Simulation and Prototype Construction of Microwave Atom Chip Components

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by

Kameron Sullivan

Advisor: Prof. Seth Aubin

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Abstract

A microwave trap makes use of a microwave field minimum, generated above a circuit and often referred to as the microwave chip, to confine specific spin states of ultracold atoms. By using such a chip in conjunction with a carrier chip, the microwave traps can be used as "beam splitters" and as the paths of an atom interferometer. The software FEKO was used to simulate these microwave traps before construction. These simulations have shown that you can generate a microwave magnetic minimum by using two "curved" traces and a single straight trace of copper on an aluminum nitride substrate. By figuring out the optimal parameters for each individual trace, we were able to successfully simulate the microwave "trap" (magnetic minimum) above the chip though it still requires tuning to optimal parameters. We also began analyzing large scale prototypes of these traces in order to experimentally verify the theory and FEKO simulations.

Chapter 1 Introduction

1.1 Objective

The overall objective of this senior thesis project is to develop microwave transmission line structures for a new type of atom chip: the microwave atom chip. These transmission lines must be designed and then simulated to obtain their target theoretical performance. These microwave structures must then be prototyped to verify that the simulations are accurate and that the design performance is met. The microwave atom chip will provide a new spin specific mechanism for controlling and trapping ultracold atoms, in particular in the domain of atom interferometry.

1.2 Motivation

The motivation behind this detailed research into microwave atom chips is to use a superposition of atomic spin states to perform trapped atom interferometry using ultracold ⁸⁷Rb. In this respect, the microwave atom chip will act as the "beam splitter" in the optical analog and will also guide the atoms along the interferometer paths. The atom interferometer is useful for obtaining precise measurements of external potential gradients, for example a gravitational potential.

1.3 Atom Interferometry

Atom interferometry works by generating a superposition of two quantum states of an atom that follow two different spatial paths before recombining to produce an interference pattern (see figure 1.1). This scheme is very similar to optical interferometry in that one can observe constructive and destructive interference as the wave-forms interact. By observing how the interference pattern changes in an external potential gradient, it is possible to measure these potentials to an extremely high degree of precision because the difference in the energy of the two states due to that potential gradient will shift the interference pattern in proportion to the energy difference. In the Aubin Lab, the plan is to build an interferometer with the superposition of two spin states of ultracold rubidium 87 (⁸⁷Rb) using microwave traps based on AC Zeeman potentials.



Figure 1.1: A schematic view of the atom interferometer. The red dashed line represents the path taken by the high field seeking spin state while the blue one represents the path taken by the low field seeking spin state. The magnitude of the external potential gradient is proportional to the phase shift in the interference pattern at the output of the two states of the two states.

1.4 AC Zeeman Potentials

The "alternating current" Zeeman (ACZ) potential allows for the creation and separation of a high microwave magnetic field seeking spin states and a low microwave magnetic field seeking spin states of an atom. We begin with a 2-level system as shown in the figure 1.1. The Hamiltonian operator for the two state ACZ effect can be expressed as a matrix expressed in the dress atom $\{|g, N\rangle, |e, N - 1\rangle\}$ basis, where N is the number of microwave photons,

$$H = \begin{bmatrix} \delta & \Omega/2\\ \Omega^*/2 & 0 \end{bmatrix}$$
(1.1)

. The energies of this Hamiltonian are

$$E_{\pm} = \pm \frac{\hbar}{2} (-|\delta| + \sqrt{\delta^2 + |\Omega|^2}).$$
 (1.2)



Figure 1.2: ACZ eigenenergies in units of . This graph shows how the energy of atom in a 2 state system changes as a function of the detuning. When the driving RF frequency is equal to the hyperfine splitting frequency of an atom, a resonance spike is achieved.

Here Ω is the Rabi frequency, proportional to an external alternating magnetic field and the magnetic moment $\vec{\mu}$ of the atom (see equation 1.3), and δ is the detuning from the applied alternating magnetic field and atomic state transition, given by $\delta = \omega_{rf} - \omega_{ge}$. The energy of an atom subject to an external magnetic field is based δ and the Rabi frequency,

$$\Omega = \langle g | -\vec{\mu} \cdot \vec{B} | e \rangle = -\mu_b \langle g | S_+ B_- + S_- B_+ + 2S_z B_z | e \rangle.$$
(1.3)

Where the B_{\pm} and is defined as $B_{\pm} = B_x \pm i B_y$, and B_x , B_y , and B_z are magnetic field components at a given spatial coordinate. The S_{\pm} are the spin raising and lowering operators. The final piece of information needed is the calculation of the inner products for equation 1.3.

In a real atom, such as ⁸⁷Rb, there are many more levels. Figure 1.3 shows the hyperfine levels of ⁸⁷Rb. However, individual transitions can be treated as a two level system.



Figure 1.3: This figure was taken from [6]. It shows the energy levels with respect to the Rabi Frequency for the F = 1 and F = 2 manifolds.

The $\{|g\rangle$ and $|e, N\rangle\}$ states are really hyperfine states defined by the hyperfine spin F and its magnetic sub-states m. The two hyperfine ground levels can be labeled with the F_+ and F_- hyperfine numbers, which are defined as

$$F = I \pm S = F_{\pm}.\tag{1.4}$$

Where F is the total angular momentum and I is the nuclear spin. It serves as our basis for the inner product calculations, i.e,

$$\langle F_{+,m} | S_{\pm} | F_{-,m'} \rangle = \pm \frac{\hbar \sqrt{(F_{+} \pm m)(F_{+} \pm m')}}{2I + 1} \delta_{m,m\pm 1}$$
 (1.5)

and

$$\langle F_{+,m} | S_z | F_{-,m'} \rangle = -\frac{\hbar \sqrt{(F_+ + m)(F_+ - m')}}{2I + 1} \delta_{m,m}.$$
 (1.6)

Where m is the magnetic quantum number. Note that for ⁸⁷Rb, I = 3/2.

