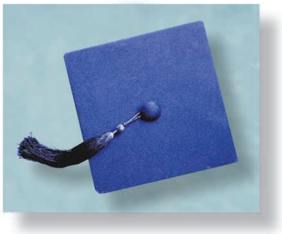

Educator's Corner

Enhancing Laboratory Experience Using 3D-Printing Technology in Microwave and Antenna Education

■ **Ming Ye, Fang Yang, Yongjun Xie, and Jie Xu**

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The development of modern wireless techniques has resulted in a need for more trained RF engineers. For college students majoring in microwaves and antennas, practical training is essential to understanding abstract electromagnetic theories and to cultivating their engineering skills [1]. However, the traditional fabrication methods for microwave devices used in university labs aren't appropriate for undergraduate students because of their inflexibility, high cost, and use of harmful chemicals.

Over the past decade, 3D printers have become very popular worldwide as a low-cost and flexible prototyping tool. Electromagnetics researchers, engineers, and learners also have paid much attention to their applications in electromagnetics [2]–[11]. At first, 3D printing could print only very limited kinds of dielectric materials. Later, with the development of material and prototyping technology, many new materials became available to microwave scientists and engineers. Today, both dielectric and conductive materials can be printed by 3D printers [3], [6]. However, it is still difficult to print good conductors with electrical conductivity that is comparable to copper, which is widely used in planar microwave circuits. It has been reported that copper adhesive tape can be used to form the metallic part of electromagnetic devices [2], [12], [13]. Alternatively, for industrial applications, electroplating is feasible for metallization [14]. Although 3D-printing technology shows many advantages

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over conventional fabrication methods such as machining, the overall performance of printed devices still has some limitations. More efforts are needed to make 3D-printing technology more widely accepted, especially for industrial applications.

There are several cases in which 3D-printed microwave devices are suitable for some special applications, such as microwave sensing, training in electromagnetic engineering, and amateur radio. For these applications, cost, flexibility, environmental protection, and other factors take higher precedence than in many industrial settings. As far as the authors know, most practical labs in microwave and antenna courses in Chinese universities are based on complex and expensive fabrication methods. For example, to realize microstrip circuits, there are two widely used methods: either a process similar to photolithography used in the semiconductor and printed circuit board industry or a process based on machinery. In the former method, chemical reactions are required to pattern the copper foil. In the latter case, the use of expensive equipment (such as computer numerical control machining or laser etching [15]) is required. This situation hinders the effective practice of electromagnetics learners in many universities. Nevertheless, as pointed out in [1], effective learning in electrical engineering can only be achieved with approaches that combine theoretical courses with proper laboratory work.

The development of modern wireless techniques has resulted in a need for more trained RF engineers.

In this work, through several demonstrations, we show that 3D-printed dielectric material, together with copper adhesive tape patterned manually using a cutter, is suitable for the realization of both planar and nonplanar microwave components. This method can be used by undergraduates as well as graduate students who have no or insufficient background in microwaves and antennas. The benefits of the method proposed in this work include:

1) The fabrication process is very flexible. Therefore, students can use this technology to practice making almost any kind of microwave device and educators can provide different project goals for different students, which allows the lab work to be individualized to ensure that each student is appropriately challenged.
2) The fabrication process is very cheap and ecofriendly, making it affordable and feasible for most universities.
3) The fabrication process is suitable for an open laboratory environment. Thus, students are not restricted to a time schedule and location.
4) Compared with the widely used fabrication method of planar circuits in China (which involves sending the design file to a specialized supplier and receiving the devices back after approximately three to seven days), the fabrication process is faster (depending on the complexity of the device, usually taking approximately 2–3 h).
5) Since all the steps are completed by the students themselves, their practical skills can be improved.
6) Students' learning interest and curiosity will be aroused and stimulated by the introduction of 3D printing.

