amp to regulate the output signal, but there are a few more details needed before the power amplifier can function. First, we encountered parasitic oscillations. As Horowitz and Hill [19] state, "These are bizarre manifestations of untamed high-frequency parasitic oscillations caused by unintended Hartley or Colpitts oscillators employing lead inductance and inter-electrode capacitances." Let's discuss the Hartley oscillator as an example to find a solution to these unwanted oscillations.

The Hartley oscillator is shown in Fig. 4.4. This oscillator has a frequency for which the LC portion of the circuit has a low impedance. The inductor and capacitor are connected in parallel and so their impedance is:

$$Z = \frac{1 - \omega^2 LC}{i\omega C} \tag{4.5}$$

Eq. 4.5 shows that when (ω^2 L C) equals 1 the impedance of this portion of the circuit is zero. As the figure shows, the base and collector of the transistor are connected to the

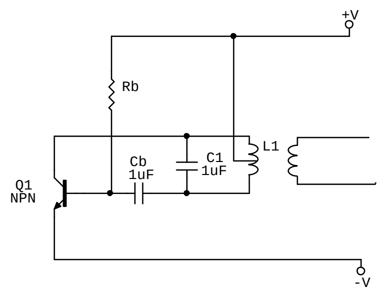

Figure 4.4: A Hartley Oscillator which may occur through some paths in our circuit and is combated by attaching 10 Ω resistors to the bases of NPN1 and PNP3. From [2]

LC branch. Therefore oscillations at the frequency ω will be amplified by the transistor. It is possible that, inadvertently, our circuit might have some inductance and capacitance from leads resulting in this kind of oscillator.

In order to damp out parasitic oscillations, which would otherwise have been amplified, we put 10 Ω resistors on the bases of NPN1 and PNP3. Neither an inductor nor a capacitor on the base would solve this problem. But, since the impedance of a resistor can't be cancelled by the impedance of a capacitor or an inductor the resistor can reduce these oscillations.

Lastly, we address thermal runaway. Some small amount of current flows from +V to NPN1 to PNP3 to -V and is known as quiescent current. This flow of current causes the transistors to heat up. According to the Early effect, as the temperature of the transistor goes up, so does the current flow, causing the temperature to increase more, which causes the current to increase and so on. This is known as thermal runaway. If we put more resistance on the path between +V and -V we can reduce this current at the expense of limiting the voltage swing on the output of the power amplifying circuit. Hayes and Horowitz [18] advise that it is a good rule of thumb to have resistors on the emitters of transistors because it prevents thermal runaway. The 0.5 Ω resistors on the emitters of NPN1 and PNP3 prevent thermal runaway while also limiting power amplification.

4.2 Board Fabrication

Our application requires four power amplifying circuits, two to drive the dipole fields, one for the z coils and another for the quadrupole rods. Therefore, we need a process to manufacture more than one circuit in a repeatable fashion. In order to fabricate our boards, we chose "Press N' Peel Blue[6]" which allowed us to make high quality circuit boards cheaply and quickly. Press N' Peel Blue (PNP Blue) is an iron-able sheet of blue resist and release agents on a Mylar sheet [36]. First, we printed our circuit design onto a PNP Blue sheet with a copier or laser printer.[7] We needed to print a mirror image of the circuit we wanted to fabricate, so we could transfer the resist[8] from the matte side of the PNP Blue sheet. We were using both sides of a copper prototype board, so we made markers outside the circuit that we could use to line up the two sides.[9]

Next, we prepared the surface on which we wanted to etch our circuit. We used double sided copper prototype boards which are usually coated with a clear protective layer that we needed to sand off. We wore Latex gloves because the oil from our hands and fingers inhibited the PNP Blue's resist from sticking to the copper. After sanding, the board needed to be washed; we used Alconox detergent with hot water because it leaves virtually no residue behind. Lastly we dried the board with a paper towel.

Since we were etching both sides of a prototype board we began with the less complicated side since some of the resist came off of the board when we ironed the other side and it was easier to touch up a simpler design. We cut the sheet of PNP Blue that had the circuit we wanted to apply to roughly the size of the circuit board we had and warmed up the iron on the Polyester setting.

With the warm iron[10] we pressed down on the PNP Blue sheet, with the matte side in

[6]which can be found at www.techniks.com at about $1.50 a sheet.

[7]The distributors do warn that the printing device must be dry toner based [36].