The corresponding eigenstates $|\pm\rangle$ of the E_{\pm} eigenenergies are a combination of the $|g\rangle$ and $|e\rangle$ states. Notably, the $|+\rangle$ eigenstate is a weak field seeker and the $|-\rangle$ is a high field seeker. In the limit of large detuning ($|\delta| >> |\Omega|$), the $|\pm\rangle$ are roughly equal to the $|g\rangle$ and $|e\rangle$ } and the ACZ energies becomes[6]

$$E_{g,e} = \pm \frac{\hbar |\Omega|^2}{4\delta}.$$
(1.7)

1.5 Microwave Atom Chip

Generating strong ACZ potential gradients (i.e. forces) requires a strong microwave gradient, which can be produced by a wire or a microstrip on an atom chip. Microstrips are thin metallic transmission traces placed above a dielectric substrate that function as transmission lines in conjunction with a ground plate beneath the substrate. A microwave atom chip is a series of one or more microstrips that produce variations on the magnetic and electric fields of their surroundings. For the purpose of the simulations discussed in this paper, a frequency of 6.8 GHz is used primarily because it is the hyperfine splitting frequency of ⁸⁷Rb (see Figure 1.3). In order to make a trap, a microwave magnetic minimum is generated using several microstrips. In this case, the low field seeking state will be attracted to the minimum, while the high field seeking state will be repelled by it. We refer to this particular configuration of microwave atom chips as microwave or ACZ Traps. The overall design of the microwave atom chips as microstrip trap, however, single microstrip transmission line simulations were run and studied to optimize key parameters.

1.6 Thesis Work

The work in this thesis is directed at developing a microwave atom chip and consists of two primary efforts: 1) numerical simulations of single and multiple microstrip transmission lines, and 2) the development and testing of single microstrips on commercial electronic prototyping circuit boards (PCBs). These goals are reflected in the thesis structure. Chapter 2 is dedicated to simulations of various microstrip configurations. Chapter 3 describes the work done with another student, Joseph Houghton, on photolithography of single microstrips on PCB boards and the tests on them using a Vector Network Analyzer (VNA). Chapter 4 concludes the thesis with a summary of the work and an outlook for future research.

Chapter 2 Microwave Simulations

Microwave circuits are notoriously difficult to design since microwaves can easily couple in unwanted ways to different circuit elements and generate detrimental reflections and standing waves. This chapter describes numerical simulations of microwave circuit elements for a future microwave atom chip. We use the commercial software FEKO to simulate two types of configurations: 1) a single microstrip transmission line (straight and curved) and 2) three parallel microstrips that generate a microwave minimum (i.e. a trap).

2.1 General Information Regarding FEKO Simulations

FEKO is a commercial software used for electromagnetic simulations of 3-D objects. It breaks up the geometric model into a discrete mesh of triangular and tetragonal sections and solves Maxwell's equations in matrix form for each discrete section. The more sections the model is divided into, i.e. the finer the mesh, the more physically accurate it is. The desired 3-D object for analysis is created in a program called "CADFEKO". Once the geometry is created and meshed, analysis of the model begins. One avenue for analysis is to use the "optimize" feature (OPTFEKO) for a given model parameter to optimize a given result of the analysis. Finally, results from

the simulations are analyzed in "POSTFEKO." [4]

In the simulations conducted on microwave atom chips, the two calculated parameters that are most important are impedance and reflection coefficients of the microstrips. The impedance is defined as the ratio between the voltage and the current in the microstrip. The desired impedance for these simulations is 50 Ω , which corresponds to no loss in power. The reflection coefficient indicates how much of the power is reflected back to the source. Ideally, we want this parameter to be as close to 0 as possible because if too much of the power is reflected back, standing waves might be generated along the trace [1].

2.2 Single Microstrip Trace

The single microstrip trace is the basic building block for our proposed microwave atom chip. We simulate several variations of this basic element: 1) a single trace on an aluminum nitride substrate, 2) a single trace on an FR4 substrate, and 3) a curved trace for directing microwaves around a corner.

2.2.1 Single AlN Microstrip Trace

The single straight trace (Figure 2.1) is a useful simulation to run because it is the main building block for more complicated structures of the microwave atom chip. The following simulations were all run at a frequency of 6.8 GHz, with an input voltage amplitude of 1 V unless otherwise specified. The materials used are a copper ground plate that is 5 μ m thick, directly underneath a 50 μ m thick aluminum nitride substrate with a thin copper trace along the top length of the substrate. The dielectric constant used for aluminum nitride was $\epsilon = 8.9$.



Figure 2.1: Straight microstrip on AlN. A thin copper trace (blue) is run along the length of an aluminum nitride substrate (green), and edge ports are connected to the ground plate at either end. Simulations were run at a variety of lengths, widths, microstrip trace widths, and frequencies to minimize reflections.

The main goal for these simulations was to observe how slight variations on the trace width affected the microstrips impedance and reflection coefficient. When using a trial and error method of varying the trace width to minimize reflections, the minimum reflection coefficient appeared to be in the range of 55.3 to 55.45 μ m for the trace width. At all points checked within this range, a reflection coefficient of 0.00595 was determined through the FEKO simulations. In order to verify these results, an OPTFEKO simulation with these parameters was run for both minimizing the reflection coefficient and optimizing the impedance. It determined the optimal trace width to be 55.63 μ m, with the result for impedance being 50.125 Ω and the reflection coefficient being 0.00615. All of the above simulations were performed with a substrate that was 3mm along the trace and 5mm wide. The smaller scale allowed for more efficient simulations, however, when the width of the microwave atom chip was reduced to 1 mm rather than 5 mm, the OPTFEKO simulation determined the optimal trace width to be 55.9718 μ m resulting in an impedance of 50 Ω and a reflection coefficient of 0.00714. This shows that the width of the substrate has an impact on the simulations, something the Aubin Lab previously thought irrelevant. The discrepancy between the results of the "trial and error" method and the results of the OPTFEKO simulation can be accounted for in the fact that the OPTFEKO had two parameters to consider rather than just one.

