Rose-Hulman Making Antennas Groovy In the Classroom (MAGIC) Antenna Kit

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Abstract—The Making Antennas Groovy In the Classroom (MAGIC) system is highly adaptable to suit a variety of demonstrations that focus on antenna fundamentals, such as, radiation patterns, directivity and gain, as well as the design procedure of various resonant antennas. Four printed circuit board antennas have been designed, built and tested. The antenna types include a quarter-wavelength monopole and ground plane, a half-wavelength dipole, a folded dipole, and a Yagi-Uda array. The system and associated experiments are suited to demonstrate antenna principles to high school students as well as college level students. Additionally, the system is robust, portable, and reproducible for under $1,500.

Index Terms—Antennas, Antenna measurements, Educational technology, Printed circuit antenna,

I. INTRODUCTION

ANTENNAS are often considered to be magical. How can a signal impressed upon one antenna be detected on another, remote antenna? This seems reasonable since the invisible electromagnetic waves are not easily understood by most students. Pre-college and college students have a rather limited understanding of antennas. To improve students’ understanding of the principles of antenna operation, the IEEE APS has sponsored the IEEE Antenna Design Challenge. Student teams are to design, construct, and test safe, inexpensive kits that promote an understanding of antennas for use by pre-college and college students. This paper describes the kit submitted into this competition by an undergraduate team of students from Rose-Hulman Institute of Technology.

Making Antennas Groovy In the Classroom (MAGIC) kit consists of three parts: the signal generator, antennas, and a receiver, each available from off the shelf vendors or easily reproducible. See Fig. 1 for a picture of the complete system. A yardstick is included in the picture for scale. A key feature of the kit is that no additional equipment is needed to make a number of basic measurements and demonstrations. Furthermore, additional antennas can be developed inexpensively using blank FR4 board and copper tape. The kit now becomes a complete and inexpensive test-bed for student antenna designs.

A. Signal Generator

The system requires a set of General Mobile Radio Service (GMRS) or Land/Mobile radios to be used as “signal generators” and “receivers.” These radios can be programmed to operate in the range of 440-470 MHz, covering the GMRS band. Antennas in this range have characteristic dimensions in the one-foot range. The antenna structures for this frequency range are large enough so that the features can be easily recognized by students and small enough that they can be easily stored. The GMRS radios are generally available with removable antennas, making the connectivity to the proposed antenna system as easy as removing the stock antenna and using a short length of coaxial cable to the antenna of choice. While these radios require licenses to operate (FCC part 95.5[1]), one can be obtained for a nominal fee and allows the system to be operated legally by students. A fee waiver is also available for school and student use provided the institution apply for an experimental license (FCC part 5.89[1]).

B. Interchangeable Printed Circuit Antennas

The radiating system is based on a set of simple, printed circuit board (PCB) based antennas with a coaxial connection. These antennas are easily reproduced using standard PCB manufacturing techniques. Specific antenna dimensions are described using a standard file format called a Gerber file. Using the Gerber files for the antennas described in this paper the end user can reproduce the kit without difficulty or advanced technical knowledge. The printed circuit board antennas are durable, lightweight and require small storage space. An antenna stand is constructed of PVC pipes and is used to stabilize the antenna system during testing. Students can design, build, and test their own novel antennas using blank PCB substrate and copper tape.

C. Receiver System

The receiver system consists of two types of devices: a second GMRS radio and two (or more) field strength monitors. Using a field strength meter, students can quantify
the relative difference in transmitted power density as a function of position. By moving the field meters around the system, students can identify peaks and minimums in the radiation pattern of each antenna.

A second GMRS radio allows students to communicate with each other using the various included antennas and experience firsthand the different effects of each antenna.

II. OVERVIEW OF DESIGN APPROACH

A. Design Goals

The design goals for the MAGIC kit fall into two major categories: design goals for the demonstration system and goals for the antenna system as described in Table I. An overview of the design approach, used for all of the antennas, is discussed here and details of each design are discussed in section III.

To make the design durable and easily reproducible a limited number of components were used. Intricate components that cannot be easily purchased were avoided since the users of the system may find them difficult to reproduce. The construction of the kit can be made using widely available tools such as screwdrivers, soldering irons, a radial saw, glue and tape.

The components, parts, and materials needed to reproduce the MAGIC kit are listed in Table II. The estimated cost and suggested source are included in the table. For harder to obtain items, a model or manufacturer is suggested.