[8]resist is a chemical that keeps the chemical bath from eating off whatever the resist is covering. This bath and eating off is known as etching.

[9]We used pads that we drilled through after one side was ironed on to use as a guide for where we should place the PNP Blue cutout on the other side.

[10]don't use steam settings

contact with the copper board, for 10 seconds until the resist stuck to the copper. Then we put a piece of paper between the PNP Blue and the iron and ironed for 4.5 minutes.[11] After 4.5 minutes we ran the copper plate under running cold water, with the PNP Blue attached, until the board was cool. When we only did one side we would then slowly peel off the PNP Blue. But when doing two sides we left the PNP Blue in place. For two sides, we dried the other prepared copper side and repeated the ironing process being careful to line up the guide holes. After peeling off both PNP Blue sheets we touched up our circuit by using Scotch tape to remove extra resist and a permanent marker to add more resist where it should have been.[12]

After the PNP blue sheets were carefully peeled off we submerged the plate in a chemical bath of 50 mL of $FeCl_3$ in 200 mL of distilled H_2O. By just setting the plates in a chemical bath the process took around two and a half hours to etch a board. However, we crafted a Teflon tube that had its end plugged and holes cut in it which was submerged in the bath with the board. This reduced the etching time to 30 minutes. We removed the board from the solution when no copper was visible.[13] When etching was complete, we used Acetone to remove the remaining resist from the board. In order to guarantee our electrical elements made good contact we sanded the copper paths. We were left with a professionally functioning board in a fraction of the time and for a fraction of the cost.

4.3 Performance of the Power Amplifying Circuits

Ok, so now we have a sketch of how the circuit will be fabricated and how it functions, on paper. But what about the "real world"? As it turns out our power amplifying circuit

[11] This was true for boards about 2 in by 3 in. For larger boards you'll need to iron for longer. The only drawback to ironing longer is more blue resist comes off than you want. You can remove most of it with Scotch tape, but not all of it.

[12] In places where you used a marker to add resist less copper will remain. This did mess up current flow in some of our boards. Therefore, if your design is really messed up it's better to remove all the resist from both sides using Acetone, before etching, and start the ironing process again.

[13] The resist sitting on top of the copper will look black or dark blue.

actually does very well at matching the input signal and can deliver up to 4.8 Amps which isn't the 5 Amps we'd hoped for. However, we actually need a 4.2 Amp signal to give us the fields we require. So, our circuits just don't have as big of a safety net as we had initially hoped.

4.3.1 Current

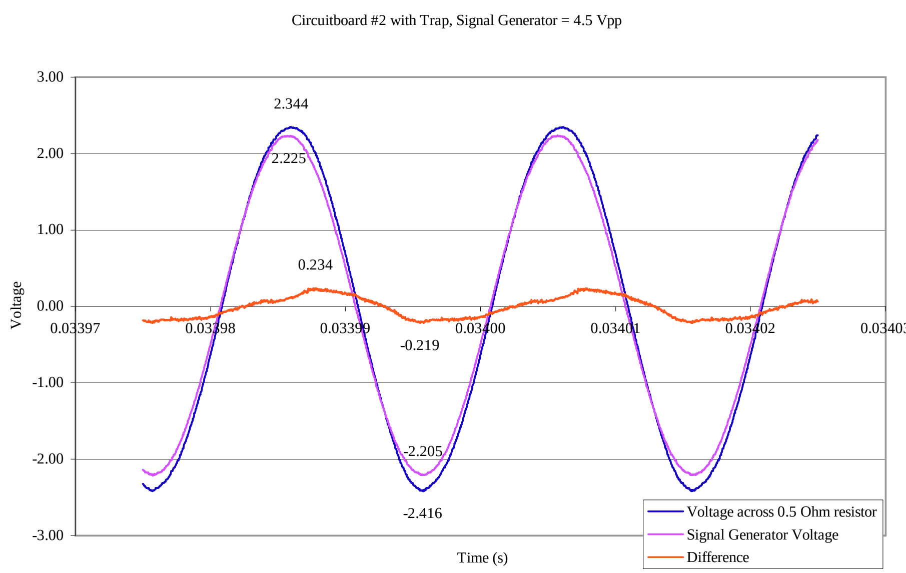

Figure 4.5: Circuitboard # 2 driven at 4.5 V_{pp} with difference between signal generator output and circuit output. The circuit output is measured at the sense resistor of Fig. 4.3