Two full microstrip length simulations were run to test the results of this optimization for a full size atom chip (2 cm x 2 cm). The first one was run at a trace width of 55.35 μ m. This value was chosen because it was within the "trial and error" range. The other simulation used a trace width of 55.9718 in accordance with the OPTFEKO results. The results of the 55.35 μ m trace width were a reflection coefficient of .00403 and an impedance of 50.4 Ω . The results of the 55.9718 μ m trace width were exactly the same. This shows that at the full length, small changes to the microstrip width are negligible. Also, overall with the longer trace, the reflection coefficient is lowered, however, the impedance increased. As previously stated, the width of the substrate itself also seems to affect the results. Therefore the width of the microwave atom chip was reduced from 5 mm to 1 mm in order to test this effect. The result was an impedance of 50.7 Ω and a reflection coefficient of 0.00756. Therefore, the wider the width of the overall microwave atom chip, the lower the impedance and higher the reflection coefficient. (See table 2.1)



Figure 2.2: Broadband performance of single straight microstrip on AlN. Left: Graph of reflection coefficient versus frequency. The maximum in the reflection coefficient is at 5 GHz and also corresponds to the minimum impedance for this microstrip. Right: Graph of impedance versus frequency. The frequency ranged from 1 GHz to 10 GHz. The resulting variations in impedance were from 51.3 Ω to 47.7 Ω , with the minimum at 5 GHz.

Figure 2.2 shows the straight trace run at multiple frequencies. In general, we want our trace to not have much frequency dependence. In other words, we want broadband performance. At the lower frequencies (below 5 GHz) we find that there is a stronger dependence on the frequencies, and the graphs seem to be more stable at the higher frequencies. However, the total range of the impedance was only 3.6 Ω , so even including the lower frequencies, the circuit can be considered broadband. The reflection coefficients are all bellow 0.025, so they can be considered quasi negligible.

2.2.2 Single FR4 Microstrip Trace

The single trace simulations and optimizations previously discussed where all assuming the following parameters: first, that the chip is the size of the chip used for the actual interferometry experiment (2 cm x 2 cm) and secondly that the substrate was made of aluminum nitride. However, we want to build large scale prototypes in order to test these simulations before manufacturing the final microwave atom chip, which means re-running the optimizations for a larger chip and with a different substrate (FR4 rather than AlN). The dielectric constant for FR4 is $\epsilon = 4.4$ and the dimensions for the prototype substrates are 150mm by 250mm and thicknesses of $\frac{1}{64}$, $\frac{1}{34}$, and $\frac{1}{16}$. inches. I ran an OPTFEKO at 6.8 GHz with Joseph Houghton for each of these thicknesses (see Table 2.1). What we found from these simulations is that by doubling the thickness of the substrate, the optimal trace thickness roughly doubles as a result. These simulations will be re-run at multiple frequencies for further comparison with the prototypes.

Table 2.1: This table shows the results of optimizing the impedance of a single microstrip trace to be 50 Ω by allowing variations in the trace width. The aluminum nitride simulation correlates to the actual microwave atom chip while the FR4 simulations the development of large scale prototypes (PCBs)

Substrate Material	Dielectric Constant	Trace Material	Substrate Thickness	Length and Width of Substrate	Trace Width	Impedance
Aluminum Nitride	$\epsilon = 8.9$	Copper	$50 \ \mu m$	2cm x 2cm	$55.35-56 \ \mu m$	50.5 Ω
FR4	$\epsilon = 4.4$	Copper	1/16 inches	150mm x 250mm	2.27mm	48.8 Ω
FR4	$\epsilon = 4.4$	Copper	1/32 inches	150mm x 250mm	0.90207mm	50.5Ω
FR4	$\epsilon = 4.4$	Copper	1/64 inches	150mm x 250mm	0.452	49.98 Ω

2.2.3 The Curved Microstrip Trace

Often, microstrip segments must be routed to different locations on the microwave atom chip, and so it is necessary to use curved microstrip traces. Such curved traces must be simulated to determine their optimal parameters for minimizing their reflection coefficients.



Figure 2.3: A curved microstrip trace. This is used for routing the trace around corners.

The curved strand is defined by a spline function. A spline function is a set of piece-wise functions that are combined to create a smooth curve for connecting points while minimizing the overall curvature. This method also ensures that near the edge ports at the substrate boundary, the trace is straight so our input signal does not enter at an angle. A simulation of such a trace was run at 6.8 GHz with an aluminum nitride substrate (see figure 2.3). The simulation was run at full length and width (2cm x 2cm) and resulted in an impedance of 40 Ω and a reflection coefficient of 0.132. The impedance is far bellow the desired 50 Ω and the reflection coefficient is much higher than the results from the straight strand. In order to solve this problems the following OPTFEKO simulations are suggested for future research. Firstly, the spline function begins for this simulation at 7/8 the length of the trace on either side of the straight component. The longer we make the curved part, the more linear the trace will become. Therefore, allowing the ratios of curved to straight elements to vary would be the first optimization parameter for improving the results for the reflection

coefficient and impedance. Alternatively, one could vary the trace width by trial and error as I did with the straight trace. By analyzing the results of these simulations, we should be able to find the best parameters to construct a low reflection curved trace similar to the straight trace as shown in figure 2.2.



Figure 2.4: Broadband performance of the curved trace. Left: Graph of frequency versus impedance. There is a clear anomaly with the simulation at lower frequencies. Right: Graph of frequency versus reflection coefficient. Again, at the low frequencies, there seems to be an issue with the simulation because the reflection coefficient is above 1, which is physically impossible. Also, the reflection coefficients is higher overall for the curved strand.