B. Preliminary Design

Printed circuit boards (PCBs) are manufactured on a non-conducting substrate used to mechanically stabilize the electrical components and connections. The materials used for the substrate vary in composition and thickness, but an easy to obtain standard substrate is called FR4 and has a dielectric...
constant of $\varepsilon_r = 4.2$. The most common (and cheapest) thickness is 1.6 mm (0.062 inches). Since the antenna is printed on the FR4 dielectric material, a portion of the radiating fields will propagate through FR4 and a portion will propagate through air. The effective permittivity depends on the width of the line on the PCB and the extent of the substrate or the distance from the line to the edge of the board. In order to take into account both modes of propagation, the effective permittivity was estimated using the numerical simulation tool CST Microwave Studio software. This estimation was used to build a preliminary model of the antennas with the desired resonant frequency of 465 MHz, the midpoint of the GMRS frequency band.

C. Modeling
The preliminary model was simulated using CST. The modeling tool was used to make minor adjustments to the antenna structures such as length, width, and position of copper traces. These parameters were adjusted to optimize the input impedance to match the 50 $\Omega$ coaxial cable connection to the radio. A balun was used in the dipole, folded dipole and Yagi antennas.

D. Prototype and Final Design Methodology
The results of the modeling were used to build a prototype with copper tape and blank FR4 board cut to a standard PCB manufacturing size that will accommodate all the antennas: 12 inches wide. Basic measurements were made in the lab and field to verify the modeled results. In some cases, adjustments to the design had to be made to finalize the balancing mechanism, because the physical implementations of the baluns are difficult to model with high fidelity. Once the operation of the prototype was verified, a Gerber file was generated and sent to a manufacturer for fabrication.

III. ANTENNA DESIGN AND SIMULATION
A detailed description of the design process for each antenna is discussed in this section.

A. Quarter-Wave Monopole Antenna with Ground Plane
The monopole antenna has the benefit that it is both simple to design/build and understand. The principle theory of operation for a monopole over a ground plane is the image theory. The image theory says that an infinite perfect electrical conductor ground plane will reflect incident electromagnetic radiation. The radiation received would be due to a direct ray and a second ray due to the reflection from the ground plane. Therefore, the quarter-wavelength monopole chosen will act like a half-wavelength dipole except it will only radiate above the ground plane. The antenna impedance will be half that of a half-wavelength dipole. By changing the dimensions of the ground plane, the antenna impedance can be tuned to better match the input impedance to that of the cable. See Fig. 2 for a schematic, photograph, and the simulated field pattern that describes the monopole design.

Two components were considered in the design of the quarter-wavelength monopole: the antenna length ($L$) and the ground plane size ($W$). At the resonant frequency of 465 MHz, one quarter of a wavelength in free space is 16.1 cm. The monopole uses a commercially available telescoping antenna which allows for quick and easy fine tuning of the length. The ground plane was constructed from a sheet of aluminum. To mimic an infinite ground plane the aluminum plate should be 10 wavelengths in length or more. Ten wavelengths in free space would be 644 cm. Given that this size is not practical to store, the size of the ground plane was chosen to be 30.5 cm x 30.5 cm so that fits in the antenna stand. The radiation pattern of a finite-sized ground plane will differ from that of an infinite ground.

Using CST, the monopole and finite ground plane were simulated. The model was used to determine that a length of 14.3 cm would produce a minimum VSWR at 465 MHz. The simulated VSWR was 1.175 and the input impedance was 42.9 + j2.23 $\Omega$. Measurements were made using a VNA that showed an antenna length of 18.5 cm to produce a resonance point at 465 MHz. At this length, the VSWR was measured to be 1.67 with an input impedance of 34.5 + j17.5 $\Omega$.

The use of a telescoping antenna has several benefits. It allows the fine tuning of the resonant frequency to match the 465 MHz used by the signal generator. It also provides a powerful tool for demonstrating different resonant points. Not only will a quarter-wavelength monopole resonate at a given frequency, but a half-wavelength monopole over a ground...
plane will also exhibit a resonance point. The telescoping antenna used is able to extend from 9.5 cm to 40 cm, which corresponds to 0.15A to 0.62λ. So the telescoping antenna can be configured to be a quarter-wavelength, and a half-wavelength monopole over a ground plane.

B. Dipole Antenna with Gamma Match

The radiation characteristics of a dipole antenna make it ideal for ground based communication. The majority of the radiated energy travels outward, broadside of the antenna with little radiation from the ends of the antenna. This creates a horizontally directed pattern that takes the shape of a torus. The simple design allows for rapid construction and ease of assembly. The schematic and photograph of the dipole antenna is shown in Fig. 3(a) and (b), respectively. Fig. 3(c) is a plot of the E-plane field pattern simulated using CST.