The power amplifying circuit's output current maintains a sinusoidal shape and scales linearly with the input voltage until the output current approaches 4.8 Amps. As can be seen in Figs. 4.5 and 4.6, when the circuit outputs 4.8 Amps the error between the signal generator and the circuit is roughly 10%. While 10% seems to indicate that our power amplifying circuit is not very precise, we do observe that there is a constant scaling factor between the input and output of the circuit. This difference is most likely due to the finite gain of the op-amp. The output of the op-amp is determined by multiplying the difference between the V_+ and the V_- by a constant (the Gain). Therefore, the op-amp needs some

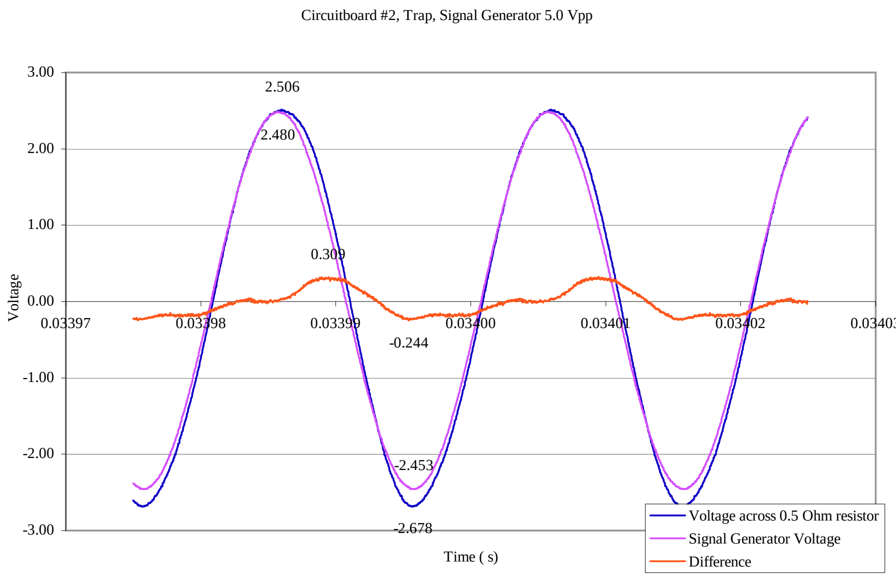

Figure 4.6: Circuitboard #2 driven at 5.0 V_{pp}

disparity between the the two pins to produce an output. So only with an infinite gain op-amp would the difference between the V_+ and V_-[14] be zero. Lastly, notice that our output signal is actually larger than the input signal. Unfortunately, above 4.8 Amps not only does the error increase to nearly 40%, but the signal also becomes deformed.

4.3.2 Frequency Considerations

The power amplifying circuit does not appear to have narrow frequency restrictions. As can be seen in Fig. 4.7, between 1 kHz and up to 100 kHz the difference between the signal generator voltage and the voltage drop across the sense resistor is less than 15 %.[15] Further, the circuit can still output its maximum current at 100 kHz. The circuit has actually been run as low as 10 Hz without incident. The only component with explicit frequency restrictions is the op-amp, which is specified to work up to 100 MHz [11] any

[14] signal generator output and circuit output

[15] As was stated earlier, it's still the case that the power amplifying circuit is outputting a higher voltage than its input.

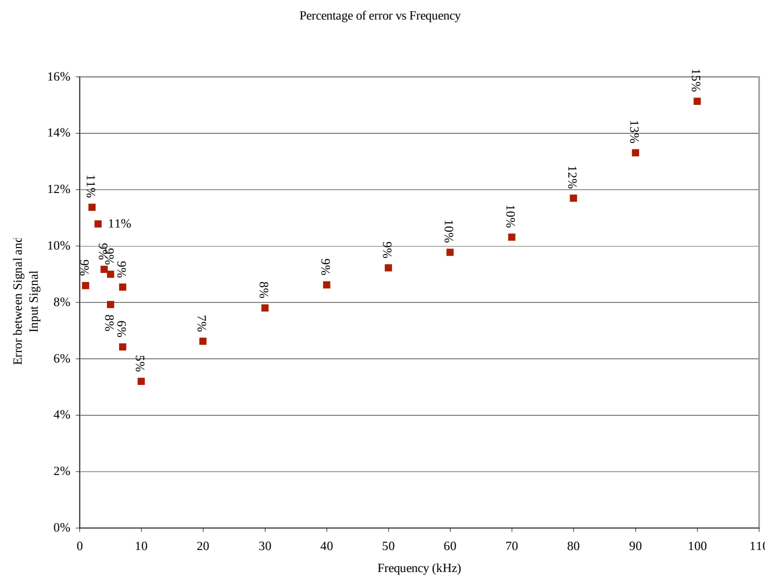

Figure 4.7: Error between the power amplifying circuit and the signal generator.

other frequency dependences are likely due to capacitive and inductive couplings. As can be seen in Fig. 4.7 while there is some unusual frequency dependence the power amplifying circuit's output is still within acceptable limits bewteen 1 kHz and 100 kHz.