The main objectives of our practical labs can be summarized as follows:

1) *Lab 1:* Students design, fabricate, and measure microstrip transmission lines (TLs). They are encouraged to use the formulas in their textbooks or the available tools to calculate characteristic impedance. By fabricating a matched line and a mismatched line, they gain comprehension of impedance matching theory and its applications.
2) *Lab 2:* Students are encouraged to design, fabricate, and measure one kind of TL resonator and filter, respectively. The main objective of this lab is to help students grasp the theory behind resonators and filters. Another objective is to introduce a material characterization method which will be useful for students' future engineering careers.
3) *Lab 3:* This lab focuses on the design, fabrication, and measurement of various microstrip patch antennas. Antennas are basic components of all wireless systems. Thus, it is important for students to have some practice working with them. Conventional patch antennas are suitable for undergraduates, while construction of novel antennas may be practiced by graduate students. During this lab, in addition to the fundamental theory of antennas, students also learn how to tune an antenna's working frequency with a small piece of copper tape, and to observe higher modes and environmental effects on the measured S-parameters of antennas.
4) *Lab 4:* Students attempt to design, fabricate, and measure nonplanar devices. All of the devices practiced in Lab 1 through Lab 3 are planar devices. However, in some applications, such as radar and satellite communications, nonplanar devices (such as waveguide components) are necessary and are presented in most microwave and antenna textbooks. As demonstrations, we show two dielectric resonator antennas, a coaxial-to-waveguide transition, and a dielectrically loaded spherical waveguide antenna.

To enhance students' skills in computer aided design, all of the devices mentioned previously are required to be simulated using commercial electromagnetic software. Through comparison between simulations and measurements, students are expected to learn how to analyze nonideal factors that can affect devices' performance, including dimensional errors, material parameter uncertainties, and surroundings. It should be noted that, due to the nature of the reflectometer that is available to the authors, all of the demonstrations are shown with measurement results of S_{11} with a highest frequency of 6 GHz. Although only a few kinds of devices are shown in this work, it is feasible to use the method described here to practice the design and fabrication of other kinds of devices, such as horn antennas, microstrip hairpin bandpass filters, and dielectric lenses. Educators may select their own devices according to their students' interests and background as well as available resources. For example, some basic examples are suitable for undergraduates, while advanced examples may be preferred by graduate students.

General Description of the Fabrication Method

As shown in Figure 1, as an example, the main steps of the fabrication process of a microstrip patch antenna are: 1) print the dielectric substrate using 3D-printing technology, 2) mount copper adhesive tape onto both sides of the substrate (one side for ground and the other for patch patterning), 3) shape the upper copper adhesive tape into a desired pattern manually using a cutter, and 4) install an RF connector at the edge to facilitate the vector network analyzer (VNA) test. This fabrication process doesn't use any chemicals and thus it is very ecofriendly. A similar fabrication process was also used in [2] and [13]. Other planar and nonplanar devices can also be fabricated with a similar process.

To shape the copper adhesive tape into the desired patterns, there are at least three possible choices: 1) cut out the individual components of a circuit pattern and then mount them in the proper positions onto a dielectric substrate (this method may have limited alignment accuracy; e.g., as seen in the left of Figure 2, where the formed gap is of low quality); 2) plot the layouts on copper adhesive tape first with a marker and then cut them out (e.g., as seen in the right of Figure 2, where the formed gap is much better than its counterpart on the left); and 3) use a piece of 3D-printed object as a kind of mask and cut the copper adhesive tape along the mask's edge (with this method, it is possible to pattern complicated circuit shapes, such as circle, ellipse, and parabola). This shaping process requires a certain level of workmanship, and thus may require some practice before the student can make the desired pattern. Of course, a good cutting tool can be of great help; for example, the stylus knife described in [16] may prove helpful.

