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# Low-Cost Additive Manufacturing: A New Approach to Microwave Waveguide Engineering Education through 3D Printing*

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This paper explains the applications of additive manufacturing to microwave waveguide engineering education, in particular the advantages of the low-cost technique called Fused Filament Fabrication. The promptness to print models, the variety of feasible geometries previously unachievable by subtractive methods and specially the reduced price, make manufacturing designs available to students and small labs without great resources. In addition, it gives students the opportunity to be involved in a full design process, including the manufacturing and measurement of their own devices, with the invaluable experience which it entails. In order to illustrate the process, several well-known passive waveguide devices working in Ku band have been printed, metallized and measured: a band-pass filter, a diplexer, a branch-line coupler and a horn antenna. Finally, the analysis of results proves the potential of 3D printing, although the main limitations are also highlighted to give a deep insight of this new technology.

**Keywords:** additive manufacturing; coupler; diplexer; filter; horn antenna; Ku band; microwave education; waveguide; 3D printing

## 1. Introduction

Education in microwave and RF technology is a fundamental part of electrical engineering curriculum. However, the content of microwave courses as well as the way they are taught have experienced several major changes throughout history [1, 2]. Nowadays, education in all fields is subject to change as a result of the rapid development of new technologies which open up an endless amount of possibilities.

From the outset, the development of the microwave discipline has been accompanied and helped by the advance of other technologies. For instance, the improvement of computational capability allowed the emergence of new numerical methods. More recently, the introduction of computer-aided design (CAD) and simulators has completely transformed the way microwave problems are faced. Nowadays, the benefits of using CAD techniques and electromagnetic simulators are widely recognized for both professional engineering design and academic applications.

Not only have computers revolutionized the microwave field, but also the development of new technologies to implement the designs. In this sense, planar transmission systems such as stripline or microstrip gained momentum in the 70s, motivated by the growth of the component-design industry and the increasing miniaturization of circuits.

In the educational field, these printed-circuit transmission lines have played an important role, specially the microstrip. At the beginning, the practical part of microwave courses was done by using laboratory kits, yet the planar technology opened the possibility of easily manufacturing designs at a low cost. Nowadays, printed circuit boards (PCB) are present in all electronic courses and microstrip is the transmission system used in most student projects.

Additionally, the development of new technologies is unstoppable, being the most recent example additive manufacturing, also commonly known as 3D printing. The promising present and future of this technology intended to revolutionize all fields may be used by electrical engineering to radically change the way microwave courses are given.

The almost exclusive use of planar technology to implement academic designs makes students to forget the existence of other transmission systems, such as waveguides. Their academic use has been unfeasible due to its high cost and manufacturing difficulties. However, the use of 3D printing overcomes all these drawbacks and allows the fast fabrication of devices with many different geometries, from the most classic ones to others previously unachievable.

This paper intends to explain the advantages of low-cost 3D printing and its potential use in microwave waveguide technology as well as the possible

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limitations of the process and the best way to deal with them. Then, several passive microwave devices are presented, all of them 3D printed and subsequently measured. They incarnate the potential of 3D printing in RF education, since they all are common devices familiar to students, very fast manufactured for less than \$25 each and whose experimental response shows a good agreement with the theoretical one.

## 2. Educational use of low-cost additive manufacturing

### *2.1 Origin and evolution*

The term Additive Manufacturing (AM), commonly referred to as 3D printing, describes the addition of material in layers to create an object from a digital model. In the last years, there has been an uprising interest in all the techniques encompassed by 3D printing and the relevance of this industry has affected all fields, including education.

The variety of 3D printing technologies [3] differs in the physical processes applied to the raw materials, being some of them more suitable to use with some materials than others. Such technologies may be categorized into four groups depending on how the 3D printers work: extruding semi-liquid material through a nozzle, selectively solidifying the material, compacting powder or using lamination. The first category, called Fused Filament Fabrication (FFF) and mainly used with thermoplastic, plays a fundamental role in AM industry, since it is the origin of the so-called "low-cost 3D printing".

Although the 3D printing industry started in the late 80s, the use of the technology was restricted to professional levels, due to the expensiveness of the printers [4]. However, two different events changed the situation: the expiration of FFF patents in 2009 and the development of the open-source movement for both hardware and software. The rise of the maker culture [5], as an extension of the Do-It-Yourself philosophy, has made 3D printing accessible and affordable for the masses: for a few hundred dollars, anyone can buy their own 3D printer. The rest of tools needed to operate a typical 3D printer are not very expensive either. As it was previously mentioned, these machines work by extruding a heated thermoplastic filament from a nozzle. The most common materials used are ABS and PLA, both of them provided in spools [3]. The price of a normal PLA spool is 25\$/kg. Finally, all the software needed to process digital models is available as open source [6].

