FAST, COMPACT, HIGH STRENGTH MAGNETIC FIELD GENERATOR

Final Document

Team Number: DEC1622

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1 Introduction

1.1 Project Statement and Purpose

The objective of this project is to build a small scaled circuit that generates a high speed magnetic field. The primary application of this project is used in magneto-optic switches for optic fiber-based technologies such as networking systems and may be also used in biomedical applications such as transcranial brain stimulation. To summarize, the method of operation for our purposes include the phase shift of optical signals induced by a magnetic field. This phenomenon is also known as Faraday rotation.

In *Figure 1*, the PCB design (manufactured by Oshpark) is our final product after testing and simulation among several other prototypes (see Appendix II).

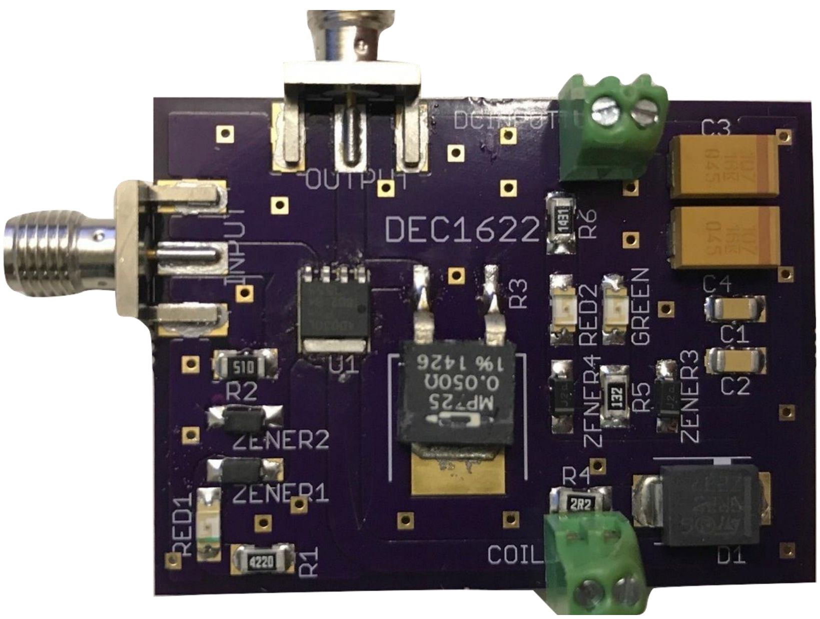

Figure 1: PCB design of final circuit - Magnetic Pulse Generator

1.2 Project Requirements

1.2.1 Non- Functional

1. Footprint size smaller than 3.5” by 2”
2. Fabrication of circuit on industrial grade PCB
3. Final product has to be able to deliver consistent results

1.2.2 Functional

1. Generate a magnetic flux density of amplitude 500 Gauss and have a rise time of 100 ns.
2. DC supply voltage of 15V
3. Final product will need to be fitted with SMA connector
4. Inductive coil needs to be large enough to fit the MO material inside the coil

1.3 Project Flow

We can generally summarize our project to three processes namely designing, simulating and testing process. The first two processes involve calculations with the assumption of all ideal components and sources used. In the testing process, we will need to prepare the layout files, fabricate our design, solder components onto the board, and run tests to ensure the circuit works in real time and meets the requirements. A detailed diagram of these processes is as follow in *Figure 2*.

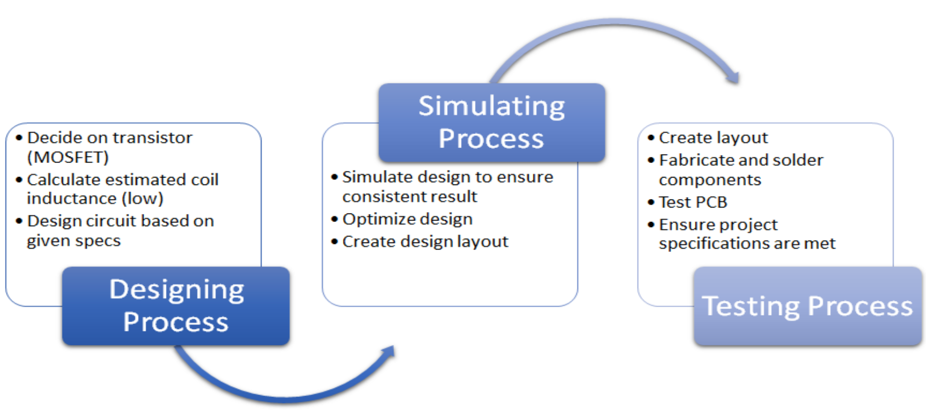

Figure 2: Processes

2 Designing Process

Since we are dealing with fast but small signals, extra care and consideration had to be taken as the input signal can be easily distorted. Time and effort is spent on designing and optimizing our circuits. In this document, we will be breaking our components down into smaller parts with individual discussions.

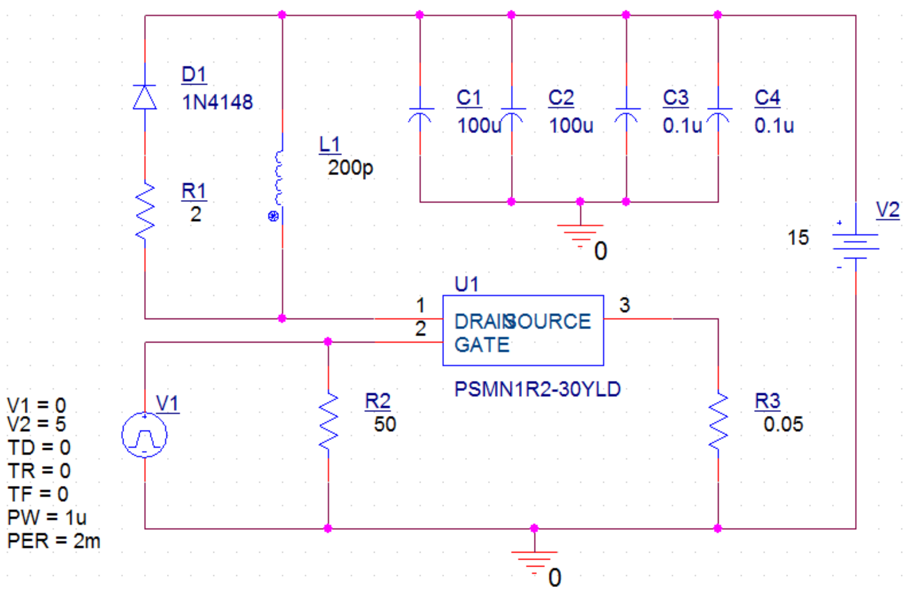

Figure 3: Schematic Diagram

2.1 Components Diagnosis

2.1.1 Capacitor

For this circuit, four capacitors are connected in parallel. Two capacitors will have a much higher capacitance value (100uF) than the other two (0.1uF). The two larger capacitors will store charge that will be released as current flowing through the inductor when the switch is turned on. Meanwhile the smaller capacitors will act as a protector for the circuit against random small spikes from the power supply by storing the excess charges into the capacitors.