Figure 2.4 shows some of the problems for the curved trace. Though we get a fairly broadband result for higher frequencies, there are some clear issues with the lower frequencies. One of the biggest issues, is that some of the lower frequencies seem to have a reflection coefficients above 1, which is physically impossible. The impedance also seems to be at impossibly high levels for the lower frequencies. Though we are still trying to figure out the problems with this simulation, the higher frequency simulations, such as 6.8 GHz, show decent performance, which we hope to improve

upon. If the issues persist, the lab might consider an alternative routing method that does not use the spline function.

2.2.4 Jagged Edge Microstrip Trace

The "jagged" edge trace (see figures 2.5 and 2.6) was considered as a possible alternative to the curved trace. However, this variation on the trace failed to carry a current past the first edge (See figure 2.7) and therefore this idea was abandoned in favor of further optimizing the curved trace.



Figure 2.5: The jagged edge trace. This corner trace is a possible alternative to the curved trace.



Figure 2.6: Parameters for Jagged Edge Corners All the edges of these jagged trace meet the specification. Figure taken from [5]



Figure 2.7: The current though the jagged edge trace when supplied with a 1 V signal at 6.8 GHz. The current all builds up on the first corner, and never makes it past the second corner.

2.3 3-Microstrip Trap

The primary feature of the microwave atom chip will be the microwave trap generated by three parallel microstrip traces, as shown in figure 2.8. The two outer traces are constructed from the curved traces discussed in section 2.2.3. In the center portion, the traces are separated by 50 μ m.



Figure 2.8: Close up view of the three trace trap. It is a combination of the straight trace shown in figure 2.1 with two curved traces on either side shown in figure 2.3. These traces are spaced 50 μ m apart at the center and 1 mm apart at the edge ports. The relative phasing of the transmission lines allows for the creation of the magnetic field minimum above the circuit.

A simulation of the 3 trace trap showed that it successfully generates a magnetic minimum above the traces. However, the results of the impedance and reflection coefficients are less than desirable.

Voltage Source	Impedance(Ω)	Reflection Coefficient
Left	56.7	0.05
Center	53.5	0.4
Right	52.8	0.05

Table 2.2: Transmission line parameters for the 3-microstrip trap circuit. This table shows the results of the 3-microstrip trap simulation at each edge port. The higher reflection coefficient at the center suggests cross-talk between the traces.

As is evident from table 2.1 above, the reflection coefficient for the middle trace is significantly higher than the outer traces. Also, none of the traces are at the ideal impedance of 50 Ω . Further simulations with the three trace trap will use better optimized versions of the curved traces.

2.4 Conversion of FEKO Magnetic field results into an ACZ energy.

I exported the magnetic field data from this simulation into Matlab and wrote a code to calculate the ACZ potential energy of an atom undergoing an atomic state transition in this microwave magnetic field. The energy is calculated using equation 1.2 from the introduction. In order to make this plot with adjustable parameters, I created a program with a graphical user interface (GUI) so that the user can input the parameters he or she wants. The code runs based on four external functions that get called into the GUI and 4 callback functions within the GUI (see Figure 2.10).



Figure 2.9: A snapshot of the GUI. The "Browse" button allows the user to browse for a .hfe text file generated by FEKO on their computer. The numeric fields allow the user to set the ground m-state and the excited m-state for a transition they wish to drive. The slider sets the detuning. The refresh button updates the plots based on the user input.



Figure 2.10: Flow chart of GUI code. The white boxes represent functions that are called into the code. The blue boxes represent the callback functions that respond to user input and adjust the parameters accordingly.

The snapshot of the GUI shows the user interface that appears when the GUI app is active. The benefits of setting up the code in an app format are that it is easy to adjust parameters for a variety of different FEKO- generates .hfe files, and if a different lab member wishes to perform these calculations, they can simply pull up the app and associated functions and run it without needing to know how to code in MATLAB. The code works by calling four different functions in the same folder (see figure 2.10). These Functions are:

- dataimport: takes the .hfe file and collects all the relevant data.
- bfield: calculates the B+ and B- fields based on the results from dataimport.
- spin: calculates the inner products (equations 1.5 and 1.6) based on the values given for m_e and m_g .

• temperature: Calculates the ACZ potential energy in temperature units μK based on the results from all the previous functions and the detuning slider value.

There are many more options that could be easily added to improve this GUI. A check box could be used to turn a logarithmic scale of the temperature on and off. A function could be written to find the local minimum of the energy/temperature. Another check box function could be used to turn gravity on and off. There are many options for further improving this code.

A full copy of the code can be found in Appendix B.

Chapter 3

Prototyping and Vector Network Analyzer Data

In order to test the FEKO simulations, we need to construct actual microwave microstrip circuits on printed circuit boards (PCBs), which can then be tested to verify agreement with the simulations. Once there is sufficient agreement between simulation and PCB experiments, one can then move on to designing and microfabricating the microwave atom chip itself.

Joseph Houghton and I were able to produce two PCBs for analysis using the method of photolithography discussed bellow. After four previous attempts to produce a PCB using this method, we were able to refine the technique and conduct some small scale experiments to see what practices would lead to the best results. Once we had these PCBs, we analyzed the microstrips using a Vector Network Analyzer (VNA) and a multimeter (to check connectivity).



Figure 3.1: Finished microstrip traces on FR4 based PCB. Left: 1/16" thick substrate PCB with spacing between the traces listed. I have denoted the sma edge ports for clarity. Right: 1/64" thick substrate with the same spacing and labels for the SMA edge ports.