4.3.3 Reproducibility

In our project we need two circuits to drive the two oscillating magnetic dipole fields which we fabricated using the "Press N' Peel Blue" process explained above. The two circuits will oscillate independently and be phase locked to each other. Further, we need power amplifying circuits to run both the quadrupole field rods and the Z-coils. What is most important in the circuit is that the output phase be predictable. So let's see how our fabrication technique worked.

Fig. 4.8 shows the negative feedback channel of three circuitboards: Casslab, Circuitboard #2 and Circuitboard #4. The Signal Generator output is also shown as the smaller of what looks like two sine waves. As Fig. 4.8 begins to show, the circuits are highly

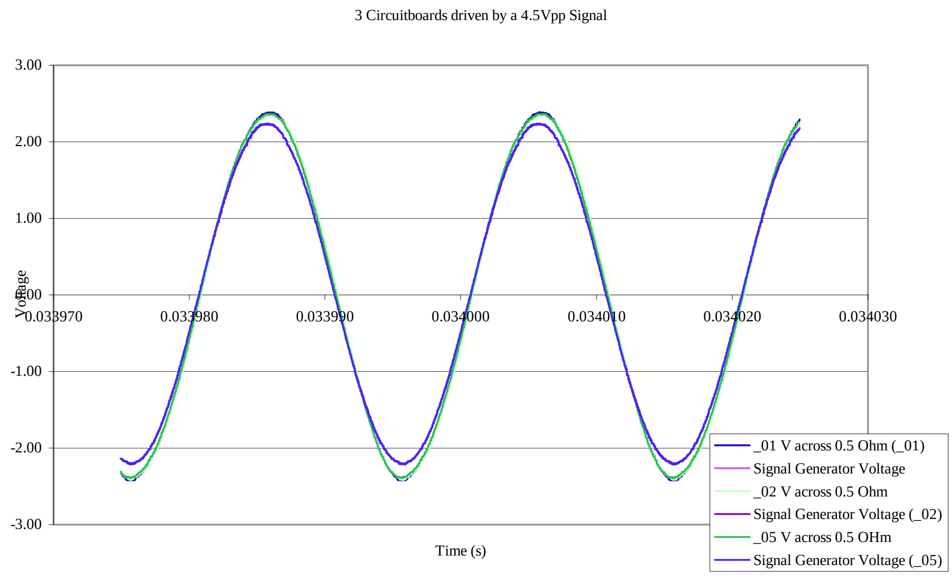

Figure 4.8: The reason for displaying this plot is to show that the three circuitboards give VERY similar outputs.

reproducible. Fig. 4.9 gives the smoothed[16] difference signal between Circuit #2 and the Casslab circuit. There does seem to be a complicated difference in the two signals, but take note of the magnitude of this difference, it is only 3% of the total signal.

In order to truly put this fact in context we ought to compare variation in the signal generator outputs too. Fig. 4.10 is meant for this purpose. The three small amplitude sinusoidal variations are the differences in the signal generators. The differences between the circuits' negative feedback channels vary by approximately twice as much. Error is always bad, but if the phase lag of the complex gain of the circuits is constant then we needn't worry since that is the most important feature of this circuit, along with its ability to produce high current signals. Careful analysis of the waveforms indicates the complex gain, which is given by Eq. 4.6, and is measured to be the information contained in Table 4.1.

[16]By smoothing I mean averaging a point with its 10 nearest neighbor points in order to reduce the noise on the signal.