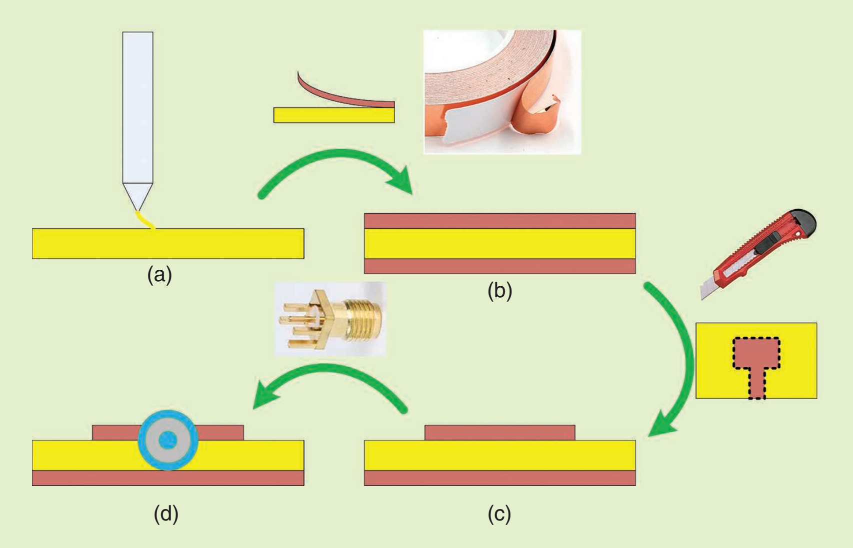

Figure 1. *A schematic view of the fabrication process: (a) print laminate; (b) paste copper tape; (c) pattern with cutting; and (d) install connector for the VNA test.*

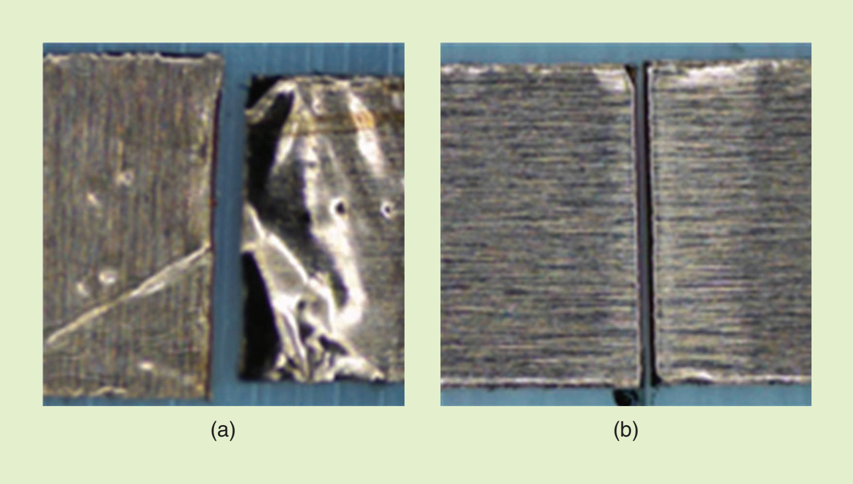

Figure 2. *A digital microscopy photo of the coupling gap using different methods. (a) Cut first and then pasted. (b) Pasted first and then cut.*

In this article, the used 3D printer (CR-100, Shenzhen Creality 3D Technology Co., Ltd., China) is based on fused deposition modeling technology. As described in [2], 3D-printing technology is effective, but the dimensional accuracy may be approximately 0.1–0.2 mm and the printed objects may have surface roughness on the order of tens of microns. It should be noted that, even for an inexpensive 3D printer, there are many printing settings (such as infill percentage and printing direction), which may influence the quality of the fabricated electromagnetic devices. Thus, it may take a lot of exploration for students to optimize their fabrication settings for their special requirements. Since 3D printers can print both nonplanar devices and planar devices and have much freedom in material selection, such as polylactic acid (PLA) or acrylonitrile butadiene styrene, 3D printing provides a lot of flexibility and thus is very suitable for learners to explore their own designs. One problem with conventional practical labs in microwave and antenna courses may be that students' projects are similar and repetitive to some degree. This situation may limit students' exploring spirits. Thus, the flexibility introduced by 3D printing is especially helpful for practical courses in universities. If 3D printers aren't available, educators may provide students with commercially available printed circuit board with one side clad with copper foil [17]. In this case, the flexibility of the practical experience will be limited.

To enhance students' skills in computer aided design, all of the devices mentioned previously are required to be simulated using commercial electromagnetic software.