3.1 Photolithography

Photolithography is a common method for creating PCBs. We are interested in using this method to create large scale prototypes of our microwave atom chips because of the potential for a high level of precision. The process for creating these PCBs begins by printing out the desired traces on an overhead transparency film. The film is placed over the PCB (based on an FR4 substrate) and then exposed to UV light. There is a commercially applied photoresist on the circuit board that, when exposed to light, will weaken so that when exposed to the developer solution (made of 1:1 ratio of sodium hydroxide (NaOH) and water), only the parts blocked from the light exposure will keep their photoresist layer. The other parts of the board now have exposed copper [8]. The next step is to expose the PCB to a ferric chloride solution (again with a 1:1 ratio of the ferric chloride to water), where the following three stage oxidation reduction reaction occurs:

$$Stage1 : FeCl_3 + Cu \longrightarrow FeCl_2 + CuCl$$
 (3.1)

The first step is for the copper to be oxidized by the ferric chloride. This the main part of the "etching" because the solid copper on the plate is now in an aqueous form with the chlorine, which begins to expose the FR4 substrate.

$$Stage2 : FeCl_3 + CuCl \longrightarrow FeCl_2 + CuCl_2$$
 (3.2)

The copper is then further oxidized by the ferric chloride in this second stage.

$$Stage3: CuCl_2 + Cu \longrightarrow 2 CuCl$$
 (3.3)

The copper chloride now further contributes to the etching. Once all the copper has been etched away in the desired regions, acetone is used to remove the photoresist from the covered region, leaving copper traces behind [9].

3.2 Recipe for PCB Photolithography

After four rounds of PCB board photolithography, the procedure Joseph and I believe will result in the best PCB is as follows:

1. Begin by printing off two copies of your trace design overhead transparencies which are to be stacked on top of each other for better coverage. For the trace design, try not to let your traces be within 0.5 inches of each other as this will result in significant cross talk.(see Table 3.1) If you have a fractile design (a star or something with lots of edges) printed in the upper corner of the transparencies, then you can increase the accuracy of your stacking by lining up these images. By doubling up on the print outs, you decrease the likely-hood that small defects in the printing will cause unwanted light exposure on your PBC.

- 2. Turn on a red light source for visibility before removing the light sensitive PCB from its package in a dark room.
- 3. Peel off the light protective coating on 1 side of the PBC, not both. Since the bottom is the groundplate, this will ensure that the bottom of the plate does not receive any light exposure.
- 4. Line up the artwork on your board and tape it down so that it does not move. The turn on two UV bulbs and move them around continually for 15 minutes to ensure even light exposure in the desired areas.
- 5. After the fifteen minutes, put the PCB plate in the NaOH developer solution until the photoresist only remains on the light-covered areas. Rinse with water.
- 6. Put the PCB in the ferric chloride bath at 305 Kelvin and agitate continuously for 25 minutes.
- 7. Remove PCB from the ferric chloride bath and rinse off the remaining photoresist with acetone.

At this point you have made the PCB and all that is left is to solder on SMA edge ports and test its microwave properties. Most of the issues we had in first creating the PCBs were due to one of two failures: not enough light exposure or not enough time in the ferric chloride solution. To fix the light problem, we decided to use UV light rather than a standard florescent light bulb. To see how long we needed to develop the PCB in the ferric chloride, I timed how long it took to completely remove all the copper from a small piece of the PBC with the copper already exposed. It took approximately 25 minutes.

Another potential issue one might come across is that if the PCB is in the ferric chloride for too long, it will start to etch the copper on the traces. Faster etching would reduce the rick of the ferric chloride eating into the traces. I propose the following experiments be conducted to see if they produce even better PCB results:

- Take several pieces of exposed copper from a PCB board and develop it in ferric chloride solutions at different temperatures. In theory, a higher temperature ferric chloride bath should lead to faster etching.
- Try adding an air pump into the ferric chloride bath. The air pump would act as a source of constant, gentle agitation. In theory, this will also lead to faster etching.
- Test out how long the ferric chloride is still effective. We used the same ferric chloride baths for all the PCB experiments. Green flecks from oxidized copper can be seen floating in the bath. It is possible that using fresh ferric chloride will also lead to faster etching. However, since the copper chloride also contributes to the etching in stage 3 of the reaction, it is possible that changing out the ferric chloride regularly is not necessary.

As of right now, we are not achieving broadband performance on the printed circuit boards. We believe this is largely due to standing waves forming when the reflected wave goes back through the trace. If circulator ports were soldered on and properly loaded as to act as the edge port, the reflections would be minimized. I would also suggest that only one trace should be printed on a circuit board at a time for single microstrip simulation confirmation so as to eliminate any chance of cross talk (see figure 3.4 and 3.5 bellow).

3.3 VNA data

The first measurements we made were from port 1A to 1B, 2A to 2B and so on for both PCBs (see figure 3.1 for edge port numbering references). A representative sample of one of these graphs is shown below in figure 3.2..



Trace 1 of 1/16" PCB Real Impedance

Figure 3.2: The VNA sweeps over multiple frequencies and measures the impedance and reflection coefficient at each point. The marker is at 6.8 GHz, which is the frequency that simulations were optimized for.

The key characteristic for these graphs are the resonance spikes. The resonance spikes are most likely caused by reflections that then generate standing waves in the trace. As the frequency increases, the spike decay down. The plot indicates that more work needs to be done to minimize the reflection coefficient and stop the standing waves from forming across a range of frequencies. At present, our PCB microstrips do not show broadband 50 Ω performance.

Another test performed on the PCBs was to check the conductivity through a trace. This was done by taking a common multimeter and seeing if a resistance could be measure across a trace. For some traces with noticeable defects, infinite resistance was measured, meaning the trace failed our conductivity test. These traces also behaved differently on the VNA due to this lack of connectivity. On the $\frac{1}{64}$ inch thick board, traces 4 and 5 were not conductive.

To investigate why some of the traces were or were not conductive, microscopic images of the traces were taken. In the figure below, the noticeable scratches and holes in the bottom right are the most probable cause of the lack of conductivity on trace 4 on the $\frac{1}{16}$ inches thick PCB.