The gamma match in the design has a dual purpose: 1) it acts as a balun, allowing the dipole to be fed with a coaxial cable without producing unwanted common mode currents on the feeding line, and 2) it transforms the input impedance of the antenna to more closely match a standard 50 Ω cable. By exploiting this second trait of the gamma match, the antenna can be designed to better match the impedance of the coaxial cable and a more efficient power transfer can be achieved.

Five parameters are critical to the design of the dipole: 1) the length of the antenna, La; 2) the length of the gamma matching stub, Ls; 3) the width of the antenna, w1; 4) the width of the matching stub, w2, and the distance between the antenna and matching stub, d. The length of the antenna (La) was designed to be one-half wavelength for a resonant frequency of 465 MHz, using CST to model the effect of the FR4 substrate.

The location of the end of the gamma match, essentially a shorted tuning stub, affects the input reactance. A discrete capacitor is used to cancel unwanted inductive reactance. The design of the gamma matching section of the antenna uses a matching stub and discrete capacitor to change the input impedance of the antenna following the design procedure outlined in Balanis [2]. Since the input impedance is not very sensitive to the line widths and the distance between the antenna and matching stub, these values were set to w1 = 12 mm, w2 = 6 mm, and d = 20 mm. The characteristic impedance of the transmission line formed by the antenna and matching stub was calculated, adjusting for the geometrical shape of the printed circuit using an effective wire radius of 0.25 times the line width. Once the characteristic impedance is known, the length of the matching stub and the capacitance value were determined using a Smith chart and graphical matching technique to transform the input impedance to match 50 Ω cable. A capacitor of 2.2 pF was chosen to cancel the reactance. The dimensions of the final design are La = 270 mm, Ls = 39 mm, w1 = 12 mm, w2 = 6 mm, and d = 20 mm.

An impedance test was conducted using a vector network analyzer (VNA). The VSWR was measured and the characteristic curve matched simulation results. At resonance, the measured VSWR was 1.21. The impedance of the antenna with the gamma matching network was measured to be 52.3 + j3.6 Ω at 465 MHz.

C. Folded Dipole

The folded dipole is a rendition of the dipole that uses a T-match the length of the dipole to create a 4-1 impedance transformation to 300 Ω while keeping the same radiation pattern as the dipole. The antenna is then matched to 75 Ω using a commercially available 4-1 balun which connects to the coaxial input of a GMRS radio. See Fig. 4 for a schematic, photograph, and the simulated field pattern.

The folded dipole has standard dimensions of one-half wavelength in length (L), and less than one tenth of a wavelength in width (w). Because the antenna is built on FR4, the velocity factor will be different than in air which will change the wavelength for the design. Using theoretical and simulation results a velocity factor was determined to account for the effect of the FR4 substrate. The velocity factor was estimated to be 0.825. Using the velocity factor the antenna length and width were estimated. The design was modeled.
using CST and the parameters of antenna length (L), width (w) and line thickness (w2) were adjusted to optimize the input impedance to be as close as possible to 300 Ω.

A matching method was necessary to transform the input impedance of 300 Ω to a 50 Ω coaxial cable. Since the antenna is inherently balanced and the coaxial cable is unbalanced, a balun was needed to remove unwanted currents on the cable. A commercially available 4-1 balun is used to transform the input impedance from 300 Ω to 75 Ω which is close to the 50 Ω impedance of the cable. Therefore, the expected VSWR is 1.2 which is acceptable under the design criterion.

To confirm the antenna was working properly, two tests were performed. An impedance test was conducted using a vector network analyzer (VNA) with absorbing cones around the antenna. The VSWR was measured and the characteristic curve matched simulation results. At resonance, the measured VSWR was 2.02 (compared to 1.2 predicted.) The VNA confirmed the impedance of the antenna with the balun at 465 MHz to be 52.9 + j37.0 Ω.

A pattern measurement was estimated using field strength meters. The location of the peaks and nulls matched the simulated radiation pattern. A difference in field strength due to polarization mismatch was measured by altering the orientation of the antenna with respect to the field meter. The field meter reading dropped dramatically when the antenna and meter polarization were 90 degrees apart.

D. Yagi-Uda with removable directors

The key feature of the Yagi antenna geometry is its directionality. See Fig. 5 for the simulated far-field pattern. The Yagi-Uda, “Yagi”, antenna is comprised of a set of parasitic elements and one driver aligned to enhance the directivity. The driven element of the antenna is connected directly to the transmitter via a coaxial cable. Three of the directors are printed on a separate PCB. The removable directors facilitate the demonstration of the effect of the directors to focus the radiation in an antenna array. This particular design incorporates a half-wave balun to eliminate currents on the outside of the coaxial line and cancel input reactance. The critical dimensions of the design are the length

Fig. 4. Folded dipole antenna design. (a) Schematic of antenna design, (b) Photograph of the printed circuit antenna, the feed and 4:1 balun are connected on the back side, and (c) E-plane Field pattern simulated with CST.