Another point that should be mentioned is that, in most of the examples presented later, no soldering is used in the installation of SubMiniature version A (SMA)-type RF connectors (seen in Figure 3). Electrical contact is formed through mechanical pressure, similar to solderless printed circuit board (PCB)-edge launch connectors. Of course, standard solderless connectors are much expensive than the common connectors we used here, as shown in Figure 3. There are some factors that compel us to use solderless connections with common connectors. First, there are many kinds of connectors suitable for substrates of different thickness (e.g., one can choose connectors with a suitable outer pin size, making connectors compatible with substrates). It is especially advantageous that, using 3D printing, it is convenient to obtain substrates with desired thicknesses (making substrates compatible with connectors). Second, if the substrate is thinner than the outer pin size of available connectors, one can use multiple layers of copper adhesive tape to make the substrate compatible with the connector (see Figure 3(a); due to multiple layers, a bit of misalignment may be formed). In our method, a good electrical connection can be ensured simply by inserting the connector at the edge of the substrate. Without soldering, the connectors can be used repeatedly. Furthermore, the dielectric substrate can also be reused many times. This makes our fabrication method more ecofriendly and more suitable for educational purposes. Of course, one should pay attention to this connection because an unreliable connection does affect the performance of the devices. If a soldering process is used, it is important to pay attention to the soldering temperature. For instance, PLA materials usually melt at around 200 °C. Thus, low melting point tin solder is preferred.

When students become familiar with 3D printing, they can use this prototyping technology in their own future study and research. Another advantage of the described method may be that, since 3D printers with remote control functions are now available, it is possible to set the assignment as open lab work. Thus, students may use their own available time to finish their lab experience and explore whatever interests them. This open lab mode is also helpful for students who need more time to finish the fabrication.


(a) (b)

Figure 3. *Digital microscope photos of the connector connection (no solder). (a) Rectangular patch. (b) Circular patch.*

Some Examples of Microwave Devices

Lab 1: TL

TLs are basic devices for any microwave system. Using the fabrication process described previously, it is possible to practice making conventional TLs, such as microstrip lines, coplanar waveguides, rectangular/circular waveguides, and coaxial lines [18] as well as new TLs, such as substrate integrated waveguides [19]. The basic components of this project may include:

- calculation of characteristic impedance
- design and simulation of a microstrip line with specified characteristic impedance
- fabrication and test of microstrip lines and observation of the reflection induced by mismatched impedances.

As an example, we use the fabrication method to realize microstrip TLs. Here, we present two examples, denoted as Line A and Line B.

White PLA is used for both lines. In Figure 4, both the simulation results and measurement results of these two lines are shown. It can be seen that the simulations agree well with measurements. The relative dielectric constant ε_r used in simulations is 2.3 and the dielectric loss is neglected (by matching simulation with measurement, one can estimate the PLA's dielectric properties. Our estimated parameters agree well with the values in [2]). Since the connector has a characteristic impedance of ~50 Ω, using formulas presented in textbooks like [18] or TL calculation tools, one can find that Line A (its characteristic impedance is ~56 Ω) is a matched line to 50 Ω while Line B (its characteristic impedance is ~85 Ω) is a mismatched line. Thus, it is expected that Line A will exhibit a lower reflection, as shown in Figure 4. It should be mentioned that we use a reflectometer to measure S_{11}. When we measure two port devices, we connect another port with a matched load. It can be seen from Figure 3 that the copper adhesive tape is somewhat roughened due to the substrate's roughness. This may be a problem for industrial applications. However, from the point of view of education, it doesn't matter, especially for low-frequency microwave bands. In all of the simulations, we don't consider the potential effect of surface roughness. If students are interested in the effect of surface roughness on circuit performance, they can research publications on this topic, such as [10].

Lab 2: TL Resonator and Low-Pass Filter

In this section, we present two demonstrations: a shorted $\lambda/4$ microstrip TL resonator and a stepped impedance low-pass filter. The theory of these devices can be found in textbooks like [18]. The basic components of this practical lab may include:

- design a shorted $\lambda/4$ microstrip TL resonator using estimated permittivity of a PLA substrate and run a group of simulations to establish the relationship between the resonator's frequency response and the PLA's permittivity
- fabricate and measure the resonator and extract material properties with simulations and measurements
- design and simulate a stepped impedance low-pass filter
- fabricate and measure the low-pass filter.