2.1.2 Diode

Diode, in series with a 2Ω resistor, forms a loop with the inductive coil. The diode will ensure the loop will only work when the switch is turned off as its polarity ensure current from the DC input will not flow into the loop from the wrong direction. When switch is off, the charging capacitors will act as a short while the diode-resistor loop will conduct the charge built up in the inductive coil in a cycle to discharge the excess current.

2.1.3 Resistor

As mentioned above, a 2Ω resistor is placed in series with the diode to aid in energy dissipation as heat from the charge built up in the inductive coil when switch is turned on.

Besides that, this design also used a 50Ω resistor in parallel to the gate of MOSFET (switch). This resistor is aimed at achieving maximum power efficiency into the gate of the MOSFET. According to maximum power transfer theorem, maximum power transfer from an external source can be achieved by pairing a load with similar resistance as the source. For our project, we have set our source (function generator in continuous pulse mode) with a 50Ω input impedance hence the value of this resistor.

2.1.4 Coil

The coil is the source of magnetic field generation. The coil is made up of insulated soft copper wire with a wire gauge of 18 AWG (1.034 mm in diameter) that was hand-wound 5 times over a plastic mound that has the same diameter as the MO material. The plastic mold ensures the coil we created is able to fit the MO material on the inside of the coil.

The magnetic field and coil are defined from the equations below:

$$B = \frac{\mu N I}{\sqrt{l + 4R^2}}$$

$$L = \frac{\mu N^2 (\pi \times R^2)}{\sqrt{l^2 + 4R^2}}$$

Note:

B : magnetic field of a coil (1 Tesla = 10,000 Gauss)

μ: permeability of free space (4π* e-7 H/m)

N: number of turns of a coil (dimensionless)

I : current through a coil (Amperes)

l : length of the coil (meters)

R: radius of the coil (meters)

L : inductance of the coil (Henries)

From the equation, we deduct that in order to get a higher magnetic field, we would need a smaller coil (length and radius) and high current.

2.1.5 Switch

2.1.5.1 MOSFET & BJT Comparisons

We will also be testing the effectiveness of two basic transistor types, MOSFET and BJT, as the switch of our circuit. We ran simulations and compared the results.

2.1.5.1.1 MOSFET As Switch

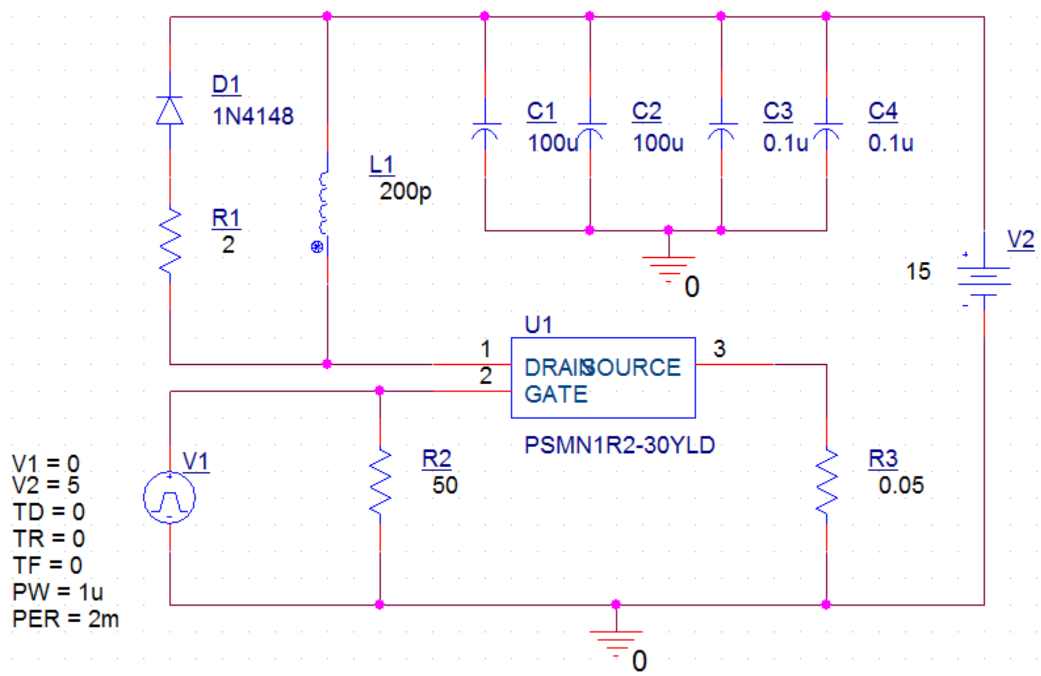

Figure 4: MOSFET Circuit

Figure 4 shows our PSPICE design with a MOSFET (PSMN1R2-30YLD) acting as the switch. This MOSFET was chosen because it was designed for fast switching without having high leakage currents. This is a n-channel MOSFET made by NXP Semiconductor with a rated Drain to Source Voltage (V_{dss}) of 30V and Continuous Drain Current (I_d) of 100A at 25°C. SPICE simulation file is obtained directly from NXP's website and imported prior to running the simulation. The simulated result will then be compared with that when BJT is acting as the switch to determine which transistor is more suitable for our cause.

2.1.5.1.2 BJT As Switch

Since BJT typically has low collector current, a Darlington configuration is used instead.

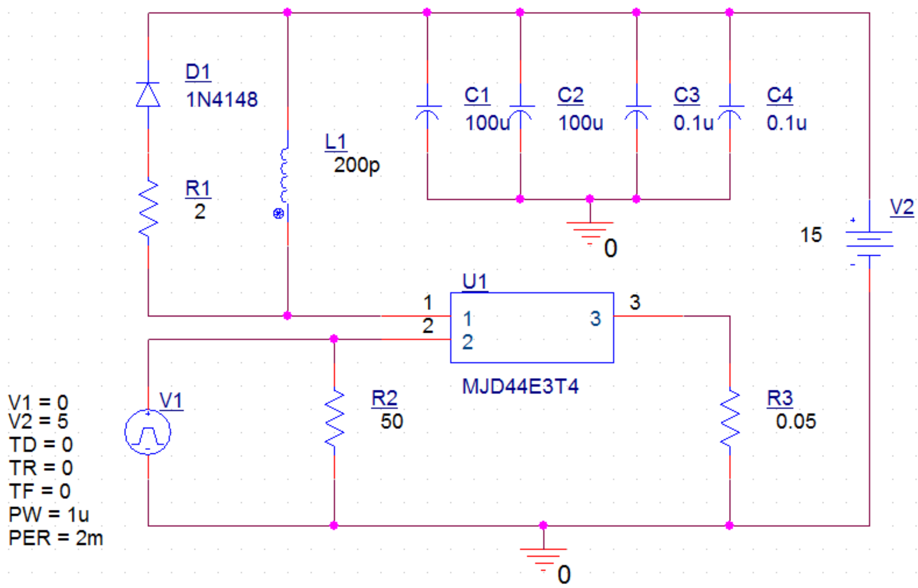

Figure 5: Darlington Circuit

Figure 5 above shows our PSPICE design with a Darlington (MJD44E3T4) acting as the switch. This is a NPN Darlington made by ON Semiconductor with a rated Collector Emitter Breakdown Voltage of 80V and Collector Current (I_c) of 10A. Usually, when a MOSFET's performance is compared to a BJT, the BJT will display more favorable results partly due to its small signal parameters lacking an additional r_Π. The Darlington is capable of taking in more current (depending on model but can be as high as 100 times more than a simple BJT) but it has a higher power consumption (due to its really high base/emitter voltage). While Darlington is made up of a pair of transistor arranged in such a way that the current amplified by the first transistor is further amplified by the seconds transistor, it is more commonly made up of NPN BJTs. Using one BJT for the purpose of this circuit is practically impossible because there is limited current going through the BJT. Hence, to meet the high current requirement of this circuit, we will be using a Darlington configuration.