Fig. 5. Yagi-Uda array antenna design. (a) Schematic of antenna design, (b) Photograph of the printed circuit antenna, with the removable directors. The feed and quarter-wavelength balun are connected on the back side, and (c) E-plane Field pattern simulated with CST.
of each of the elements, the spacing between the elements, and to a lesser extent, the line width of the elements.

First, a Yagi was designed assuming operation in air at the resonant frequency of 465 MHz. The line width of the elements (w) was chosen to be 3 mm. The element lengths and spacing between elements were determined using the following the design procedure outlined in Balanis [3]. To account for the radiation through the FR4 substrate, it is expected that the length of each element should be shorter than that the length of the elements designed to operate in free space. It was assumed that if all of the element lengths are reduced by a common factor, k, the Yagi implemented on the PCB substrate would have similar radiation properties as the Yagi designed to operate in free space. The Yagi dimensions and FR4 substrate were modeled using CST. The optimization feature was used to simulate the radiation properties of the antenna as a function of the length shortening factor (k). The results of the simulation found the value of k that maximizes the front to back radiation ratio, minimizes the beam-width was minimized, and minimizes the side-lobe level. For the final design the Yagi antenna elements lengths were shortened by this factor of k = 0.740. The input resistance of the final design calculated using CST was calculated to be 30 Ω, which should result in a VSWR of 1.7.

A quarter-wavelength transformer was used to cancel surface currents on the cable and transform the input impedance. A quarter-wavelength coaxial loop is connected at points B and C, as shown in Fig. 5(b). The Yagi active element (point A) is connected directly to the signal generator cable. A common ground is created with copper tape connection to the outer conductor of all three ports.

The VSWR and impedance of the Yagi antenna were measured using a VNA. At resonance, the VSWR was 1.47 (compared to 1.7 predicted) and the input impedance was 70.3 - j12.3 Ω at 465 MHz.

E. Summary of Antenna Measurements

For each antenna the input impedance and VSWR were measured using a VNA to verify the design. A summary of these measurements are in Table III.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>VSWR</th>
<th>Input Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monopole</td>
<td>1.67</td>
<td>34.5 + j17.5 Ω</td>
</tr>
<tr>
<td>Dipole</td>
<td>1.21</td>
<td>52.3 + j3.6 Ω</td>
</tr>
<tr>
<td>Folded Dipole</td>
<td>2.02</td>
<td>52.9 + j37.0 Ω</td>
</tr>
<tr>
<td>Yagi-Uda</td>
<td>1.47</td>
<td>70.3 - j12.2 Ω</td>
</tr>
</tbody>
</table>

IV. DEMONSTRATION OF ANTENNA PRINCIPLES

Many investigations may be made to demonstrate the “magic” of antennas with this system. Even with the simplest demonstration, a good foundation can be built for education about electromagnetics and antennas through experiential learning and intuition building.

Demonstration can be used to introduce the concepts of directivity, gain, and polarization and are well suited for undergraduate level students or high-school students. Since most high schools do not have access to VNAs and spectrum analyzers, the included field meters allow students to learn about the design tradeoffs of the included antenna systems with qualitative measurements. The system is also appropriate for demonstrating advanced topics, such as balancing and matching techniques. Investigations using lab equipment that is often available at universities allow students to gain measurement and testing experience. Using network analyzers, students could investigate the impedance characteristics of each antenna design, and using this information, perform calculations for radiation efficiency, matching networks, and VSWR. The kit can also be used as a test-bed for student antenna designs, which can be easily prototyped using FR4 substrate and copper tape.

A. Demonstrations in the Field

Experience has shown the effects of surrounding structures that are found in a classroom or laboratory will cause electromagnetic reflections that will change the radiation characteristics of the antennas and/or interfere with the measurements. Therefore, the types of demonstrations that can be made in the field were separated from those can be successful in the lab. The indoor testing environment of a basketball arena was sufficient to make relative measurements of field patterns and polarization. The basketball arena was a standard size full-court (94x50 feet); it had a wooden floor and a ceiling height of at least 65 feet. The suggested principles that can be demonstrated in the field are described below.

1) Principle of radiation

Printed antennas can be shown to work as radiators in place of manufactured antennas, by using GMRS radios to transmit and receive. The radiation strength should decrease as the distance squared as shown by field strength meters. Any of the antennas can be used in this demonstration.