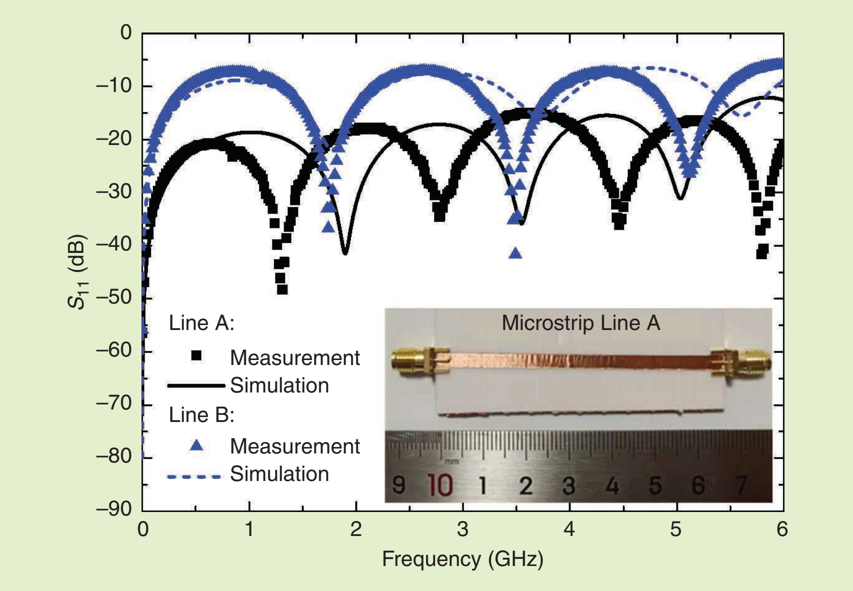

Figure 4. *Measurement and simulation results of two microstrip lines. The inset is a photo of Line A.*

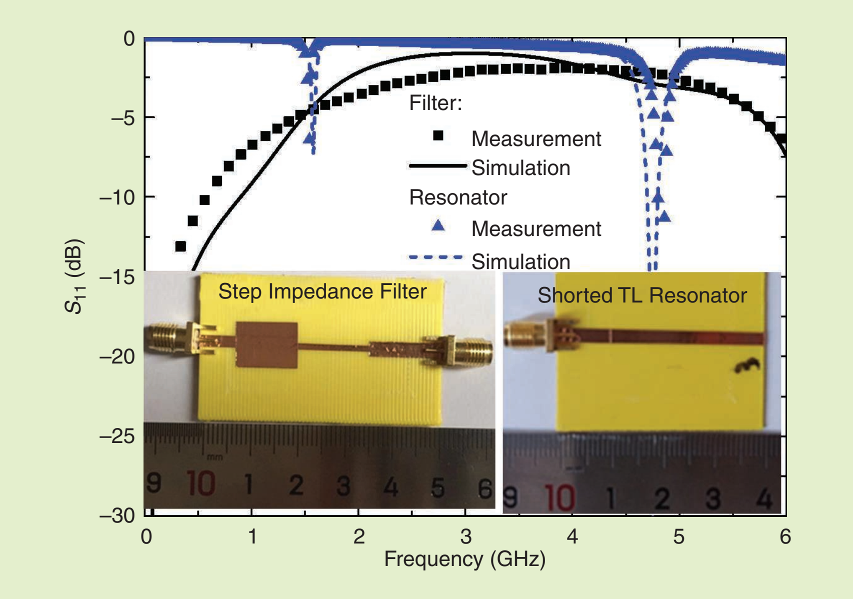

Figure 5. *Measurement and simulation results of a TL resonator and low-pass filter. The insets are photos of the resonator and filter.*

For these two devices, we use yellow PLA to print the dielectric substrate. The stepped impedance low-pass filter is designed following the insertion loss method described in [18]. Simulation and measurement results as well as photos of the devices are shown in Figure 5. It can be seen that the simulations agree quite well with measurements. The results of the resonator are helpful for determination of the dielectric properties of the printed dielectric substrate. One can also use other kinds of resonators, such as the T-shaped resonators described in [2]. Dielectric material characterization is important for circuit design and implementation, and it is also a research topic that has attracted much attention. If possible, educators in universities can also design a special practicum on this point and it could be easily extended to diverse microwave sensor topics such as ice detection sensors [20] and liquid sensors [21].