2.1.5.2 MOSFET Input Capacitance

Since we are dealing with high speed signals with high amplitude, capacitance can be a real problem. Effects of parasitic capacitance in the board can be lessen through careful circuit design. However, there exist capacitance between the drain and gate of the MOSFET too. In fact, MOSFETs usually have three major capacitances: input capacitance (C_{iss}), output capacitance (C_{oss}), and reverse transfer capacitance (C_{rss}). Of the three, we have identified the input capacitance as a major variable especially since it has the highest value. This is because gate insulation has to be very thin in order to get decent throughput (change in drain current for a change in gate-source voltage) thus increasing the gate-source capacitance (one component of input capacitance with the other being gate-drain capacitance).

It is really tricky determining the range for input capacitance when picking our MOSFET. The input capacitance has to be low in order to decrease the rise time of our overall circuit. Lower input capacitance means the gate can be charged quickly and turned on faster. On the other hand, the input capacitance is also involved in driving the MOSFET to be in a deeper saturation state that allows more drain current to flow through which in turn helps boost the magnetic flux density in the inductor coil considering current is proportional to the magnetic flux density output.

In order to better understand the idea of input capacitance, we have used several MOSFETs each with different input capacitance values. These are:

- CSD17322Q5A (580 pF)
- IRL3714S (670 pF)
- PSMN4R0-30YLD (1272pF)
- PSMN1R2-30YLD (4616 pF)

As expected, the MOSFET with lowest input capacitance (CSD17322Q5A) displayed the shortest rise time (83.2 ns) but it also allows the lowest amount of current to flow through (1.64 V / 0.05Ω = 32.8 A) based on our reading on the current sensing resistor. According to our calculations, the circuit is thus able to produce 343.481 G in magnetic flux density. Since our targeted magnetic flux density is 500 G, we have a little window to increase the input capacitance. This should increase the rise time slightly while increasing the magnetic flux density produced as well.

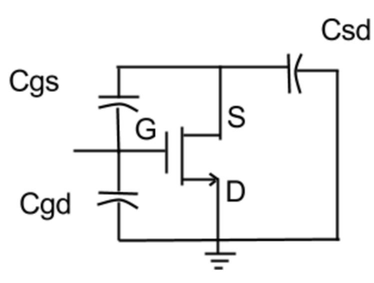

Figure 6: Parasitic capacitance found in a MOSFET

2.1.6 Zener Protection

For the Zener diode, under a certain voltage (< 5V), it will act like a regular diode which allows the current to flow from its anode to cathode. Exceeding the Zener voltage (known as peak-inverse voltage), the diode will break down and be reverse biased so current will flow in the opposite direction. The diode remains a constant voltage regardless of the amount of current (without exceeding the maximum current). This property is favorable and acts as a voltage regulator helping us to maintain a constant voltage across the inductor.

2.1.7 Current Sense Resistor

Since magnetic field is hard to be measured and observed, we added a current sensing resistor to the source pin of the transistor. This resistor has a small resistance (0.05Ω) is specially made to be able to detect small changes in current. This resistor makes it possible for us to observe the inductor current which is in series with the current sensing resistor thus both having the same current value. The resistor is connected to a SMA connector which can be plugged into an oscilloscope to observe waveform and measure parameters (voltage in particular). Current can then be determined through calculation based on Ohm's law which is then used to calculate the magnetic flux density.

3 Simulating Process

As mentioned in the introduction, the focus of the simulation will be at the inductor of the circuit where the magnetic field will be generated. Thus, the current through the inductor needs to be sufficiently high in order to obtain a high magnetic field. We can also observe its switching speed at the inductor where we seek to have a short rise time.

For simulation purposes, we will be using PSPICE (OrCAD Capture CIS) due to its simplicity. Furthermore, we managed to understand the procedure to import new SPICE simulation files into PSPICE making it possible for us to simulate using components of our choice (view Appendix). In order to make better comparisons, we decided to fix several variables. Hence, each circuit will have the same pulse input with magnitude 0-5V, pulse width of 1us, and pulse period of 1ms. This gives us a duty cycle of 0.1% to ensure that this circuit will not overheat. We will measure current in series to the inductor while ignoring any voltages since this is allowed in the simulator program but not real life.

3.1 Simulation Analysis Using PSPICE

3.1.1 Inductance

The inductance values for both the MOSFET and Darlington circuit is manipulated. The result shown will be labeled as such:

- Green - Inductance = 146 pH
- Red - Inductance = 146 nH
- Blue - Inductance = 146 uH

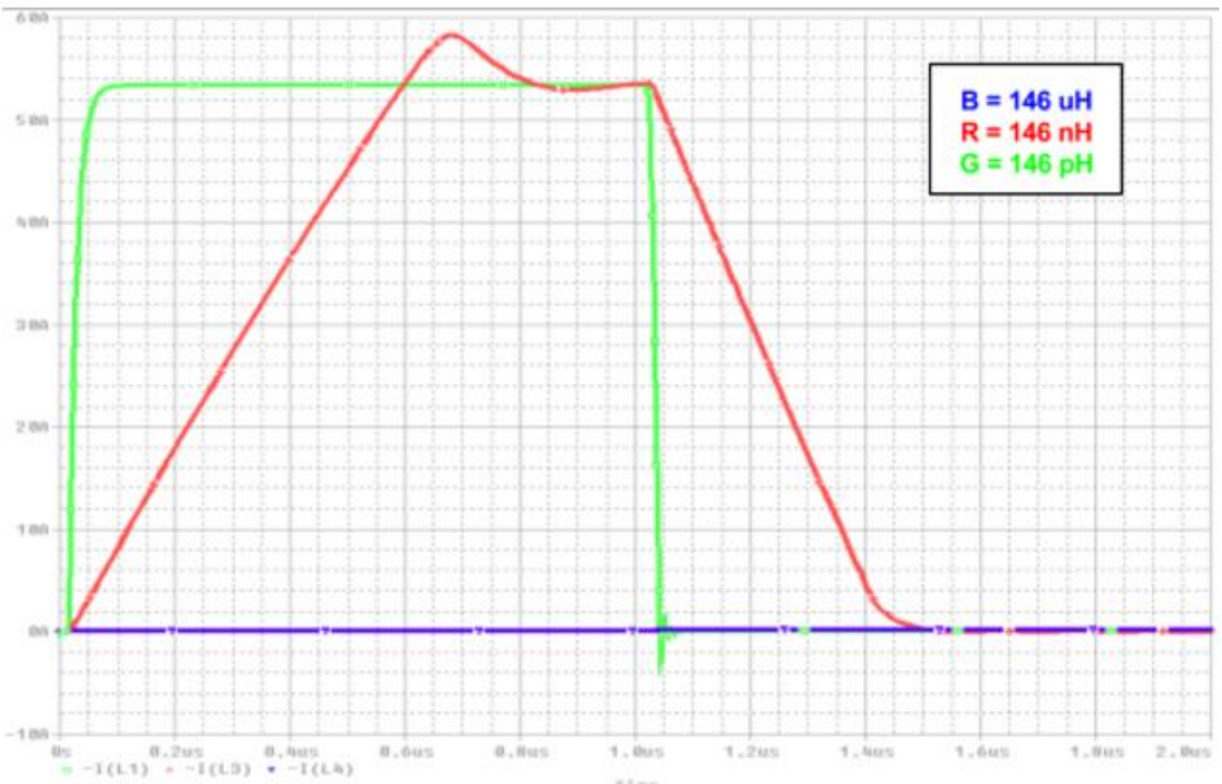

Figure 7: Three inductance value plot (MOSFET circuit)

