Circuit Design for RF Exposure

[EE433 2013]

ABSTRACT

This project focused on the design, construction, and testing of a 1.3 MHz loop antenna and supporting circuit in order to build a mobile radiating device to expose a fox to low level RF fields. Biologists at Virginia Polytechnic Institute and State University are interested in the effect that these low level fields have on the behavior of foxes. The project was divided into different modules as designated by a block diagram. These modules included a 555-timer circuit, an oscillator circuit (at 1.3 MHz), several low-pass filters, a matching network, and a loop antenna. The loop antenna was designed and simulated using a free program called 4NEC2. An extensive search for an oscillator led to the discovery and use of a phase locked loop integrated circuit with an onboard voltage controlled oscillator (VCO). The VCO was biased with a center frequency at 1.3 MHz through the use of resistors and capacitors per the device characteristics provided in the datasheet. A matching network was designed using 4NEC2 to impedance match the electrical circuit to the antenna. Testing the magnetic field strength of the loop antenna was not possible given available resources, so simulation of the loop antenna with a tested input power and regression analysis was used to model the device. Though the matching network removed the reactive impedance of the load, the results of the simulation revealed weaker than optimal magnetic field strength.

INTRODUCTION

This project was conceived by biologists from Virginia Polytechnic Institute and State University ("Virginia Tech") who are interested in the effect of exposing foxes to low-level RF fields at 1.3 MHz. The project involves creating a physically small loop antenna and RF-emissions circuit, which must be impedance matched to the loop antenna. The circuit must be lightweight, portable, and be capable of generating a center frequency of 1.3 MHz that can be frequency modulated. Once this project is built on a breadboard, it must be designed in ExpressPCB for printed circuit board implementation.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Desired Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop Antenna Diameter</td>
<td>25-30 cm</td>
</tr>
<tr>
<td>Magnetic Field Strength</td>
<td>90 nT</td>
</tr>
<tr>
<td>Battery Life</td>
<td>8 hrs</td>
</tr>
<tr>
<td>Weight</td>
<td>1 lbs.</td>
</tr>
<tr>
<td>Size</td>
<td>Compact</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>1.3 MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1 MHz</td>
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</table>

Table 1: System Requirements for Fox Collar Module

In order to build a circuit that meets all of these specifications, the circuit must include a power source, a 1.3 MHz VCO, a 555 timer to control the VCO, a passive filter to remove higher order harmonics from the 555 timer signal, a matching network, and terminal block connectors to attach the loop antenna to the board. A general block diagram of the system is shown in Figure 1.
The goal of this project is to construct the circuit detailed above with low power consumption, a compact and lightweight design, and ensure there is enough input power into the antenna to ensure a magnetic field strength of roughly 90 nanoTesla (nT) at a distance of 15 cm from the center of the loop.

METHODOLOGY

The free application 4NEC2 was used to model the radiation pattern and output from a loop antenna. Through a simple graphical user interface (GUI), the frequency, size/shape of antenna, and input voltage was specified, and the near field was computed and plotted in two and three dimensions. The modeling process was not without faults; there were several major obstacles to overcome when modeling the antenna.

The first major obstacle was actually constructing the geometry that would model a perfectly circular loop antenna. 4NEC2 allows only approximations of circular/spherical surfaces through use of straight-edged approximations. As such, the loop antenna was approximated using a 16-sided polygon, illustrated in Figure 2 below. Notice that the voltage source (a small circle) is placed on an arbitrary wire in the closed loop.

The second major obstacle to modeling is the long wavelength required for implementation. An operating frequency of 1.3MHz results in wavelength of approximately 230 meters. 4NEC2 is not able to accurately perform analysis on any wavelengths greater than 1/1000th of a “segment” (a predetermined length of a wire used by the analysis engine) for analysis, and considering the total length of the loop is less than 1/230th of wavelength, the program gives a segmentation warning when displaying the results.

In order to overcome these obstacles, the geometry required for our project was modeled at frequencies much higher than our desired frequency so that the previously mentioned segmentation errors did not occur. The power of the radiated H-Field 15cm away from the loop (a distance specified by the customer) at frequencies ranging from 100MHz-1200MHz was recorded and plotted in MATLAB in order to perform a regression analysis that would provide a general estimate for the power radiated with a given input voltage at 1.3MHz. The result is a plot of resonant frequencies that appear as peaks, and non-resonant frequencies that appear as valleys. This is shown in Figure 3.
Figure 3: Strength of magnetic field 15 cm above the center of loop antenna. Resonant frequencies appear as peaks. Regression analysis was performed using this plot.

