Electromagnetic-Wave Fun Using Simple Take-Home Experiments

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***Abstract*—Simple take-home experiments are used at two universities on two continents to spark and expand student interest in the otherwise theoretical coursework in electromagnetic waves and antennas. The students obtain kits from the instructors and can do their experimental homework anytime they like, at home or in a standard undergraduate circuits lab, while combining it with theoretical exercises designed to match the experiments. Topics are covered in the order of electromagnetic wave complexity: (1) uniform plane waves in the optical frequency range with a laser pointer, gelatin and plastic polarizers; (2) frequency selective surfaces for WLAN; (3) non-uniform plane waves in VHF/UHF frequency coaxial cables; (4) quasi-TEM waves in microstrip at UHF frequencies; (5) a "cantenna"; and (6) microwave oven leakage detector.**

***Index Terms*—Electromagnetic waves, antennas, education, experiments.**

I. Introduction

This paper describes a set of simple experiments implemented at the University of Colorado, Boulder and Technische Universität Wien (TUW), for teaching electromagnetic waves in the third year (ECEN 3400 and ECEN 3410 at CU Boulder, and Wave Propagation at TUW). The experiments require simple household items and basic undergraduate circuit test equipment found in any electrical engineering department, namely a function generator and oscilloscope. A subset of the experiments are packaged as take-home kits at TU Wien named "Wave Propagation Season's Holiday Experiments" and are gifted to the students in the last lecture before the winter holidays. The items are obtainable at a reasonable price in large quantities, such that the kits can be given away for free. At CU Boulder, the microwave oven leak detector experiment is held as a competition where students win awards for longest detected range, lowest cost and best quantitative readout. The experiments are designed to balance theory in electromagnetic waves and give students appreciation of various types of waves across the EM spectrum, as well as their similarities and unified mathematical description.

The take-home exercises are designed to cover topics in the order of electromagnetic wave complexity: (1) uniform plane waves in the optical frequency range with a laser pointer, gelatin and plastic polarizers; (2) polarization filters, frequency selective surfaces and metamaterials; (3) non-uniform plane waves in VHF/UHF frequency coaxial cables; (4) quasi-TEM waves in microstrip at UHF frequencies; (5) cantenna; and (6) microwave oven leakage detector, which can also be used to demonstrate a standing wave. The remainder of the paper gives detailed descriptions of the instructions, experiments and shows some example results. Enjoy!

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II. Uniform Plane Waves in Gelatin

In this project, the students examine basic properties of plane waves in the optical region of the spectrum (green or red light, 500 to 700-nm wavelengths). The source of the plane wave is a laser pointer, and the wave power is detected using your own sensors (eyes), but could also be detected with a photodetector, similar to [1]. The contents of the project package are a red laser pointer, 3 optical polarizers (about 1.5 cm×1.5 cm in size), 2 packets of unflavored gelatin and a protractor, similar to the materials in [1] and shown in Fig.1.

The students are given the following instructions:

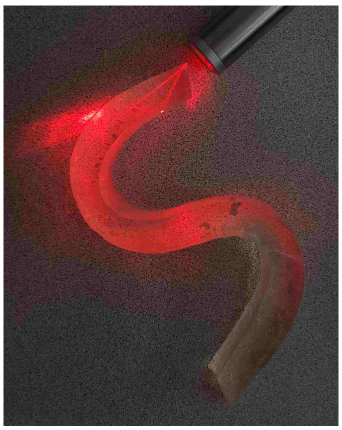
- Use a large glass or plastic container (about 15 cm×15 cm), and fill it with gelatin to at least 1 cm thickness.
- To prepare the gelatin, add 1/3 cup of cold water to 2 bags, stir and then add 1 cup of hot water and stir until gelatin powder is completely dissolved.
- Pour into tray and refrigerate until firm.

A. Snell's Law and Total Internal Reflection

In this part of the project, we use Snell's law to find the unknown permittivity of a material. A rectangular piece of gelatin is used as the medium with a permittivity different than air, aligning a sharply cut edge of the gelatin piece with the protractor main axis. The students first measure the angle of refraction as a function of the angle of incidence using the laser pointer and protractor and fill out a table with rows that are reflected angle and relative permittivity and columns are incident angles of 15°, 30°, 45°, 60° and one additional angle of choice. The laser pointer beam is polarized, but it is hard to control the polarization, so in this part of the project we do not consider wave polarization. After performing the measurements, the students answer the following questions:

- What are the basic electromagnetic principles that explain why the laser light remains in the gelatin even when it is curved like in Fig.1b?
- Based on the angle measurements, find the relative permittivity and index of refraction of the gelatin and fill in the two last rows of the table.