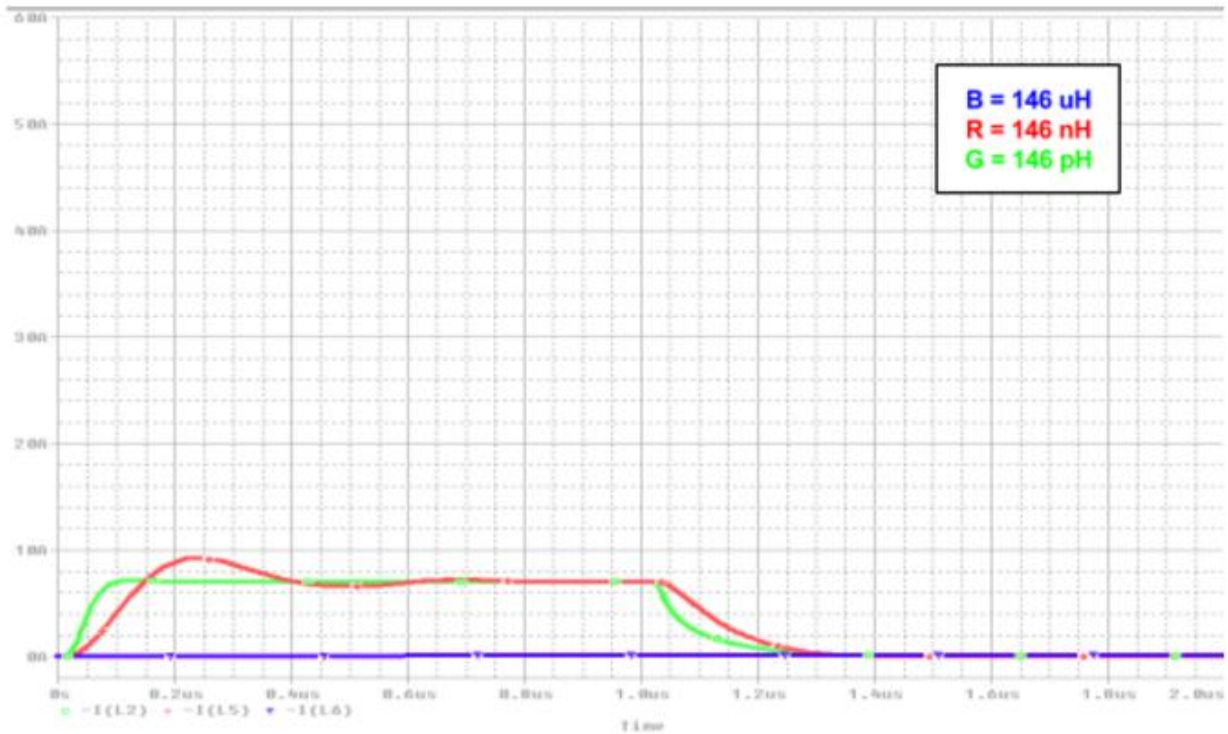

Figure 8: Three inductance value plot (Darlington circuit)

Let's first focus on the red plots (146 nH) of both *Figure 7* and *Figure 8*. As clearly shown in both graphs, the outputs are far from ideal. Since the inductor current's pulse width should be linearly affected by the input pulse width, the current curves above failed to maintain at the peak for 1um (pulse width). This shows that the inductor is not charging and discharging fast enough. Based on Circuit theory, we can say that, initially when the input pulse is HIGH (MOSFET switch is turned on), the inductor starts charging. However, before the inductor is fully charged (hence the lack of a clear pulse width), the input pulse started a downwards descend to LOW as the switch is turned off. The inductor current starts decreasing as well. At a point when the charge in the inductor is higher, the inductor slowly discharges hence the apparent horizontal line. This does not last long and the inductor current slowly falls as it discharges the remaining charges creating the negative slope. As the graphs also show, this slow charging and discharging dragged the rise time of the pulse significantly. This is not good for our intended purpose of the circuit. So, we need to tweak the circuit further.

Next, let’s analyses the green plots of both Figures. The value of the inductor used is extremely small at 146 pH (which is realistically impossible). From the plot, we noticed how the MOSFET is outperforming the Darlington again. Out of curiosity, we also tried using higher value of inductance (Blue plot). Both MOSFET and Darlington plot are very close to zero.

Two important observations we obtained from this simulation is as followed:

- MOSFET will work better for our circuit. The MOSFET’s affinity to current makes it the ideal transistor choice than the Darlington as proven by its significantly higher peak and shorter rise time. The MOSFET has a higher tolerant to heat as well which is an added bonus.
- The inductance value can gravely affect the peak magnitude and rise time of the inductor current. Hence, we should do some extensive calculations for a suitable inductance value for our final design’s coil.

3.1.2 Capacitance Values

On the other hand, we compiled several plots with different capacitance values and even removed the capacitance altogether for both circuits. Interestingly, the results are all similar. All plots show insignificant changes regardless of the presence or absence of the capacitors and their respective values. This is because the power source in the simulator is ideal thus it is able to provide any amount of current required by the circuit. This will not be the case in real life testing as the power source has limited current supply.

4 Testing Process

4.1 Hardware

4.1.1 Test Bench

After printing out and soldering the designed PCB, we will also be using the Digital Multimeter, Power Source, Function Generator, and Oscilloscope to further test our physical circuit. Since simulated circuits are usually in ideal condition, the physical PCBs will surely show different results. We will need to ensure the printed PCBs fulfills the project specification before the demonstration day itself. After all, if successful, it is the PCBs that will be used by the industry and not a non-existing simulation file.

4.1.2 Coil

As mentioned before, it is very hard to measure the inductance of the coil. Calculations based on equations may yield close results by assuming certain factors are constant which is never the case. Testing the coil physically is thus the better option. For the purpose of comparison, we decided to make another coil using a thinner copper wire with diameter 24 AWG. This coil will therefore have a smaller inductance value than our default coil. Each board will then be measured twice, first using the default coil and again using the smaller coil.

4.1.3 PCB Design

Figure 9 shows the layout of the PCB using EAGLE Schematic Editor. Firstly, we need to find each component's footprint which is used to create schematic on EAGLE. The overall footprint of this PCB is 1.8 inch x 1.4 inch.