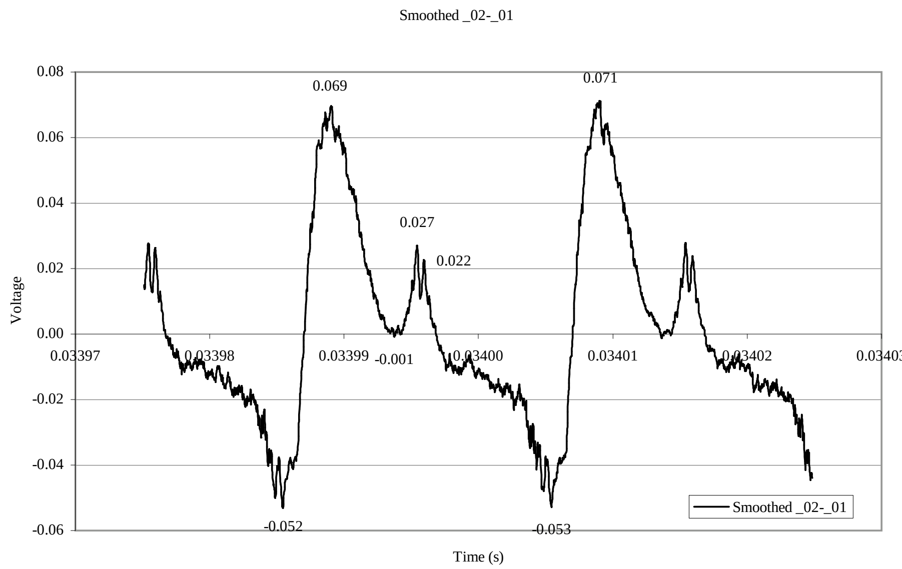

Figure 4.9: The smoothed difference between Circuitboard # 2's output signal and the Casslab circuitboard's output signal. Notice the scale of the error compared to the 5 V_{pp} signal.

$$G = \frac{V_{out}}{V_{in}} e^{i(\Phi_{out} - \Phi_{in})} \tag{4.6}$$

where G is the complex Gain.

Circuit	Gain Magnitude	Error of Mag	Gain Phase	Error in Phase
Casslab	1.0835	0.031%	$-0.27090\,^\circ$	$0.37095\,^\circ$
Circuit #2	1.07621	0.34%	$0.22491\,^\circ$	$1.26228\,^\circ$
Circuit #4	1.05190	1.8%	$0.62791\,^\circ$	$1.85873\,^\circ$

Table 4.1: Circuits and their complex gains

Notice the circuits are practically unity gain, in Voltage, as was mentioned previously. Also to be noted is that, within statistical uncertainty, the phase of the complex gain is zero for all three circuits. Further, the deviation of the phase lag on any one board is small

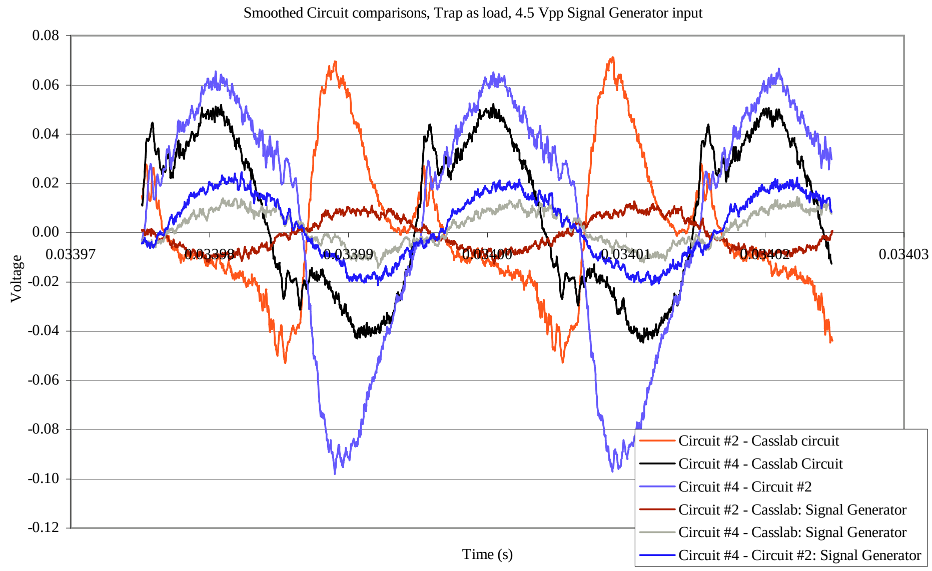

Figure 4.10: The differences between circuitboard outputs are the three signals with largest amplitude. The differences between the signal generator's signal input into those boards are shown as the three smaller amplitude signals. The main purpose for this figure is to show that the circuitboard's signal is almost as reproducible as the signal generator (perhaps within a factor of 2).

and thus gives us hope that the power amplifying circuits connected as noted above will indeed have controllable phases. The above studies were done with the circuits one at a time. However, circuits can be run off of phase locked signal generators using the same power supply with no crosstalk between the circuits.