(a)



(b)

Fig. 1. (a) A take-home experiment kit that consists of a laser pointer, a protractor and a pack of gelatin. (b) Photo of internal reflection demonstrated with a laser pointer and a gelatin waveguide.

- How accurate is your measurement? Explain how you would quantify the quality of your experiments and the correctness of the results.
- Calculate the angle of total internal reflection (TIR) from the mean value of the measured permittivity.
- Think of a way to measure the TIR angle of the gelatin and sketch your method. Then measure the TIR angle and quantify how close it is to the calculation.

B. Polarization and Brewster's Angle

In this part of the project, we examine how light reflection and refraction depends on polarization. The students are given the following additional experiments and asked to write up their procedure and conclusions to answer the question why reflection and refraction depend on polarization:

- Three optical polarizer pieces are in your lab kit. How are these polarizers made and how do they work? State your sources.
- Take one polarizer and pass light through it; rotate the laser pointer to see how well polarized it is. What would you expect to see if the laser pointer is (a) unpolarized and (b) linearly polarized?
- Place two polarizers in parallel (or stack them), in two possible orientations and summarize your observations.
- Next, place a third polarizer between the two and rotate it, observing the transmission. Explain and compare to the previous two scenarios.
- Define the Brewster angle and measure it for gelatin and from that estimate the dielectric constant.
- Colored glass has a different permittivity in the optical part of the spectrum than glass that is not colored. Find a piece of colored glass (e.g. beer bottle). Find the dielectric constant of a sample of colored glass.

III. Frequency-Selective Surfaces

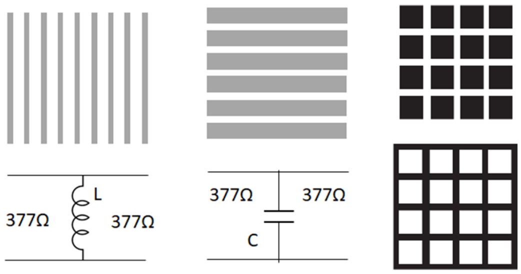
In the next project, following up on polarization, students are tasked to measure frequency- and polarization-selective surfaces and examine the duality principle and complementary electromagnetic structures as described originally by Booker [2]. The instructions to the students suggest several types of patterns, see Fig. 2a, with high pass, low pass, band pass, and band stop responses. The first task is to cut periodic patterns into aluminum foil sheets. One cutting technique is similar to making folded paper snowflakes in handicraft classes (see Fig. 2b). Alternatively, the aluminum foil is glued to cardboard and the pattern can then be cut with a utility knife, or copper/aluminum tape on a Mylar sheet can be used.

The students document the geometry of the fabricated pattern with photos and use [2] and equivalent transmission-line models shown in Fig.2a to predict the frequency response of the reflection and transmission coefficients. Subsequently, they are asked to carry out several experiments with a WLAN router to evaluate received signal strength and achievable data rates with and without their frequency- and polarization-selective surfaces in the line-of-sight path of the WLAN router's antenna. The periodic surface in the vicinity of the WLAN router may act as a reflector and enhance the antenna gain, or as a shield which reduces it, depending on position and orientation. The goal of these experiments is for students to appreciate *why* the metallic patterns act differently than a plain metal plate.

If a network analyzer is available, after the assignment is turned in, the lecturer sets up a demo with two broadband conical monopole antennas to characterize selected surfaces in the classroom. This experiment serves as an introduction to polarizing filters and frequency selective surfaces with many interesting applications [3], [4] that students are encouraged to learn more about.