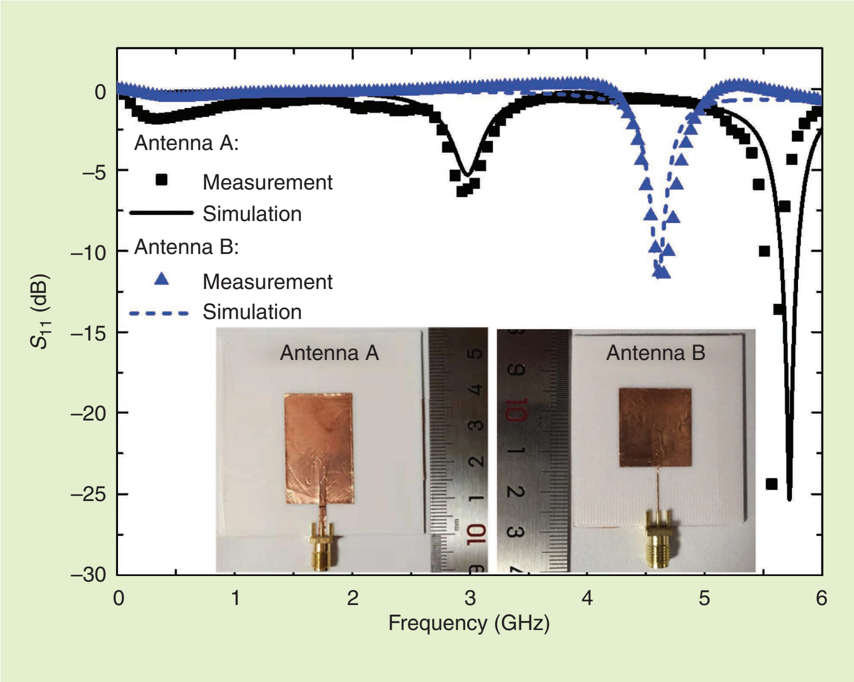

Figure 6. *Measurement and simulation results of Antennas A and B. The insets are photos of the antennas.*

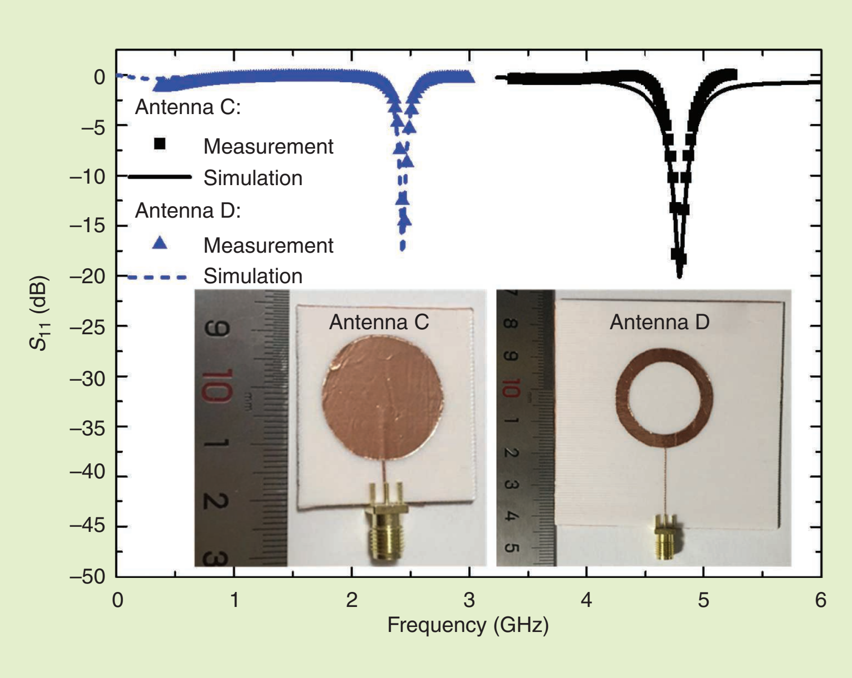

Figure 7. *Measurement and simulation results of Antennas C and D. The insets are photos of the antennas.*

Lab 3: Microstrip Patch Antennas

Microstrip patch antennas, due to their low profile, low cost, and conformity, have been studied for decades and they are presented in many publications like [22]. In this lab, the following aspects may be included:

- design and simulation of rectangular/circular/ring patch antennas
- fabrication and measurement of these antennas (the measured antenna parameters depend on the available measurement resources, such as reflection coefficient, gain, radiation pattern, and polarization).

Here, four microstrip patch antennas are presented. All of these antennas are fabricated with white PLA materials. Antennas A and B are rectangular patch antennas. Antenna C is a circular patch antenna, while Antenna D is a ring patch antenna. It can be seen from both Figures 6 and 7 that the simulations agree fairly well with the measurements.