4.3.4 More on the Trap

We put the 0.22 μF capacitor in place to cancel out inductances in the trap. If we did a good job at matching the capacitance and inductance we would cancel out the imaginary parts of the impedance leaving a purely resistive trap between the power amplifying circuit output and the sense resistor. So let's use a 2.5 Ω resistive load and compare the resistor's results with the trap/capacitors configuration. In Fig. 4.12 the circuit is connected to the

2.5 Ω resistor and is delivering 2.68 V amplitude, or 5.36 Amps amplitude.

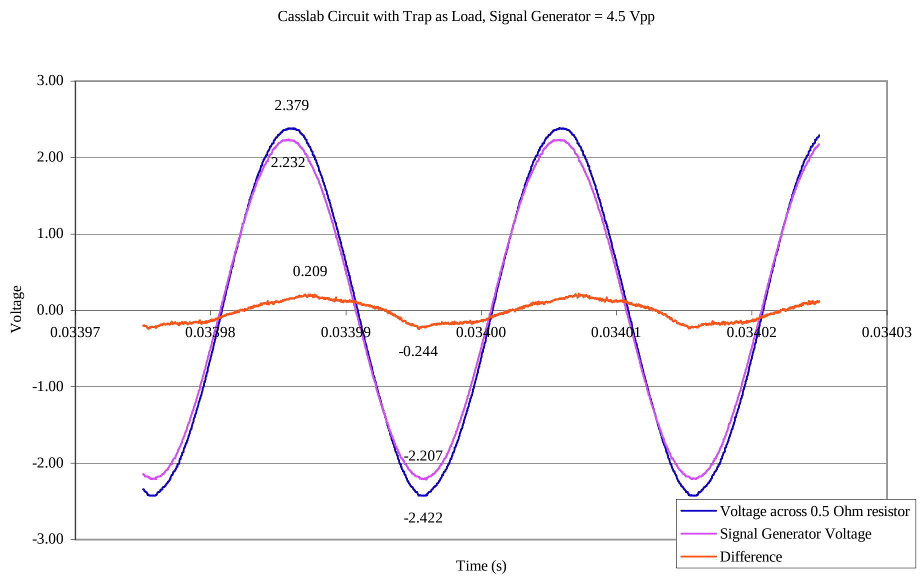

Figure 4.11: Casslab circuit outputting to the trap.

Fig. 4.11 shows the negative feedback signal compared to the Signal Generator output with the trap as the load. The circuit does a pretty good job matching the signal generator's output. Remember, as far as voltage goes this is a unity gain circuit, the purpose is current gain. We can compare the signal differences between the resistor and the trap given in Fig. 4.12. However, in Fig. 4.12 we can see that the signal generator levels are different. So let's look at how the Circuit's error with the signal generator depends on the load.

Fig. 4.12 gives the difference between the signal generator output and the circuit output for both loads and then the difference between those differences has been calculated. Assuming the output is linear in the input signal, which is demonstrated with Figs. 4.5 and 4.6, Fig. 4.12 shows that the difference between the trap and a 2.5 Ω load is about a 4% deviation in the scaled[17] signal the circuit generates. Therefore, the circuit behaves almost identically to a 2.5 Ω as it does the load, except a slightly higher current is available to the test load before distortions arise.