IV. Non-uniform Plane Waves in a Coaxial Cable

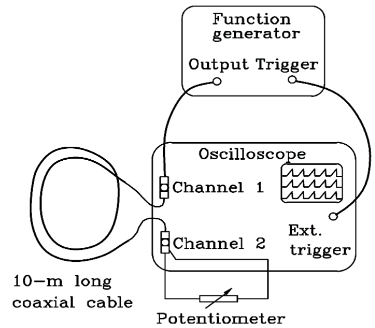
In this project, the students become familiar with wave reflection and transmission in the context of guided TEM waves. The equipment and parts are available in any standard circuits lab: a simple function generator; a 2-channel oscilloscope (it is convenient if the scope has a 50-Ω and a high-impedance input option); an approximately 10-m long 50-Ω coaxial cable; 2 shorter coaxial cables; 2 Tee BNC connectors, 2 low-inductance potentiometer resistors; and an ohmmeter. At the University of Colorado, Boulder, students have 24-hour access to a circuits lab with over 25 benches with scopes,



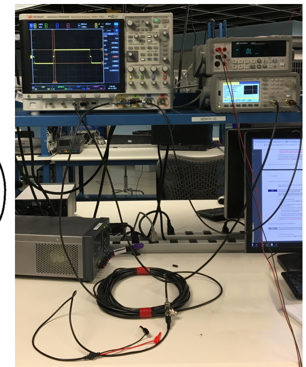
(a)

(b)

Fig. 2. (a) Basic patterns (Booker complementary structures) for frequency selective surfaces with high-pass, low-pass and band-pass functionalities, showing equivalent transmission line circuits for normal incidence with linearly-polarized plane waves. (b) Example fabricated aluminum foil with slots and a cross-shaped pattern.



(a)



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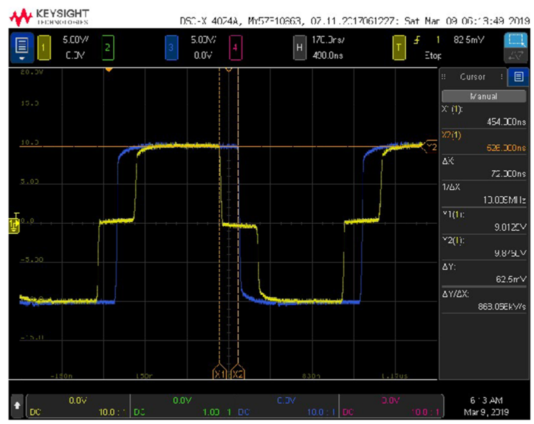

(c)

Fig. 3. (a) Sketch of setup for “cable radar”, or simple time-domain-reflectometry. (b) Measurement setup in the lab showing the signal generator at the top right, the 10m RG-58 coax cable on the table, and the oscilloscope on the top left. (c) Oscilloscope display for open-ended 10-m coaxial line shows a 2-V value of the voltage when 1 V is output from the function generator. The measured delay between the 1-V and 2-V values allows calculation of the cable length.

function generators and multi-meters, and they are given the remaining parts.

The students first put together a simple time-domain reflectometer (TDR), or cable radar [5]. A sketch of the setup is shown in Fig.3. They are instructed to use a Tee connector at channel 1 and connect a long (roughly 10 m) piece of coaxial cable from channel 1 to channel 2 of the scope. They set the function generator to a 1-MHz square wave with 1-V amplitude, and the input impedance of channel 2 of the scope to 50 Ω (or use a Tee to connect a 50-Ω load). By observing the traces on the oscilloscope, and knowing that the relative permittivity of the dielectric in the line is $\epsilon_r = 2.5$, students calculate the length of the cable from the measured time delay between the pulse at the generator end and the pulse at the load. Next, they set the input impedance of channel 2 of the scope to a high value (i. e., remove the 50-Ω load) and have to explain the result, Fig.3(b). Knowing that the input impedance of the scope is typically 1 MΩ in parallel with a 20 pF or so capacitor, the students observe an effectively longer cable since the 20 pF simulates about 20 cm of cable, assuming an approximately 1 pF/cm distributed line capacitance. Students should understand why the pulse shapes at channel 1 and 2 look different and should be able to quantify the delay required to reach the final amplitude.

A. Resistive and Reactive Loads in Time Domain

In this part of the project, the signal generator is set to pulse mode with a relatively long pulse length, so that any reflected pulses die out before the next pulse is generated, e.g. a 5-μs pulse with a 50% duty cycle and 1 V amplitude. The horizontal scale of the scope is adjusted to observe one cycle and so that the rising edge is measurable. With a high input impedance of the scope, the students are asked to explain the amplitudes and delays of the pulses observed on both channels. They next perform the following measurements and analysis:

- Connect a Tee to channel 2 and a variable resistor in parallel with the scope input using a Tee connector. Adjust the value of the resistance until there is no reflection, measure the value of this resistance with an ohmmeter and compare it to the characteristic impedance of the coaxial line (50 Ω).
- Set the potentiometer resistance to some value larger than 50 Ω (e.g., 75) and then to a value smaller than 50 Ω (e.g., 25). Calculate the values of the resistance from measurements of the reflected pulse amplitude and compare to resistance measurement with an ohmmeter.