The modeling tools in 4NEC2 included a module for creating a matching network. The user specifies an input impedance, and the application automatically includes the simulated input impedance of the geometry being edited. At 1.3MHz, the polygonal geometry has an input impedance that is essentially purely reactive. This makes sense, as the antenna is 95cm of 30 gauge wire. With an output impedance of 46 Ω (purely real) from the transistor amplifier, the matching network is unable to match a purely reactive to purely resistive load. However, it can minimize the reactive portion of the antenna so that the circuit sees no resistance at the input to the antenna. Providing the input impedance, load impedance, and frequency, Figure 4 shows a module in 4NEC2 that calculates the components for a low-pass “Pi” network matching circuit.

Figure 4: Matching circuit program included in 4NEC2. Inputs are the output impedance of circuit, input impedance of loop antenna (calc.), and type of matching network.

A frequency modulation (FM) transmitter was designed in hardware to create the signal that was to be propagated through the designed loop antenna described above. The FM transmitter utilized two separate circuits to create the waveform, a LM555 timer circuit to create the message signal and a CD4046BE Phase Locked Loop integrated circuit with an onboard voltage controlled oscillator (VCO) to construct the carrier. The LM555 timer circuit was designed in an astable configuration to create a 32 kHz square waveform. Two resistors and a capacitor were used to construct this circuit. The resistor and capacitor values determined the frequency of the square waveform. The relationship between the component values and the output frequency is described in Equation 1.

\[ f = \frac{1.44}{(R_1+2 \times R_2) \times C} \quad (1) \]

The 32 kHz square waveform was then fed into a passive 2nd order low pass filter to remove the higher order harmonics from the waveform. The output of the 2nd order low pass filter resulted in
a 32 kHz (nearly) sinusoidal signal. The output frequency for each stage of the low pass filter was dependent upon the resistor and capacitor values. The relationship between cutoff frequency \( f_c \) and resistor and capacitor values is shown in Equation 2.

\[
f_c = \frac{1}{2\pi(R\times C)}
\]  

(2)

The 32 kHz sinusoidal signal at the output of the low pass filter was used as the voltage input (VCO\(_{in}\)) to the CD4046BE VCO.

The output of the CD4046BE VCO is controlled by four variables: \( V_{cc} \), \( VCO_{in} \), \( R_1 \), and \( R_2 \). Various combinations of these variables result in a number of different outputs. The relationship among the four variables is shown in Figures 5a, 5b, and 5c, taken from the CD4046BE datasheet.

Figures 5b and 5c demonstrate how the magnitude of \( VCO_{in} \) relative to \( V_{cc} \) and the selected values for \( R_1 \), \( R_2 \), and \( C \) affect the center and minimum frequency. Figure 5a shows how the ratio of \( R_2 \) to \( R_1 \) affects the sensitivity of the output frequency to change of \( VCO_{in} \). Larger resistance value for \( R_2 \) relative to \( R_1 \) results in a larger frequency deviation in the FM signal. The values of \( R_1 \), \( R_2 \), and \( C \) were selected to produce a FM signal centered around 1.3 MHz with a minimum bandwidth of 800 kHz.

The maximum current at the output of the VCO was 5mA, which would provide limited power to the antenna. As a result, a common collector transistor configuration was used as a current amplifier.

The common collector amplifier served multiple purposes in the overall design of the FM transmitter. The common collector amplifies the current of the FM signal as well as makes the output impedance of the FM transmitter very small in comparison to the output impedance of the VCO. Because the input impedance to the loop antenna has an almost negligible real component (short circuit), the small output impedance allows a greater power transfer to the antenna. A MATLAB function was utilized for the design of the common collector amplifier, and can be found in APPENDIX I. In order to achieve a small output impedance and relatively large input impedance, multiple iterations of the MATLAB function were ran with varying \( R_B \) and \( R_E \) values. This process allowed for the current gain to be optimized with an input impedance near 1 k\( \Omega \). The final designed current gain of the amplifier was 21.37 with an output and input impedance of 6.35 \( \Omega \) and 1.03k\( \Omega \) respectively. The complete hardware circuit is shown in Figure 6.
RESULTS