Figure 3.3: Microscopic images of traces. Top left: reference with ruler circled in red. Top right: clean trace for the 1/32" PCB. Bottom left: trace 3 on 1/16" PCB and showed conductivity Bottom Right: trace four was not conductive. Arrows point to noticeable major defects. Colors, contrast and brightness were all adjusted on these images for better visibility of defects.

The next test that we performed was to see if "cross-talk" occurred between traces, especial ones that were spaced closer together. This was done by attaching the VNA cable to edge port 1A, then a 50 Ω load on 1B. Then a similar load was attached to 2A and the other end of the VNA cable was attached to 2B (see figure 3.1 for edge port numbering references). The purpose of the loads was to prevent reflections.



Figure 3.4: Cross talk in the $\frac{1}{16}$ " PCB. The most cross talk seems to occur between trace one and trace two, with the rest being very close to the noise.



Figure 3.5: Cross talk in the $\frac{1}{64}$ " PCB. Most of the cross-talk on these traces seems to be negligible.

In comparing the graphs above, it seems that the thinner trace and substrate leads to a reduction in cross talk between traces. This is probably due to the reduced surface area of the trace making more difficult for the signal to jump traces. Table 3.1 summaries the tests conducted on the 1/16" and 1/64" PCBs.

Substrate Height	Trace Number	Connectivity	Cross-Talk	Noticeable Defects
	1	Yes	reference point	
	2	Yes	-20 dB	
1/16"	3	Yes	-35 dB	
1/10	4	No	N/A	Scratch through the trace
	5	No	N/A	Scratch through the trace
	6	Yes	-40 dB	
	1	Yes	reference point	
	2	Yes	-35 dB	
1/64"	3	N/A	N/A	Edge-ports require more soldering
1/04	4	Yes	-50 dB	
	5	Yes	-50 dB	
	6	Yes	-50 dB	

Table 3.1: Results of our tests on the two PCBs. The table documents that small defects can break the connectivity of the PCB and that within 0.5", traces experience significant cross-talk.

Chapter 4 Conclusions

In conclusion, the research described in this thesis falls into two categories: numerical simulations of microstrips traces and the development of FR4-based PCBs with microstrip structures. Both of these research initiatives support the long term goal of developing a microwave atom chip for producing ACZ potentials to manipulate ultracold atoms. Several variations of microwave atom chips where simulated in FEKO. The research on these simulations lead to the following conclusions:

- The Straight Trace(AlN) was shown to be near its optimal parameters for a trace width between 55.35 and 56 μm. These simulations also showed that the impedance and reflection coefficient also depend on the overall length and width of the microwave atom chip. Plots of frequency versus the reflection coefficient/impedance show that the circuit is fairly broadband.
- The Curved Trace was shown to have a significant reflection coefficient and a non 50 Ω impedance at a trace width of approximately 56 µm. Also, there is a clear issue with the simulation at lower frequencies.
- The 3-Microstrip Trap : In spite of working with a less than optimal curved trace model, the three trace scheme was successful in generating a magnetic field minimum (the microwave trap) above the microwave atom chip. However,

the impedance varies drastically between the traces and the reflection coefficient for the center trace was far beyond negligible.

The Straight Trace (FR4) showed that as the thickness of the substrate doubles, the width of the trace to achieve a 50 Ω impedance also approximately doubles. At a substrate thickness of 1/16 inches, the optimal trace width was 2.27 mm, 1/32 inches was 0.90207 mm, and finally the 1/64 inches height corresponded to an optimal trace width of 0.452.

The following simulations will need be run in the near future:

- The various FR4 simulations run at multiple frequencies.
- A curved trace run with OPTFEKO to determine the ideal parameter values for this particular trace design.
- 3 microstrip trap run with the optimized parameters of the curved trace.

In addition to simulations, a couple of large scale prototypes have been build, and we have started tests on them. If we can get to the point of prototyping a three trace trap, then we would be able to use small dielectric spheres (microspheres) suspended in a dielectric medium to verify the existence of the electric field minimum "trap". If we can successfully manipulate the microspheres with the prototype, then our theoretical results from the FEKO simulations will have been verified, and we can move forward to the production of the actual microwave atom chip.

Appendix A Circulator Ports

The single strand microstrip model can be used to test an ideal circulator model. A circulator consists of three ports (A,B,C), and operates in the following manner: a signal into A is output to B; a signal to B is output to C; and a signal to C is output to A. A circulator is often used to protect a signal source: normally a signal travels from port A to port B and then to a load, but if there is a reflection of some of at the load, then the reflection will go from port B to port C (so long as C is terminated with a proper 50 Ω load) and is thus redirected from port A.(See figure bellow.)



Figure A.1: Circulator Port Circulator showing how the signals are redirected. [1].

Another easy way to imagine this is through linear algebra. If you express the 3

ports as the vector $\begin{bmatrix} a \\ b \\ c \end{bmatrix}$, and we want to find a linear transformation that makes the above vector become $\begin{bmatrix} c \\ a \\ b \end{bmatrix}$ then once can use the matrix: $\begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$ acting on the first vector to produce the desired transformation. The matrix above is called the scattering matrix, and when it is applied to an edge-port, this in essence defines a circulator port.

Appendix B Code sample

The following is the functions called into the GUI and the GUI itself for converting magnetic field data into a temperature plot.