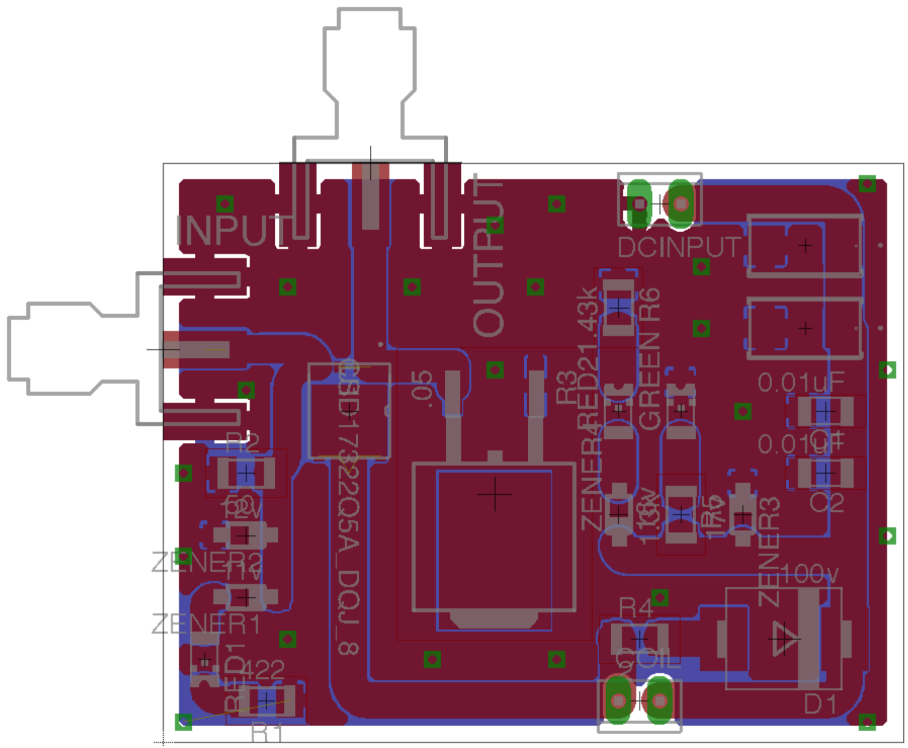

Figure 9: PCB layout using EAGLE

4.1.4 Protomat

After creating the PCB layout with EAGLE, we will then print it out using the Protomat machine. The Protomat etches board designs onto copper plates based on Gerber files uploaded to the accompany program. The user will also have to load drill bits manually into the machine and calibrate to ensure the boards produced are undamaged.

4.1.5 Reflow Oven

Instead of soldering the tiny components manually, we decided to use the reflow oven. A special paste is used to stick the components onto their respective pads. The board is then placed inside the oven and wait. The board produced is neat and tidy. The components are also better attached to the pads and cold joint can be avoided.

4.2 Software

PSPICE allows us to export the output data into csv files that we can then use in MATLAB for further calculations or create graphs. The oscilloscope we used also has the same function. Hence, we can compare the files from both program as another mean of better understanding our circuit.

4.2.1 Matlab

MATLAB is also another integral software for our project. With the correct codes, MATLAB made it possible to calculate multiple equations at one go and plot it all into a single graph for comparison purposes. For example, we have used this program to observe the relationship between current, inductance, length of coil, and radius of coil.

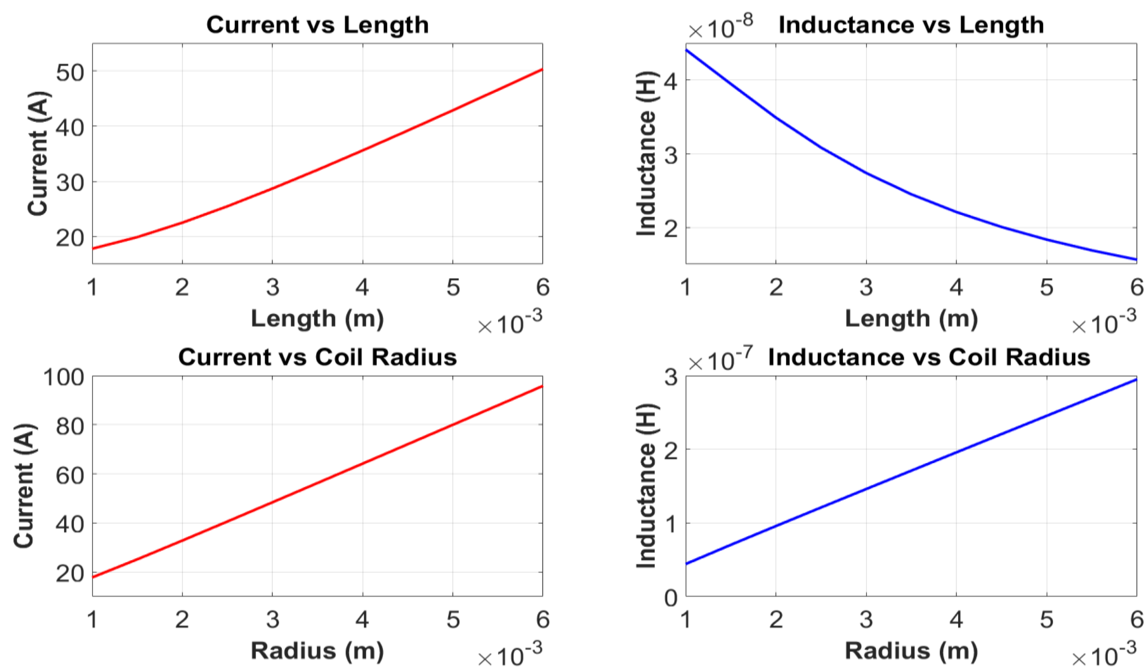

Figure 10: Useful Plot Using Matlab

5 Results

5.1 Simulation Results

A table is provided below which summarizes our findings on the effects of each components on the circuit after running several simulations.

Variable	Analysis Result	Conclusion
Transistor (MOSFET vs Darlington)	MOSFET shows better magnitude and shorter pulse width (57A and 1.05us) than Darlington (7A and 1.4us)	MOSFET works better for our project
Inductance	Low inductance will result in current with higher magnitude and shorter rise time especially in the MOSFET circuit	Smaller inductance value is more favored
Capacitance	Presence and absence of capacitors seems to have insignificant effect on inductor current	In simulation, the ideal source provides the capacitance the circuit needs thus removing the capacitances show no difference in result.
Diode & Resistor Loop	Plot start losing its shape when missing either diode or resistor and goes into a weird shape once both are removed.	Both diode and resistor needs to be present especially when the inductance value is high

Table 1: Conclusions after design and testing process

5.2 Final Design Results

For our final design, we compared the results of all the PCBs created using the Protomat. From there we chose the layout with the best results and used it to fabricate an industrial-grade PCB by Oshpark.