As there is no piece of equipment to physically measure the strength of the magnetic field resulting from our loop antenna, the best estimate of the output power comes from the regression analysis performed in MATLAB. Continuing the curve shown in Figure 3 to 1.3 MHz indicates that there will be roughly 3.5-5 nT of magnetic field strength 15 cm from the center of the loop. This field strength assumes an input voltage of 1V peak to peak to the loop antenna as was achieved in the laboratory when building the supporting circuit. Although the magnetic field strength changes with frequency, the radiation pattern 15cm away from the loop does not vary with frequency. An example of the 3D radiation pattern generated by 4NEC2 at 1.3 MHz is shown in Figure 7.

As mentioned in Methodology, the output impedance of the transistor amplifier circuit is purely real with a resistance of 46Ω. In order to match this to a purely reactive load, a matching network must simply remove the reactive component of the load, which is 10.6j Ω for the loop antenna detailed in this report. The “Pi” network shown in Figure 4 was used to accomplish this. The result is a load with an input impedance of 0-.05j Ω; in other words, it effectively becomes a short. Attempting to add any real resistance to the load would result in power loss across the resistor and a weaker magnetic field strength, which is undesirable. Therefore, a matching network that creates a short will suffice for this application.

The circuit shown in Figure 6 was built on a breadboard and was powered with four AA batteries ($V_{cc} = 6V$). All component values used to build the circuit were matched to within 5% of the designed value. The oscilloscope capture for both the output of the 555 timer circuit as well as the VCO can be seen in Figure 8.

![Figure 6: Complete hardware circuit including oscillator, 555 timer, low pass filter, BJT amplifier, and matching network.](image)

![Figure 7: 3D radiation pattern of loop antenna 15 cm above plane of radiation (Z-axis).](image)

![Figure 8: Oscilloscope capture of output of low pass filter (555 timer) and the corresponding frequency modulated output of the VCO with ideal matched load.](image)

In Figure 8, the effect that the amplitude of the 32 kHz sinusoidal signal has on VCOout is evident. It can be noticed that at the peaks of the 32 kHz sinusoidal signal the frequency at
\( \text{VCO}_{\text{out}} \) is at a maximum, and at the valleys of the 32 kHz sinusoid signal the frequency of \( \text{VCO}_{\text{out}} \) is at a minimum.

For testing, a 47 \( \Omega \) resistor was used for proof of concept of the circuit in an ideal scenario (results seen in Figure 8 above). In order to model the actual antenna load, a 1.35\( \mu \)H inductor was placed as the load. The magnitude of the signal was very similar to that seen in Figure 8, with the exception of the fact that the voltage signal was distorted. The result of this modeling is shown in Figure 9.

The current of \( \text{VCO}_{\text{out}} \) was calculated using the RMS voltage of \( \text{VCO}_{\text{out}} \) and the input resistance to the common collector amplifier and was found to be 2 mA. Using the same method, the current across \( R_L \) (a resistance inserted to represent an ideal load) at the output of the common collector was calculated to be 20 mA. Thus, the measured current gain of the amplifier with a 47 \( \Omega \) load was found to be 10, and with the antenna load was found to be 9.5\( \angle -90 \).

**DISCUSSION OF RESULTS**

Comparing the actual magnetic field strength of 3.5-5 nT with the desired value of 90nT reveals that our design fell short of its ideal targets. As previously stated, this figure is drawn completely from regression analysis, as simulation at the desired frequency of 1.3 MHz produced suspect results. Running the 4NEC analysis engine at this low frequency displays a field strength of 143 nT, much higher than the regression analysis would indicate. This is likely due to warnings received when performing analysis on a small antenna with a very long wavelength, and this result should not be taken to be accurate.

There are multiple solutions to the issue of a weak magnetic field, none of which were feasible to solve given the time constraints on this project. However, some ideas for future work include increasing the input power (voltage or current) into the wire, or adding more loops/turns to the loop. Increasing the input power his requires increasing the source voltage, with consideration to the fact that altering the source voltage will require a larger device to hold more batteries. In addition, the source voltage is assumed to be \( V_{cc} \) in all circuitry shown above. Altering \( V_{cc} \) will alter the stable operation characteristics of the circuit, such as the frequency of the 555 timer and the VCO. By increasing the number of turns in the loop, the radiation pattern could benefit from constructive interference and increase the magnetic field strength. However, the modeling of such a system would be much more complex. An alternative solution would be to alter the wire gauge and re-simulate to observe its effect on the magnetic field strength.