B.1 constants

```
/*
    Kameron Sullivan
                      */
classdef Constants
   properties (Constant)
       %Defining u as vacum permitivity in units of (Tesla meters)/A
       u=1.25*10^(-6);
       %define ub as the Bohr Magneton in J/T
       ub=9.274009994*10<sup>(-24)</sup>;
       %define planks constant in J*s
       h=1.054571800*10<sup>(-34)</sup>;
       %boltzman constant
       k_b = 1.38064852e-23;
       I=3/2;
       %I for rubidium 87
       S=1/2;
       %spin of electron
   end
   methods ( Static )
       function Fp = Fp()
           Fp = Constants.I + Constants.S;
       end
       function Fm = Fm()
           Fm = Constants.I - Constants.S;
       end
   end
end
```

B.2 dataimport

```
/*
    Kameron Sullivan
                       */
function [dat] = dataimport(filename)
   startRow = 16;
   formatSpec = '%33f%18f%18f%18f%18f%18f%18f%18f%18f%18f%[^\n\r]';
   %% Open the text file.
   fileID = fopen(filename,'r');
   textscan(fileID, '%[^\n\r]', startRow-1, 'WhiteSpace', '', 'ReturnOnError', false, 'EndOfLine
   dataArray = textscan(fileID, formatSpec, 'Delimiter', '', 'WhiteSpace', '', 'TextType', 'str:
   fclose(fileID);
   %% Allocate imported array to column variable names
   dat.X = dataArray{:, 1};
   dat.Y = dataArray{:, 2};
   dat.Z = dataArray{:, 3};
   dat.ReHx = dataArray{:, 4};
   dat.ImHx = dataArray{:, 5};
   dat.ReHy = dataArray{:, 6};
   dat.ImHy = dataArray{:, 7};
   dat.ReHz = dataArray{:, 8};
   dat.ImHz = dataArray{:, 9};
   %calc of dimensions
   dat.numz=min(diff(find(diff(dat.Z))));
   dat.numx=numel(find(diff(dat.Z)))+1;
   %Calc of complex H
   %.* is for a element wise multiplication
   dat.CompHx=reshape(dat.ReHx+1i.*dat.ImHx,dat.numz,dat.numx);
   dat.CompHy=reshape(dat.ReHy+1i.*dat.ImHy,dat.numz,dat.numx);
   dat.CompHz=reshape(dat.ReHz+1i.*dat.ImHz,dat.numz,dat.numx);
   dat.xplot = linspace(min(dat.X)*1e6,max(dat.X)*1e6,dat.numz)';
   dat.zplot = linspace(min(dat.Z)*1e6,max(dat.Z)*1e6,dat.numx)';
end
```

B.3 spin

```
S.sm = 0;
S.sz = 0;
if me==mg+1
    S.sp=Constants.h*sqrt((Constants.Fp+me)*(Constants.Fp+mg))/(2*Constants.I+1);
end
if me==mg-1
    S.sm=Constants.h*sqrt((Constants.Fp-me)*(Constants.Fp-mg))/(2*Constants.I+1);
end
if me==mg
    S.sz=Constants.h*sqrt((Constants.Fp+me)*(Constants.Fp-mg))/(2*Constants.I+1);
end
end
```

B.4 bfeild

B.5 temperature

```
%out front in the equation definition.
temp.Ep=(Constants.h/2)*(-abs(d*1e6).*ones([dat.numz,dat.numx])+ ...
sqrt((d*1e6).^2+(temp.0.*temp.0c).^2));
temp.Em=(Constants.h/2)*(abs(d*1e6).*ones([dat.numz,dat.numx])- ...
sqrt((d*1e6).^2+(temp.0.*temp.0c).^2));
temp.T=temp.Ep.*(1e6/Constants.k_b);
temp.xplot = linspace(min(dat.X)*1e6,max(dat.X)*1e6,dat.numz)';
temp.zplot = linspace(min(dat.Z)*1e6,max(dat.Z)*1e6,dat.numz)';
```