5.2.1 PCB Milling Using Protomat

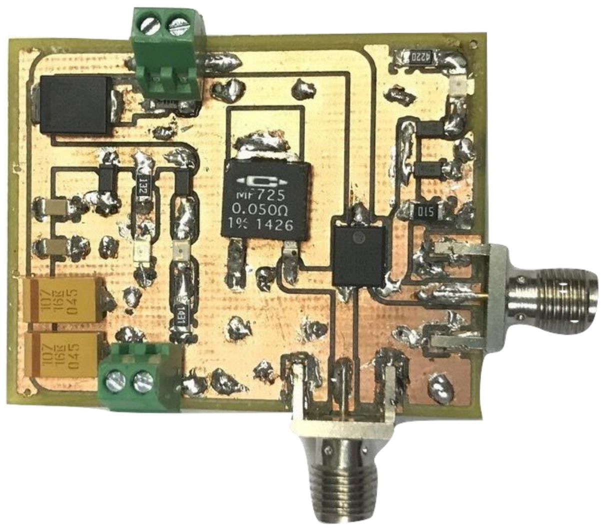

Figure 11: PCB with the best and consistent results using the Protomat

Inductance	**102 nH**	78.5 nH
Rise time (10% - 90%)	**83.200 ns**	129.967 ns
Rise time (20% - 80%)	58.467 ns	94.313 ns
Mean voltage	1.640 V	2.027 V
Max voltage	1.640 V	1.947 V
Magnetic flux density	**343.481 G**	407.709 G

Table 2: Average values obtained from three measurements

From *Table 2*, the results for the **102 nH** inductor gives us the value of **83.2 ns** rise time which is suitable since our goal is to make the rise time to be less than 100 ns. From the result also, a magnetic flux density of **343.481 G** was obtained which is close to what we wanted that is 500 G.

5.2.2 INDUSTRIAL-GRADE PCB

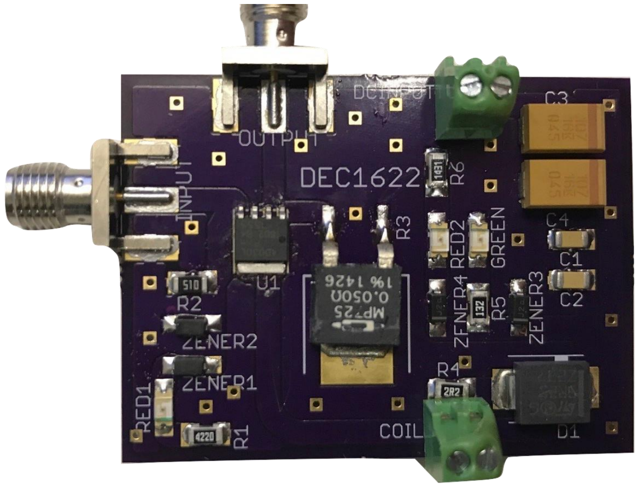

Figure 12: Industrial-Grade PCB

Inductance	**102 nH**
Rise time (10% - 90%)	**111.45 ns**
Rise time (20% - 80%)	75.635 ns
Mean voltage	2.07 V
Max voltage	2.07 V
Magnetic flux density	**433.54 G**

Table 3: Average values obtained from four measurements

From *Table 3*, we obtain the results of 111.45ns and 433.54 G. Based on our result from the previous design, we decided that we still have room to increase the input capacitance of our MOSFET which is exactly what we did. The result reflects our new MOSFET is even better suited for the project as the rise time and magnetic flux density is now even closer to our project specification. Since this board is printed using better equipments, soldered using a reflow oven, and have the coil soldered directly onto the board, we expect it to perform with less noise as well.

5.3 Theoretical vs. Analysis

From the previous chip (CSD17322Q5A with input capacitance of 580 pF) result, low input capacitance MOSFET decreased the rise time significantly, but voltage across the current sensing resistor dropped also. Since we had headroom for rise time, we can increase the input capacitance slightly higher. When input capacitance increased, it will increase depletion width, which means allowing more current to flow from drain to source (deeper saturation). Like we expected, the rise time increased, meanwhile, voltage across the current sensing resistor also increased. Rise time of **111.4ns** is close to our goals, and the magnetic flux density is changing from **343.481 G** to **433.54G** which is closer to 500 G.

6 Issues/Challenges

6.1 PSPICE SPICE File

When we first did the simulation, we had trouble importing the footprint and the SPICE files. The reason was because we don't really know how to import it. This issue was resolved by learning how to import it online. Once we know how to import it, we can easily do the simulation. Other than this problem, we also had trouble with finding some SPICE file for our MOSFET. We tried emailing the manufacturing company to help us and they suggested to use a different MOSFET that have similar properties to the MOSFET that we wanted to use.

6.2 EAGLE Components Footprint

For the layout using EAGLE, it was hard at first since we have no experience with the program. Also, some of the parts we wanted to use did not have footprints readily built into EAGLE. Our solution was to substitute them with components of similar footprint and customized it to fit the requirements of each component.

6.3 Protomat Calibration

Since the Protomat machine is ancient, special attention is needed when calibrating it. Rings on the drill bits have to be sanded to fit into the allocated holes. Oil is applied as well to ensure the arm of the machine is able to pull out the drill bits smoothly. Also, the feedback system in the arm will not automatically detect if it failed to pull out the drill bit. The user will also have to manually adjust the drill bit in the arm to avoid etching too deep into the copper board which damages the board.

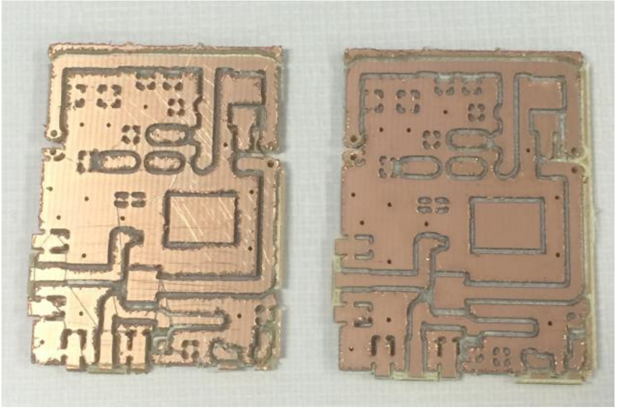

Figure 13: Example of PCB boards with deep etches due to poor calibration

6.4 Deciding on Switch

For the circuit design, we had to decide whether to use a MOSFET or a Darlington configuration to act as the switch. To resolve this problem, we did some simulations to compare both switches and see which switch gives the best result for our project requirements. In the end of the simulation, the results show that MOSFET works better for our circuit.

7 Conclusion

We gained experience using a multitude of software and hardware such as PSPICE, EAGLE, Protomat, reflow oven, and etc. We applied our knowledge and successfully managed to design a circuit that can generate high magnetic flux density (433 G) with a short rise time (111 ns). Through a series of simulations and physical testing, our board, coupled with the correct induction coil and MOSFET, is capable of providing values close to the 500 Gauss and a rise time of 100ns as dictated by our client. Our client had expressed their satisfaction with our results thus ending this project on a high note.