2) Principle of directivity

The antenna beam-width can be measured relatively using field strength measurements. Any of the antennas can be used to verify the measured beam-width is comparable to the modeled beam-width. The Yagi design is more directive than the other designs and can be used as a comparison. The Yagi can be tested with and without the directors to demonstrate the effect of the directors to focus the radiation energy in the forward direction.

3) Principle of polarization mismatch

Radiation strength is reduced when polarized antennas are mismatched. All of the antenna designs are linearly polarized and the field meters are linearly polarized. By rotating the field meter relative to the antenna, a reduction in the received strength can be observed.

4) Principle of resonance

The radiation strength is increased when the monopole length is close to resonant length. By adjusting the length of the radiating element, the resonant point can be determined when a maximum is observed by the field meters.
B. Demonstrations in the lab

The following set of demonstrations assume that a VNA and a high frequency spectrum analyzer are available.

1) Principle of resonance

VNA measurements of VSWR can be used to compare to results predicted by models. By extending the length of the monopole radiator, students can observe and quantify the change in VSWR as a function of monopole length. Students can also observe the change in VSWR in the presence of a ground plane or proximal metal objects.

2) Principle of balancing and matching

External currents on coaxial cables cause radiation properties to change in an unbalanced feed. A VNA and spectrum analyzer can be used to compare the VSWR and received signal strength with and without a balun. Measurements of VSWR are improved with proper matching. The matching effect can be demonstrated by making simple adjustments to the gamma matching network. For example, the capacitor can be changed by replacing the original capacitor; this requires a soldering iron. The length of the gamma match tuning stub can be adjusted with short sections of copper tape connected across the two parallel conductors of the antenna and the matching stub. Students can conduct measurements to quantify the effects of the real and imaginary components of impedance match and compare these results to the theory.

V. ASSEMBLY INSTRUCTIONS

The reproduction of the antennas is greatly simplified by submitting the Gerber files to a PCB manufacturer. There are some connections that need to be soldered to the PCB. The associated Gerber files and details regarding how to attach the connectors can be downloaded from the MAGIC website at http://www.rose-hulman.edu/~walter/MAGICKIT/. A less expensive and technically feasible option would be to construct the PCB antennas using copper tape and blank FR4 boards to the specifications described.

VI. CONCLUSIONS

Many investigations may be made to demonstrate the “magic” of antennas with this system. Even with the simplest demonstration, a good foundation can be built for education about electromagnetics and antennas through experiential learning and intuition building. The first demonstration can be used to introduce the concepts of directivity, gain, and polarization and is well suited for high school or undergraduate level students. The system is also appropriate for demonstrating advanced topics. Investigations using lab equipment that is often unavailable at lower levels allow students to learn about the design tradeoffs of the included antenna systems. Using VNAs, students could investigate the impedance characteristics of each antenna design, and using this information, perform calculations for radiation efficiency, matching networks, and VSWR.

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REFERENCES


Andrew Anderson is a senior ECE major. After graduation in May 2010, he plans to start his career in the field of DSP with Rincon Research Corporation in Tucson, AZ. In the project he worked with Ryan to design, construct and test the half wave dipole.

Tom Campie graduated with a BS in electrical engineering from Rose-Hulman in November 2009. He is now working for Rockwell Collins in Coralville, IA. He was responsible for the system level design and prepared the initial proposal.

Ben Cook is an electrical engineering graduate student at Rose-Hulman institute of Technology. His focus is in RF and Electromagnetics, and he has done research in transmission line crosstalk and high voltage pulsing. Ben will be attending graduate school at KAUST in Jeddah, Saudi Arabia with a specialization in Electromagnetics and Nanotechnology.

Michael Fiedelday is a graduate ECE student who plans to finish his graduate degree in the fall. He hopes to continue to work in the field of electromagnetics professionally with ITT Corporation in Fort Wayne, IN. He was the lead designer of the Yagi on this project.

Josh Licata is an undergraduate electrical engineering major at Rose-Hulman, planning to graduate 2010-11. He has an interest in electromagnetics and plans to attend graduate school. He designed, built, and tested the monopole antenna.

Blake Marshall is a senior ECE student who plans to attend graduate school in the following years. He hopes to continue to pursue work in electromagnetics. On the project, he focused on the design and testing of the folded dipole as well as contributing as the schedule coordinator.

Ryan White is a senior ECE student who plans to go to work for the U.S. Air Force after graduation, and attend graduate school at a later date. He focused on the half wave dipole and laying out the education modules throughout this project.
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