Lab 4: Nonplanar Devices/Antennas

Up to this point, all of the devices presented were planar. In this section, to demonstrate the flexibility of the fabrication method, a few kinds of nonplanar devices are presented. The main components of this lab include:

- design, simulate, fabricate, and measure dielectric resonator antennas
- design, simulate, fabricate, and measure dielectric-filled coaxial-to-waveguide transition and dielectric-loaded waveguide antennas.

First, aperture coupled dielectric resonator antennas are used for demonstration. The feeding circuit of the antennas is formed by microstrip line with an aperture in its ground. The detailed theory of dielectric resonator antennas may be found in [22] and the references therein. Two kinds of dielectric resonators are used as radiators: a cylindrical sapphire resonator and a 3D-printed PLA resonator. It should be noted that, for dielectric resonator antennas, dielectric materials with a higher relative dielectric constant and lower loss tangent may be preferred.

The PLA dielectric resonator used here is suitable for educational purposes since no additional materials are needed. It should be noted that, when printing the PLA resonator, the infill parameter of the 3D printer is set at 100% to achieve as high a relative dielectric constant as possible. The photos of the two antennas are shown as insets in Figure 8. The simulation and measurement results of S_{11} of these two antennas are shown and compared in Figure 8. It can be seen that the simulations agree well with the measurements, with a bit of frequency shift for the sapphire resonator. As for the PLA resonator, the measured resonant frequency is a little higher than the simulation and the measured bandwidth is obviously wider than the simulation. These discrepancies may be attributed to factors such as material parameter error and aperture dimension error.

Waveguide components are indispensable for applications such as radar and satellite communications. 3D-printed waveguide components have been reported [11]. It is possible to use 3D-printing technology to make a dielectric base and then obtain a metallic waveguide through a specific metallization process. Or one can use metal 3D-printing technology directly. On the one hand, for the purpose of engineering education, we would like a small waveguide component to finish the printing process on a suitable time schedule. On the other hand, conventional small waveguide has a high cutoff frequency, which may exceed the measurement frequency range of our reflectometer. With all of these taken into consideration, we finally decided to practice with a dielectric-filled coaxial-to-waveguide transition. First, we use 3D printing to fabricate a cuboid (its dimensions are close to the standard WR-90 rectangular waveguide with length 23 mm; the infill parameter for printing is 100%) with a proper blind hole for inserting a coaxial connector (the feeding connector is ~ quarter wavelength from the shorted wall). Then, we use copper

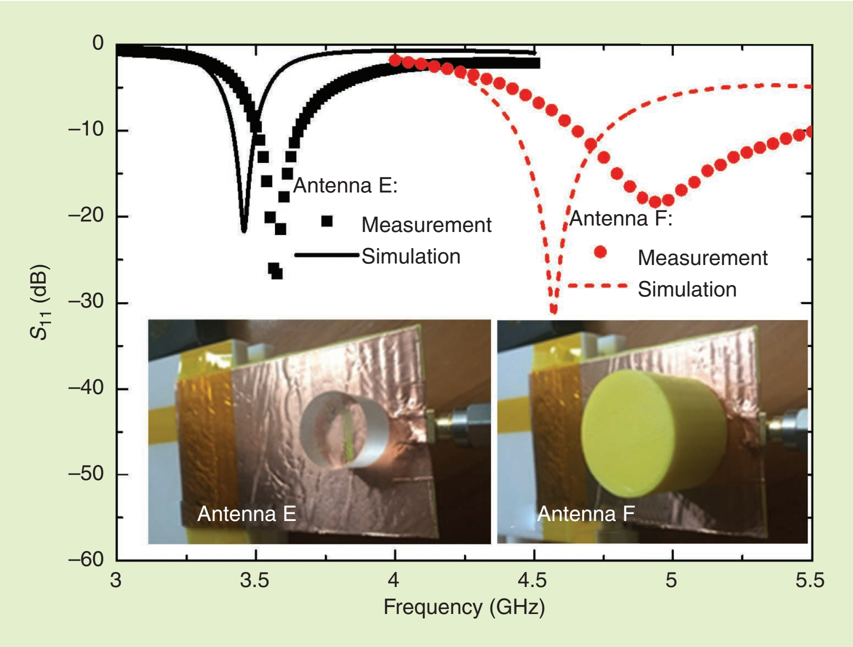

Figure 8. *Measurement and simulation results of two dielectric resonator antennas. The insets are photos of the two antennas.*