8 Appendix I - Operation Manual

Function Generator and DC Power Supply Setup:

1. Make sure DC supply and pulse generator are turned off.
2. Set the DC supply to output 15V, but do not turn it on
3. Set the Output Function to be “Pulse”
4. Set the Run Mode to be “Continuous”
5. Set the output load to be “50 Ohms”
6. Set the period to be 10 ms (0.01seconds)
7. Set the pulse width to be 1 us (duty cycle = 0.01%)
8. Set the Low Amplitude to be 0V
9. Set the High Amplitude to be 5V
10. Set the Leading Edge to be 18 ns
11. Set the Trailing Edge to be 400.0 ns

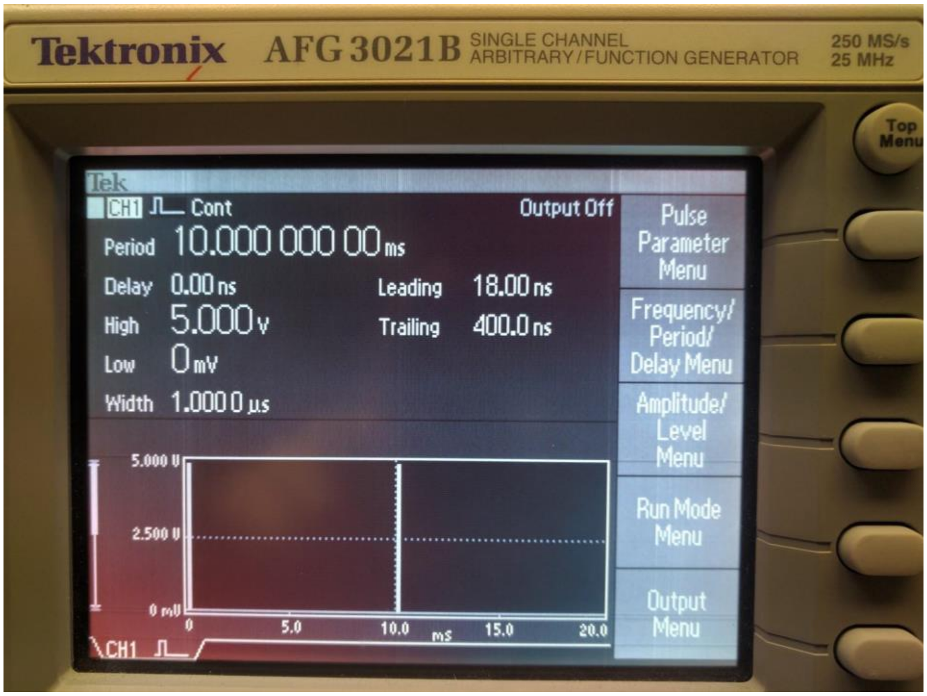

Figure 14: Function generator setup

Instructions

1. Make sure the DC power supply and function generator output is turned off before setting up its values and connecting it to the circuit.
2. Set the equipment as instructed above.
3. After connecting the input terminals, connect the output terminal to the oscilloscope.
4. When everything is connected, turn the DC power supply and function generator on and record the output observed on the oscilloscope.

Error Indicators (LED)

There are 3 LEDs on the board (1 green and 2 red). The green LED indicates that the DC power is on. The red LEDs are connected to Zener diodes and they signal that the voltage is too high and might damage the circuit.

9 Appendix II - Alternative/Initial Versions

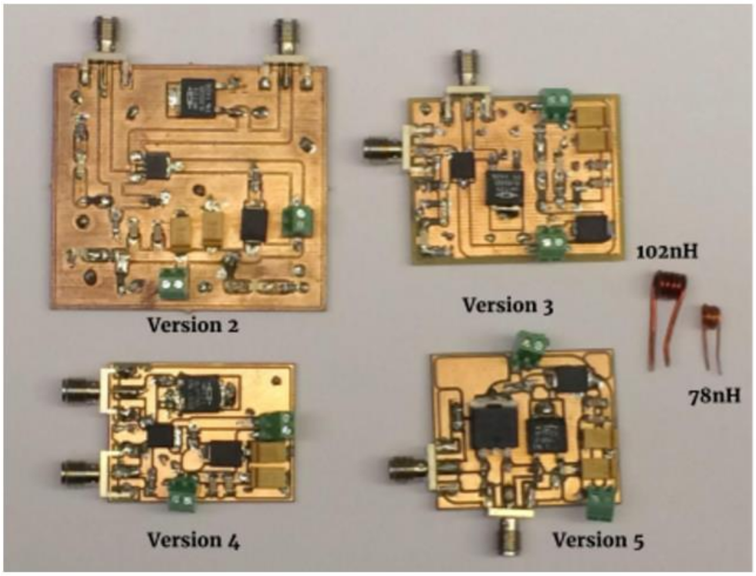

Figure 15: Prototypes of different versions using Protomat

Other than the obvious decrease in size, each board differs in terms of components used and design layout. A short explanation explaining the difference in each version is provided.

Version 1

Version 1 is the first explored board and has a MOSFET with 4616 pF input capacitance and protective circuit. Since we did not have a good PCB layout, we failed to make the first board work.

Version 2

In this version, we still used the MOSFET with high capacitance(4616pF). Since version one does not work, and was hard to troubleshoot, we made version 2 using the same layout with version 1 but larger. Therefore, it is easier to troubleshoot, and thankfully it works!

Version 3 (The best results)

Version 3 is an improved board of version 2. Based on increased experience in doing layout and Protomat, and version 2’s measured results, we would like to have a compact size, and using a different MOSFET with lower input capacitance (670 pF).

Version 4

In version4, we used the MOSFET with input capacitance 580 pF as the switch and we excluded the protective circuit (LEDs). So this board will compare with version 3 to explore how the protective circuit will affect the circuit performance.

Version 5

Version 5 is also an experimental board. We used the MOS FET with input capacitance of 670 pF as the switch and we also did not include the protective circuit. In addition, we did not use the back plane as the ground instead, we connected all the grounds together on the top plane. (We learned that it gives out more parasitic capacitance and was not good for our circuit).