- Connect a wire shorting the center and outer conductor and sketch the result.
- Connect a capacitor at the end of the long cable. Sketch the waveform observed on channel 1 for two capacitor values. Calculate the value of the capacitance and show your work.

B. Measuring Cables in Frequency Domain

For this part of the project, the function generator is set to a sinusoidal output at a 30-MHz frequency and 0.5 V amplitude. Unless otherwise noted, channel 1 is terminated with a high impedance, and channel 2 with 50 Ω. This is done to provide a matched load at the end of the transmission line (channel 2) while measuring an intermediate position (channel 1) without disturbing the waves on the line. The phase is calibrated by connecting a 50-Ω load on channel 1 instead of the long cable.

With the long cable connected to channel 1, the students observe the voltage on channel 2 and compare the amplitude and the phase. Based on the cable electrical length from the previous part, the phase can be estimated and compared knowing that a one-wavelength long cable produces 360°. By inspecting the amplitude on channel 2, and remembering that voltage in a cable varies like $\exp(-\alpha z)$, the attenuation coefficient α in Np/m can be calculated.

The goal is for students to understand that the voltage (and current) along the cable are a result of forward and backward (reflected) waves, which add destructively and constructively down the cable. Since the setup is not a slotted line, we cannot measure the voltage along the cable. However, we can change the frequency, so that the cable looks like it is changing length. The long piece of cable is terminated in an open circuit, and the frequency varied until the cable is one electrical wavelength long. Then the signal generator output is set to 1/20 of this frequency and waveforms observed on channels 1 and 2 compared. Next, the frequency is adjusted so that the cable is $\lambda/2$, $\lambda/3$, $\lambda/4$ and 1λ long and the results are discussed.

V. Quasi-TEM Waves with Copper Tape

Quasi-TEM waves in a microstrip line can be investigated with a function generator and oscilloscope, using removable copper tape on a piece of FR-4 substrate with one side metalized. A 60-mil thick substrate 30 cm×30 cm in size, copper tape and two 3-GHz ($2) SMA jack connectors are provided as a kit. The spacing between the center and ground pins of the connector is such that the substrate can be inserted with a snug fit. The size of the substrate is chosen to fit a quarter of a guided wavelength at the highest frequency of the function generator (e.g. 250 MHz).

The students first design a 50-Ω through-line assuming the substrate has a permittivity of 4.6 and measure V_{out}/V_g around the highest frequency of the function generator using the setup shown in Fig. 4, with the oscilloscope set to a 50-Ω input impedance. The line is not matched because the given permittivity of the substrate is not correct. The students then make an open stub in the middle of the line, as long as possible, and vary the frequency until they see a drop in the output voltage which corresponds to the frequency when the stub is a quarter of a guided wavelength. From that, they calculate the effective permittivity, and then find the actual permittivity of the substrate using well-known microstrip formulas [6] or online calculators [7]. The goal of this exercise is for students to understand the concept of effective permittivity in non-uniform transmission lines and the effect of simple resonators coupled to transmission lines. For extra credit, they can use additional copper tape and design a low-pass filter and measure it using the same setup by varying the frequency of the generator and observing the voltage on the oscilloscope.

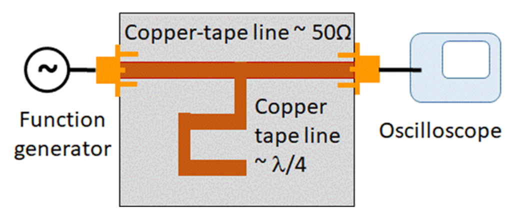

Fig. 4. Block diagram of setup for measuring the dielectric constant of a microstrip substrate.

VI. Open-ended Circular Waveguide – the "Cantenna"

Fig. 5. A kit with canned food and coaxial flanges alongside a finished cantenna.