The main issue that exists with the hardware design of the FM transmitter is matching the output impedance of the amplifier to the input impedance of the loop antenna. As previously stated, the impedance of the loop antenna is purely imaginary. The imaginary component was matched with a pi-network, which resulted in an input impedance that was essentially a short. Solutions for matching the real component
were explored to include the possible implementation of a balun or transformer.

The difference in the measured and designed values for the current gain of the common collector amplifier was due to the load resistance chosen. The load resistance was chosen relative to the output impedance of the amplifier to obtain maximum power transfer to the load; however RL also affects the input impedance of the amplifier which must be matched to the output impedance of the VCO for max power transfer to the amplifier. As a result, a compromise had to be made in matching both circuits that caused the current gain to be lower than the designed value.

CONCLUSIONS

Though the project is not a complete success, it is not a complete failure either. At the very least, executing the project detailed above involves learning an entire analysis engine for modeling loop antennas (4NEC2), as well as understanding the multiple considerations and factors that alter radiation patterns. A variety of topics, ranging from passive filters to matching networks to integrated circuit implementation were revisited in order to understand how the supporting circuitry works.

As far as compact and lightweight are concerned, the device characteristics will be dictated by the source voltage required to create a stronger magnetic field. Considering the negligible weight of a PCB and its associated components, the vast majority of the weight will come from the battery supply. Given the current design with 4 AA batteries and a PCB, the product will only weigh ounces more than the 4 AA batteries. This circuit, along with its battery supply, is capable of being housed in a box no larger than a sticky note pad with 1” thickness.

This is both lightweight and compact relative to the size and weight of a full grown fox.

The supporting circuitry, including a matching network, was completed and tested using an oscilloscope to prove FM modulation was occurring. However, this design was not transferred to a PCB blueprint for later use. Issues with finding and properly biasing a voltage controlled oscillator at the correct center frequency took much longer than anticipated, and delayed the project sufficiently that there was not adequate time to design the PCB in PCB Express. Transferring the design into a PCB does not involve any further engineering, unless there are plans to alter the source voltage to increase the radiated magnetic field strength.

REFERENCES

APPENDIX I

%Common collector Zout calculator

1. clear all;
2. close all;
3. clc;
4. 
5. 
6. R2 = 47200;
7. 
8. Re = 100;
9. Rs = 1000;
10. RB = 1500;
11. Rload = 47;
12. 
13. rpi = 2.5/(3.2/Re);
14. 
15. %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
16. %Zout
17. InparINV = (1/Rs)+1/RB;
18. Inpar = (rpi + (1/InparINV))/100;
19. Zoutinv = (1/Re) + (1/Inpar);
20. Zout = 1/Zoutinv;
21. %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
22. %Zin
23. Zin1 = rpi + (100)*((Re*Rload)/(Re+Rload));
24. Zin2 = (1/Zin1) + (1/RB);
25. Zin = 1/Zin2;
26. %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
27. %gain
28. Av = (100*(Re*Rload)/(Re+Rload))/((rpi + (100*(Re*Rload)/(Re+Rload)));
29. Ai = Av * (Zin/Rload);
%Author: P.M. Wears
%Date: 21 NOV 2013
%Purpose: Used for regression analysis of magnetic field strength.

tested_frequencies=[100 110 120 130 140 150 175 200 250 300 350 400 450 500
550 600 650 700 750 800 850 900 950 1000 1050 1100 1150 1200];
field_strength=[1.09 1.01 .953 .906 .87 .843 .818 .848 1.18 2.27 4.41 1.9
1.32 1.17 1.27 1.95 4.6 2.74 1.75 1.49 1.52 1.9 3.26 3.65 2.21 1.72 1.49
1.71];
field_strength=field_strength.*1e-3;

tesla=4*pi*1e-7.*field_strength;

%Plot the results of the data points taken above
plot(tested_frequencies,tesla.*1e9)
xlabel('Frequency (MHz)')
ylabel('H-field (Near) (nT)')
title('Frequency vs. H-field Strength')
grid on