10 Appendix III - Bills of Materials

Quantity	Digi-Key Part Number	Item Description	Cost Per Unit	Total Cost	Vendor	Link
10	497-6085-1-ND	Diode	$0.45	$4.52	Digi-Key	**digikey link**
10	MMSZ5247BT1GOSCT-ND	Zener Diode 17V 500mW	$0.23	$2.30	Digi-Key	digikey link
3	MP725-0.050-FCT-ND	0.05Ω Current Sense Resistor	$9.37	$28.11	Digi-Key	digikey link
50	P2.2ECT-ND	2.2Ω Resistor	$0.02	$1.06	Digi-Key	digikey link
50	P49.9FCT-ND	49.9Ω Resistor	$0.03	$1.41	Digi-Key	digikey link
50	P422FCT-ND	422Ω Resistor	$0.03	$1.41	Digi-Key	digikey link
50	P1.3KECT-ND	1.30KΩ Resistor	$0.02	$1.06	Digi-Key	digi key link
50	P1.43KFCT-ND	1.43KΩ Resistor	$0.03	$1.41	Digi-Key	digikey link
100	160-1169-1-ND	Green LED	$0.13	$13.26	Digi-Key	digikey link
25	1276-2740-1-ND	10000 pF Capacitor	$0.06	$1.44	Digi-Key	digikey link
10	399-3677-1-ND	0.1 µF Capacitor	$0.33	$3.29	Digi-Key	digikey link
10	399-5214-1-ND	100 µF Capacitor	$1.12	$11.17	Digi-Key	digikey link
10	490-1312-1-ND	0.01 µF Capacitor (Ceramic)	$0.01	$0.12	Digi-Key	digikey link
5	ED2675-ND	Wire-to-Board Connector	$1.13	$5.65	Digi-Key	digikey link
10	ED10561-ND	Wire-to-Board Connector	$0.55	$5.46	Digi-Key	digikey link
10	568-11554-1ND	MOSFET N CH 30V 100A	$1.69	$16.93	Digi-Key	digikey link
10	1N4148WTPMSCT-ND	General Purpose Diode	$0.14	$1.40	Digi-Key	digikey link
10	BZT52C6V8-FDICT-ND	6.8V Zener Diode	$0.21	$2.10	Digi-Key	digikey link
10	BZT52C11-FDICT-ND	11V Zener Diode	$0.21	$2.10	Digi-Key	digikey link
10	BZT52C12-FDICT-ND	12V Zener Diode	$0.22	$2.20	Digi-Key	digikey link
10	BZT52C16-FDICT-ND	16V Zener Diode	$0.21	$2.10	Digi-Key	digikey link
10	399-5214-1-ND	100 µF Capacitor	$1.12	$11.17	Digi-Key	digikey link
10	MMSZ5247T1GOSCT- ND	17V Zener Diode	$0.24	$2.40	Digi-Key	digikey link
6	568-11556-1-ND	MOSFET:PSMN1R	$1.27	$7.62	Digi-Key	digikey link
10	J716-ND	Coaxial Connector	$4.31	$43.10	Digi-Key	digikey link
			Total Cost	$172.79		

Figure 16: Bill of materials for the first semester

Quantity	Digi-Key Part Number	Item Description	Cost Per Unit	Total Cost	Vendor	Link
10	J716-ND	SMA Connector Jack, Female Socket 50 Ohm Board Edge, End Launch Solder	$3.72	$37.16	Digi-Key	digikey link
20	ED10561-ND	Wire-to-Board Connector	$0.55	$10.92	Digi-Key	digikey link
5	IRL3714ZSCTL-ND	MOSFET N-CH 20V 36A D2PAK	$2.30	$11.50	Digi-Key	digikey link
5	296-29018-6-ND	MOSFET N-CH 30V 87A 8SON	$1.04	$5.20	Digi-Key	digikey link
10	399-3770-1-ND	100 µF Capacitor	$1.22	$12.19	Digi-Key	digikey link
20	1276-2740-1-ND	0.01 µF Capacitor	$0.08	$1.58	Digi-Key	digikey link
10	497-6085-1-ND	Diode Standard 200V	$0.46	$4.60	Digi-Key	digikey link
10	BZT52C11-FDICT-NI	Zener Diode 11V 500	$0.17	$1.70	Digi-Key	digikey link
10	MMSZ5247BT1GO SCT-ND	Zener Diode 17V 500	$0.19	$1.92	Digi-Key	digikey link
5	568-10433-2-ND	MOSFET n-CH 30V 9	$0.28	$1.39	Digi-Key	digikey link
6	J716-ND	SMA Connector Jack	$3.72	$37.16	Digi-Key	digikey link
20	ED10561-ND	Wire-to-Board Conne	$0.55	$10.92	Digi-Key	digikey link
2	D2TO-.050A-ND	Sensisng resistor	$15.32	$30.64	Digi-Key	digikey link
10	296-29018-6-ND	MOSFET N-CH 30V :	$1.04	$10.40	Digi-Key	digikey link
10	399-3770-1-ND	100 µF Capacitor	$1.22	$12.19	Digi-Key	digikey link
20	1276-2740-1-ND	0.01 µF Capacitor	$0.08	$1.58	Digi-Key	digikey link
5	497-6085-1-ND	Diode Standard 200V	$0.46	$4.60	Digi-Key	digikey link
3	MP725-0.050-FDKR-	Sensisng resistor	$9.37	$28.11	Digi-Key	digikey link
10	160-1167-1-ND	Red LED	$0.27	$2.70	Digi-Key	digikey link
1	Wire-MW-18-1/2	Magnetic wire	$13.91	$13.91	BulkWire	Bulkwire
3	PCB	PCB		$28	Osh Park	Osh park
			Totoal Cost	$240.37		

Figure 17: Bill of materials for the second semester

A significant amount of cost increase is noticed in this semester because there is a total of five boards soldered and tested compared to one board on the previous semester. Besides that, the current sensing resistor is costly ($10 and $15 per unit). There are two different types of current sensing resistors as they have two different power ratings.

11 Appendix IV - MATLAB Code

```
N= 5;                      % N-> # of turns in the coil (dimensionless)5
l=0.001:0.0005:0.006;      % l-> lengh(meter) from 0.1cm to 0.6cm
R=0.001:0.0005:0.006;      % R-> radius of the coil (meters)from 0.3cm to 0.6cm
B_g=500;                   % B_g-> magnetic field produced by the coil (Gauss)
u=4 *pi*10^(-7);          % u -> permeability of material used in the center of coil(H/m)
%calculated how length affect coil
for i=1:11
B_T=B_g *10^(-4);                                  % Converting magnetic filed units:from Gauess to Tesla.
Il(i)=(B_T.*sqrt(l(i)^2+4*R(1)^2))/(u*N);                % Equation from MFG Design paper for single coil
Ll(i)=(u*N^2*pi*R(1)^2)./(sqrt(l(i)^2+4*R(1)^2));   % Equation for inductor
end

%calculated how radius of the coil affect coil
for i=1:11
    B_T=B_g *10^(-4);                              % Converting magnetic filed units:from Gauess to Tesla.
Ir(i)=(B_T.*sqrt(l(1)^2+4*R(i)^2))/(u*N);                % Equation from MFG Design paper for single coil
Lr(i)=(u*N^2*pi*R(i)^2)./(sqrt(l(1)^2+4*R(i)^2));   % Equation for inductance
end
subplot(2,2,1);
plot(l,Il,'r','LineWidth',3); grid on;
title('Current vs Length','FontSize',24,'FontWeight','bold');
xlabel('Length (m)','FontSize',18,'FontWeight','bold');
ylabel('Current (A)','FontSize',18,'FontWeight','bold');
subplot(2,2,2);
plot(l,Ll,'b','LineWidth',3); grid on;
title('Inductance vs Length','FontSize',24,'FontWeight','bold');
xlabel('Length (m)','FontSize',18,'FontWeight','bold');
ylabel('Inductance (H)','FontSize',18,'FontWeight','bold');
subplot(2,2,3);
plot(R,Ir,'r','LineWidth',3); grid on;
title('Current vs Coil Radius','FontSize',24,'FontWeight','bold');
xlabel('Radius (m)','FontSize',18,'FontWeight','bold');
ylabel('Current (A)','FontSize',18,'FontWeight','bold');
subplot(2,2,4);
plot(R,Lr,'b','LineWidth',3); grid on;
title('     Inductance vs Coil Radius','FontSize',24,'FontWeight','bold');
xlabel('Radius (m)','FontSize',18,'FontWeight','bold');
ylabel('Inductance (H)','FontSize',18,'FontWeight','bold');
```

Figure 18: MATLAB code to optimize coil measurements