end

B.6 GUI

```
/*
    Kameron Sullivan
                      */
classdef MagToE < matlab.apps.AppBase</pre>
   % Properties that correspond to app components
   properties (Access = public)
                              matlab.ui.Figure
       MagToEApp
       tempAxes
                              matlab.ui.control.UIAxes
       detuningMHzSliderLabel matlab.ui.control.Label
       detuningMHzSlider
                              matlab.ui.control.Slider
       BplusAxes
                              matlab.ui.control.UIAxes
       BminusAxes
                              matlab.ui.control.UIAxes
       m_eEditFieldLabel
                              matlab.ui.control.Label
       m_eEditField
                              matlab.ui.control.NumericEditField
       m_gEditFieldLabel
                              matlab.ui.control.Label
                              matlab.ui.control.NumericEditField
       m_gEditField
       HFEFileEditFieldLabel
                              matlab.ui.control.Label
       HFEFileEditField
                              matlab.ui.control.EditField
       BrowseButton
                              matlab.ui.control.Button
       RefreshButton
                              matlab.ui.control.Button
   end
   properties (Access = private)
                             string% Description
       CurrentHFEFile
       HFEDataSet% Description
   end
   methods (Access = private)
       function UpdatePlots(app)
           \% disable refresh button while calculating plots
           app.RefreshButton.Enable = false;
           % calculate data sets
```

```
B=bfield(app.HFEDataSet);
        S=spin(app.m_eEditField.Value,app.m_gEditField.Value);
        T=temperature(app.HFEDataSet,B,app.detuningMHzSlider.Value,S);
        % plot contours
        contourf(app.tempAxes,app.HFEDataSet.xplot,app.HFEDataSet.zplot, ...
            log(T.T'),200, 'linestyle', 'none');
        contourf(app.BplusAxes, app.HFEDataSet.xplot, app.HFEDataSet.zplot, ...
            log(abs(B.p')), 20, 'linestyle', 'none');
        contourf(app.BminusAxes, app.HFEDataSet.xplot, app.HFEDataSet.zplot, ...
            log(abs(B.m')), 20, 'linestyle', 'none');
        % display colorbar
        colorbar(app.tempAxes);
   end
end
% Callbacks that handle component events
methods (Access = private)
   % Button pushed function: BrowseButton
   function BrowseBtnPushed(app, event)
        [f,p] = uigetfile('.hfe');
        app.CurrentHFEFile = [p,f];
        app.HFEFileEditField.Value = app.CurrentHFEFile;
        app.HFEDataSet = dataimport(app.CurrentHFEFile);
        UpdatePlots(app);
   end
   % Value changed function: detuningMHzSlider
   function detuningChanged(app, event)
        app.RefreshButton.Enable = true;
   end
   % Value changed function: m_eEditField
   function m_eChanged(app, event)
        app.RefreshButton.Enable = true;
   end
   % Value changed function: m_gEditField
   function m_gChanged(app, event)
        app.RefreshButton.Enable = true;
   end
   % Button pushed function: RefreshButton
   function RefreshButtonPushed(app, event)
        UpdatePlots(app);
    end
end
% Component initialization
```

```
methods (Access = private)
```

```
% Create UIFigure and components
function createComponents(app)
    % Create MagToEApp and hide until all components are created
    app.MagToEApp = uifigure('Visible', 'off');
    app.MagToEApp.Position = [100 100 652 481];
    app.MagToEApp.Name = 'Mag to E';
    % Create tempAxes
    app.tempAxes = uiaxes(app.MagToEApp);
    title(app.tempAxes, 'Temp')
    xlabel(app.tempAxes, 'X')
    ylabel(app.tempAxes, 'Y')
    app.tempAxes.Position = [1 155 354 327];
    % Create detuningMHzSliderLabel
    app.detuningMHzSliderLabel = uilabel(app.MagToEApp);
    app.detuningMHzSliderLabel.HorizontalAlignment = 'right';
    app.detuningMHzSliderLabel.Position = [13 123 84 22];
    app.detuningMHzSliderLabel.Text = 'detuning(MHz)';
    % Create detuningMHzSlider
    app.detuningMHzSlider = uislider(app.MagToEApp);
    app.detuningMHzSlider.Limits = [0 10];
    app.detuningMHzSlider.ValueChangedFcn = createCallbackFcn(app, @detuningChanged, true
    app.detuningMHzSlider.Position = [118 132 150 3];
    % Create BplusAxes
    app.BplusAxes = uiaxes(app.MagToEApp);
    title(app.BplusAxes, 'Bp')
    xlabel(app.BplusAxes, 'X')
    ylabel(app.BplusAxes, 'Y')
    app.BplusAxes.Position = [376 341 265 141];
    % Create BminusAxes
    app.BminusAxes = uiaxes(app.MagToEApp);
    title(app.BminusAxes, 'Bm')
    xlabel(app.BminusAxes, 'X')
    ylabel(app.BminusAxes, 'Y')
    app.BminusAxes.XTick = [];
    app.BminusAxes.YTick = [];
    app.BminusAxes.Position = [376 185 254 143];
    % Create m_eEditFieldLabel
    app.m_eEditFieldLabel = uilabel(app.MagToEApp);
    app.m_eEditFieldLabel.HorizontalAlignment = 'right';
    app.m_eEditFieldLabel.Position = [310 123 29 22];
    app.m_eEditFieldLabel.Text = 'm_e';
    % Create m_eEditField
```

```
app.m_eEditField = uieditfield(app.MagToEApp, 'numeric');
        app.m_eEditField.ValueChangedFcn = createCallbackFcn(app, @m_eChanged, true);
        app.m_eEditField.Position = [354 123 100 22];
        app.m_eEditField.Value = 2;
        % Create m_gEditFieldLabel
        app.m_gEditFieldLabel = uilabel(app.MagToEApp);
        app.m_gEditFieldLabel.HorizontalAlignment = 'right';
        app.m_gEditFieldLabel.Position = [310 72 29 22];
        app.m_gEditFieldLabel.Text = {'m_g'; '};
        % Create m_gEditField
        app.m_gEditField = uieditfield(app.MagToEApp, 'numeric');
        app.m_gEditField.ValueChangedFcn = createCallbackFcn(app, @m_gChanged, true);
        app.m_gEditField.Position = [354 72 97 22];
        app.m_gEditField.Value = 1;
        % Create HFEFileEditFieldLabel
        app.HFEFileEditFieldLabel = uilabel(app.MagToEApp);
        app.HFEFileEditFieldLabel.HorizontalAlignment = 'right';
        app.HFEFileEditFieldLabel.Position = [16 22 52 22];
        app.HFEFileEditFieldLabel.Text = 'HFE File';
        % Create HFEFileEditField
        app.HFEFileEditField = uieditfield(app.MagToEApp, 'text');
        app.HFEFileEditField.Editable = 'off';
        app.HFEFileEditField.Position = [83 22 371 22];
        % Create BrowseButton
        app.BrowseButton = uibutton(app.MagToEApp, 'push');
        app.BrowseButton.ButtonPushedFcn = createCallbackFcn(app, @BrowseBtnPushed, true);
        app.BrowseButton.Position = [497 22 100 22];
        app.BrowseButton.Text = 'Browse';
        % Create RefreshButton
        app.RefreshButton = uibutton(app.MagToEApp, 'push');
        app.RefreshButton.ButtonPushedFcn = createCallbackFcn(app, @RefreshButtonPushed, true
        app.RefreshButton.Enable = 'off';
        app.RefreshButton.Position = [497 72 100 73];
        app.RefreshButton.Text = {'Refresh'; '};
        % Show the figure after all components are created
        app.MagToEApp.Visible = 'on';
   end
end
% App creation and deletion
methods (Access = public)
   % Construct app
   function app = MagToE
```

```
% Create UIFigure and components
createComponents(app)
% Register the app with App Designer
registerApp(app, app.MagToEApp)
if nargout == 0
clear app
end
end
% Code that executes before app deletion
function delete(app)
% Delete UIFigure when app is deleted
delete(app.MagToEApp)
end
end
end
```

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