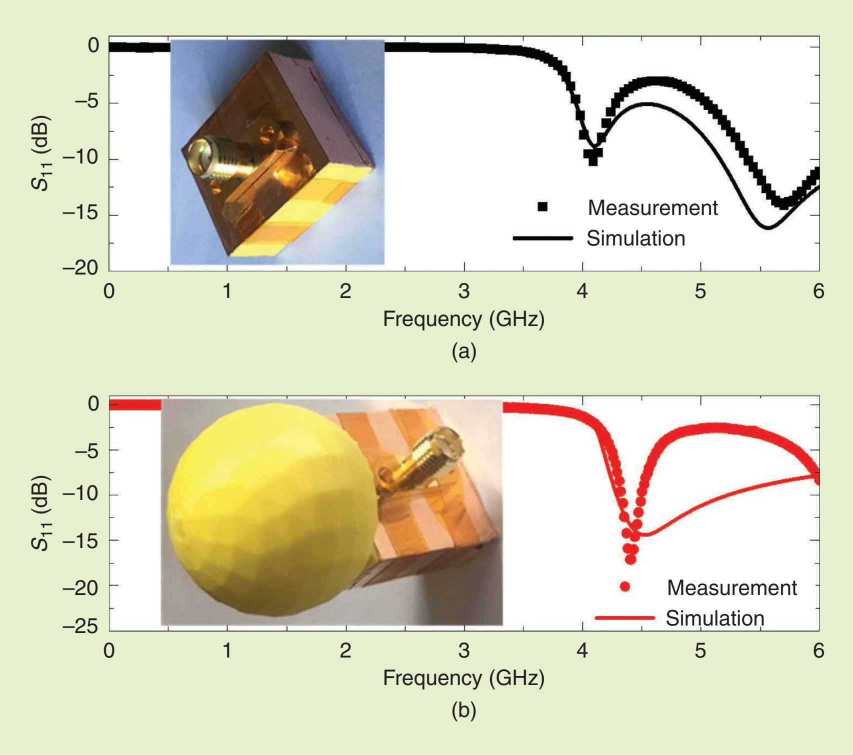

Figure 9. *Measurement and simulation results of (a) coaxial-to-waveguide transition and (b) spherical dielectrically loaded antenna. The insets are photos of the two devices.*

adhesive tape to enclose the dielectric cuboid, but with one face open. Last, the coaxial cable, a commercially available SMA connector, is inserted into the connection. Since no bolts are used, we use adhesive tape to fasten the connector. Of course, it is possible to use nylon bolts to fasten the connector. Simulation and measurement results are shown in Figure 9(a). It can be seen that the simulated cutoff frequency agrees well with the measured cutoff frequency, which is ~ 4 GHz. Compared with the cutoff frequency of a standard WR-90 waveguide, which is ~ 6.6 GHz, the cutoff frequency is reduced, as is expected with dielectric filling. It should be noted that waveguide flanges are omitted in our fabrication. However, the flanges can be included if necessary.

The coaxial-to-waveguide transition can be seen as an antenna since part of its input energy can be radiated into free space. There are multiple publications about this open-ended waveguide antenna [23]. As an improvement method, the dielectric load technique is studied and verified. Here, as a further example of a nonplanar microwave device lab, a spherical dielectrically loaded antenna is simulated, fabricated, and measured, as shown in Figure 9(b). The dielectric sphere is printed together with the waveguide. It can be seen that the simulations agree well with the measurements. As presented in [24], electromagnetic simulations are also extremely useful for educational purposes.

Conclusions

Low-cost, low-environmental impact 3D-printed dielectric materials and copper adhesive tape are used to fabricate microwave devices. This method is quite useful for educational purposes. Both planar and nonplanar devices are designed, fabricated, and measured. Simulations agree well with measurements. The advantages of the design lab include its flexibility, low cost, and lack of chemical processes, and thus ecofriendliness. It is feasible for most universities and can be expected to help learners grasp both the theory and the practice of microwave and antenna technology. In addition, the prototyping process is also suitable for experimentation in scientific research.

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