[17]scaled so to take into account the circuit's input signal was different

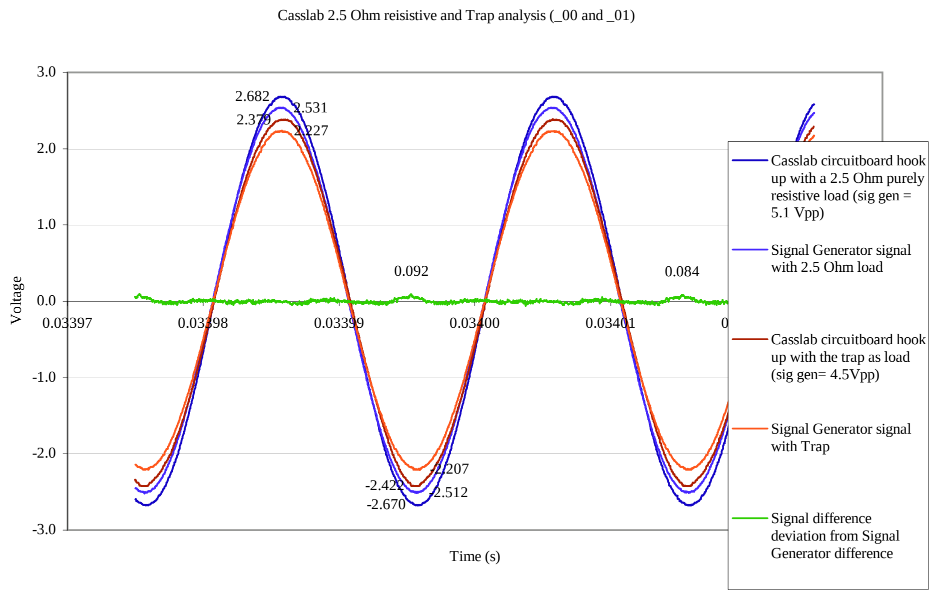

Figure 4.12: The Casslab circuit driving a 2.5 Ω resistor and the trap with a 0.44 μF capacitor connected in series. The difference between the power amplifying circuit's input and output signal is also compared. Finally, the two signal differences are compared and shown to be, at their greatest, 4% of the total signal.

4.3.5 A Note on Load Restrictions

The circuit constructed is a current source that can deliver nearly 5 Amps with a voltage swing of ± 24V. We have used both a 2.5 Ω resistive load and the trap with little difference in the circuits ability to output 5 Amps. The only noted difference is that demonstrated in Fig. 4.12. A purely resistive load can be supplied, without substantial error in waveform, a higher current than the trap/capacitor/resistor combination can. This is perhaps because the capacitor has not quite matched the inductance of the trap.

4.4 Troubleshooting the Circuit

If the power amplifying circuit's output goes haywire, first check the obvious things: power to the board, power to the op amp. Then check that the grounds are connected.[18] The boards we built are modular for everything except the diodes. Therefore, any component, except for the diodes, can be replaced without soldering or unsoldering anything on the board. That's very important since the boards can't withstand unsoldering. Usually the pad comes off with the solder the first time you disconnect a component.

If the signal at the sense resistor isn't what it ought to be start at the beginning. Check the signal coming out of the signal generator at the op amp, that's pin 3 on the OPA604A. Now check the negative feedback at pin 2. These should be the same, if not then either 1) the op amp has burned out which can be checked by checking for shorts across pins, or 2) one of the elements down the line is malfunctioning. Finally, check the output of the op-amp. If the voltage is either at +24 V or -24 V the op-amp has railed due to a malfunction further in the circuit.

Next, trace the signal into PNP2 and check the signal at the emitter. Check that the voltage of the signal is dc offset by a diode drop and then two diode drops, respectively between D4 and D3 and at the collector of PNP1. Check the temperatures of NPN1 and PNP3. They should be about the same temperature. If one is substantially hotter, then often times the other transistor is shorted. Check that the transistors are still functioning by checking that there is one diode drop across the base-emitter and collector-base and that when the leads of the voltmeter are reversed the voltage drop is infinite.[19] The last thing to check is the current source. Check that between D2 and the 7.4 KΩ resistor (R4) there is a DC voltage of 22.8 V.

[18]We had a lot of grounding issues, so make sure large guage wires are used in grounding and that contacts are very good.

[19]Most of the time when a transistor burns up there is a short across its pins. However, if nothing else seems to be wrong, then the first thing you should do is replace the transistors (most often the NPN).

4.5 Conclusion

In conclusion, we have fabricated a current amplifier capable of supplying 4.8 Amps to the trap. This value is 0.6 Amps higher than the necessary current to the quadrupole path.[20] By phase locking the magnetic dipole fields 90° relative to one another and through their relative orientation, these fields will create a rotating bias field. This will provide us with a trap in which to evaporatively cool our atoms to attain BEC. Further, this rotating field will be used while interferometric experiments are conducted in order to cancel out background noise sources. These techniques will be employed in order to develop a BEC interferometer capable of measuring phases on the order of $10^{-11}\frac{rad}{s}\frac{1}{\sqrt{Hz}}$.

[20] whose current requirements are greater than either of the dipole or z coil paths

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