Principles of circular metallic waveguides are explored in an experiment with a home-made open-ended waveguide antenna, referred to as a "cantenna". Various internet resources describe how to build such directive antennas as a replacement for the typical omni-directional dipole antenna as a means to boost Wi-Fi reception. The students receive a kit containing a flange N-connector and a N-to-reverse SMA pigtail cable, and they are responsible for finding an (empty and clean) can.

The students in this project first learn how to critically review building instructions presented on websites. They are advised to review the cutoff frequencies of circular waveguide (e.g. [6, section 3.4]) to explore which metallic cans available as a packaging for canned fruits, vegetables or stackable snack chips (Pringles) are suitable as a waveguide for 2.45 GHz. The calculations show that, despite some internet fame as suitable cantenna candidates, Pringles cans are too narrow to be used as a circular waveguide at 2.45 GHz. The learning objective is to see why the diameter of the can (cut-off) is relevant to the antenna operation.

The students then choose their own can, and based on its inner diameter calculate the waveguide wavelength either using [6] or an online calculator such as [8]. The feed probe is then constructed from the N-connector and a short length of wire soldered to it, and placed in the can approximately a quarter wavelength from the closed can wall, see Fig. 5. The students then connect the fabricated antenna to their Wi-Fi router using the supplied N-to-reverse SMA pigtail and compare the Wi-Fi reception on their cell phones at 2.45 GHz to the one obtained with the regular omni-directional antenna. They are also encouraged to experiment with the orientation of the cantenna, e.g., since it is directional the reception will degrade compared to the regular antenna when oriented in the opposite direction.

When a network analyzer is available, students can bring their antennas to class and optimize the length of their feed probe for best return loss within the Wi-Fi band.

VII. Microwave Oven Leakage Detector

This experiment teaches students fundamentals of waves, such as polarization and free space loss, as well as fundamentals of antenna and detector circuit design. Each student is given a microwave Schottky diode (e.g. RB886CS), a light emitting diode (LED), and some wire as a starting kit to create a low-cost microwave oven leakage detector. The use of a conventional kitchen appliance microwave oven as a 2.45 GHz RF source eliminates the need for specialized RF equipment and allows students to experiment at home.

First, students need to decide on an antenna type to use, where a classical $\lambda/2$ dipole is certainly the easiest starting point and can be easily trimmed after fabrication to maximize received power. The Schottky diode is soldered directly to the antenna terminals, and it can directly provide bias to an LED soldered back-to-back. The detector is tested using a household microwave oven, loaded with a glass of water to avoid damage. Typical microwave ovens will leak enough RF to light up the LED when placed closely to the edges of the oven door or the back-side fan. This simple circuit allows experiments to determine the polarization of the leaking radiation, as the brightness of the LED will vary with the rotation of the detector antenna.

In a lab exercise at CU Boulder, students are encouraged to upgrade their first simple detectors to allow for a more quantitative leakage detector with higher sensitivity. Prizes are offered for students with the highest sensitivity and the most elaborated readout capability, while at the same time the cost of the overall detector should be kept low. A schematic of one of the winning designs is shown in Fig. 6, with

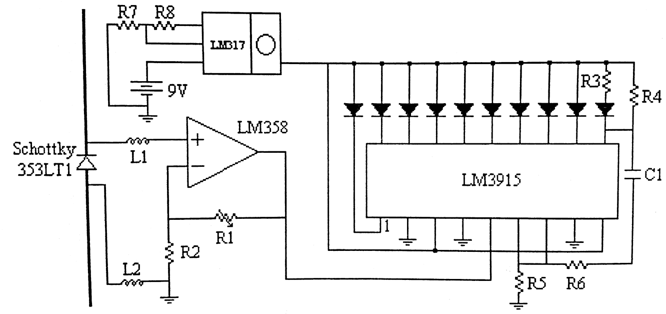

Fig. 6. Winning circuit for a microwave oven leakage detector. The component values are: R1=50kΩ, R2=R3=100Ω, R4=1kΩ, R5=1.2kΩ, R6=470Ω, R7=440Ω, R8=1.32kΩ; C1=100μF; L1=L2=10nH.

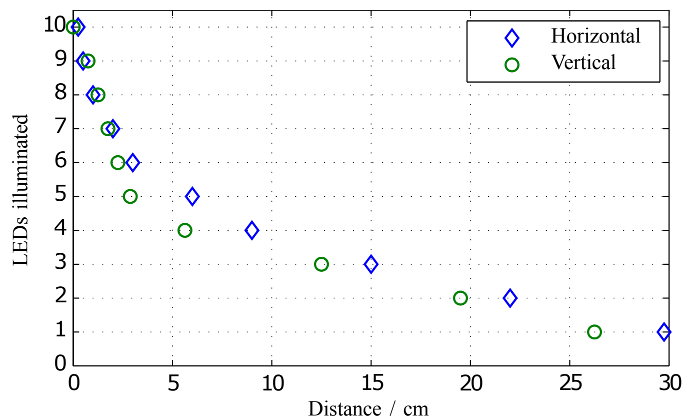

Fig. 7. Measured LED readings of a student designed microwave leakage detector for two polarizations in front of a microwave oven.

circuit values given in the caption. The dc output of the RF detector is amplified in a LM358 operational amplifier, and then fed into a LM3915 logarithmic LED driver. This allows for quantitative field measurements with good sensitivity over a relatively wide dynamic range. Using a similar detector circuit but omitting the operational amplifier, hence creating a slightly less sensitive detector, another student performed measurements to quantify the leakage from his microwave oven; the results are shown in Fig. 7. The difference in leakage radiation between horizontal and vertical polarization is clearly recorded.

VIII. Student Response

At both universities the classes utilizing these take-home experiments are evaluated by faculty course questionnaires (FCQs). While those FCQs do not directly ask about the take-home experiments, the free-form fields give valuable insight to the acceptance of those experiments by the students.

At TUW comments about the take-home experiments were invariably positive. The majority of students that mentioned them in their FCQs claimed that the experiments increased their motivation to attend the class (class attendance is optional at most Austrian Universities), and helpful to understand the theory. A few students called the experiments “simple and at a high-school level”, but still welcomed them since there are few experiments in the general EE curriculum for students to perform themselves.

At CU Boulder, the electromagnetic sequence of classes was in the past viewed as difficult and too mathematical. Some FCQ comments from 2019 by students related to including experimental projects and homeworks include:

- This course was phenomenal.
- The homework projects, while difficult, forced me to understand the material at a fundamental level. Please keep these for future classes as it forces students to understand the concepts and not "plug and chug" through equations.
- In addition to the foundational material, you included practical tips and application found in the real world, and that was very helpful.
- The projects in this class, while being long assignments, are well worth the effort. The coax and jello dielectric project really helped solidify the concepts as I learned by doing.
- Possibly add more lab experiments.
- I wish that all classes were taught this way.

IX. Conclusion and Some Additional Experiments

In summary, this paper describes a set of simple experiments that can be done either at home or in a basic undergraduate circuits laboratory with minimal extra hardware. The experiments described here are by no means conclusive, and the co-authors at both universities are developing new experiments for next year's classes. For example, we are now working on a more comprehensive demonstration of cutoff in metallic waveguides made of aluminum-foil coated cardboard boxes. To demonstrate cutoff, students can place a cell phone (in Wi-Fi mode) on one side of such a home-made waveguide for two different size waveguides - one below, and one above cutoff in S-band. With proper shielding of the other side of the phone, they observe almost no signal in one case, and good transmission in the other. They can also build circular/elliptical waveguides with kitchen paper towel rolls to demonstrate the same principle. Another demonstration with a microwave oven involves a demonstration of standing waves. A helical antenna is built with copper tape, a yogurt ("Yoplait" brand) cup, an aluminum pie plate as the ground plane and one SMA connector, with a Schottky diode detector soldered at the feed back-to-back with a LED. As the antenna is moved farther or closer to the microwave oven wall, a standing wave can be observed by the LED lighting up at $\lambda_0/2$ distances away from the oven. An additional set of experiments that we would love to include is using a software defined radio (SDR) for observing effects of multipath propagation on the digital signal constellation. Unfortunately, at this time our class budgets are not sufficient to provide each student a take-home SDR, so some of these experiments are included in a follow-on RF lab class.

Finally, it is important to make a connection between the simple experiments and practical applications. We accomplish this during class time, for example, after the students demonstrate an optical dielectric gelatin waveguide (Fig.1b), a discussion on real fibers and optical communications is covered briefly and a real fiber is passed around. Other examples include a base-station amplifier with microstrip matching circuits (related to Fig.4), standard gain horn antennas (related to Fig.5), and a calibrated field probe for verifying compliance with EM safety (related to Fig.6).

Acknowledgment

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