Among 3D printing endless applications, the ones involving design and engineering stand out significantly. 3D printers allow manufacturing geometries unfeasible until now with traditional subtractive technologies, like CNC milling. Besides, the idea of low-cost 3D printing opens up this variety of manufacturing possibilities to everybody, not only big companies or high-level labs.

### *2.2 Use and impact in microwave and RF education*

Visualization is one of the most powerful tools to help students understand the phenomena they are studying. Figures and models provide a different insight of reality, and even though they do not replace theoretical results, they transmit invaluable intuition. In this sense, the appearance of simulators and visualization software tools in the recent years has proved to be very useful, for instance when depicting the electric and magnetic fields through microwave transmission lines.

3D printing takes a step forward and allows students to *touch* real designs made on demand. In the RF field, this technology may, for instance, be used to manufacture waveguides and other devices based on this transmission system [7–9], as explained in later sections. Besides, this process may be conducted in small labs without extraordinary resources, as the cost of low-cost 3D printers and the materials associated is reasonable.

In the RF field, traditional education is based on students acquiring a theoretical background as the first step. Then, in order to apply that knowledge, they are asked to design a device which fulfills some specifications. In the best case, students obtain a simulated response of their design thanks to software tools. However, in most cases there is a lack of experimental verification due to the absence of resources. Sometimes students receive practical lessons by measuring in the laboratory existing devices specially prepared for such use, but they rarely get to manufacture and test their own designs.

3D printing may be able to change this reality by enabling students to conduct a whole design process, from the early stages to the final measurement of their own models. It joins together the two aforementioned approaches followed in education nowadays. Once the design is completed, the physical structure may be printed in few hours and subsequently measured. Therefore, students are intended not only to learn how to measure real devices, but also to check that their response matches the simulated one. Besides, each student may design their own individual device with different specifications, due to the brief time needed to print the models.

Facing a whole design process has another advantage for students too. All manufacturing processes entail restrictions that must be taken into account when designing a device, and 3D printing is not different. As a result, students must keep in mind that their device must be physically achievable,

**Table 1.** Estimated material investment in a 3D printing lab

| Material | Price ($) |
|---|---|
| Printer | 1000 |
| Plastic spools (25$ each) | 125 |
| Paint (60$ per 20-gr bottle) | 60 |
| Other tools | 65 |
| | **1250 $** |

something not always considered when the design process ends with a simulated response.

A real example of this can be found in the senior thesis presented in [10], where a waveguide diplexer is designed, printed and measured by a Bachelor Degree student. This kind of hands-on projects have been traditionally restricted to Master courses, but 3D printing allows to integrate manufacturing and production earlier in the engineering curriculum. The involvement of students in manufacturing has been proved to have a good impact in their performance and a great effort is being made towards this direction [11–12].

Finally, an estimation of the initial investment needed to start using 3D printing in microwave education as expounded in this article appears in Table 1. Only the cost of material is included, although some training courses would also be necessary, in case there is nobody with experience in this field.

### *2.3 Limitations of the process*

Only the advantages of low-cost 3D printing, particularly when it is applied to waveguide technology, have been considered until now. However, there are certain drawbacks which must also be kept in mind.

Firstly, low-cost 3D printers present a limited accuracy, i.e. layer height. The minimum value in a normal low-cost machine is ±0.1 mm. It results to be a key factor, since it marks the minimum variation of dimensions of the structure susceptible to be built, and therefore affects the design. Consequently, printing accuracy establishes an upper limit for frequency: it is unrealistic to try to print devices intended to work above 15 GHz. Besides, accuracy may be a significant issue when dealing with very sensitive devices, in which tiny changes of dimensions lead to a very different response.

The second drawback and the most important one too is the metallization. As low-cost 3D printers extrude plastic, it is imperative to cover the inner surface of the printed waveguide devices with a layer of metal paint, so that electromagnetic energy is confined within the structures. In order to complete this task, devices must be printed in separate parts to be able to reach their interior. Consequently, this may limit the feasible geometries of some devices. Besides, finding a good and reasonably-priced metal-loaded paint to cover the devices is a hard task. Conductivity is not very high and varies with frequency, causing significant insertion losses which may hide narrow-band frequency responses.

**Table 2.** Characteristics of educational 3D printing in the microwave field

| Advantages | Disadvantages |
|---|---|
| • Short time<br>• Low cost<br>• Enhancement of education experience | • Printing accuracy<br>• Metallization process |

Other complications arise from the metallization process, being the most important one the misalignment. Since the structures are divided in parts to be painted, they must be carefully aligned and stuck by glue, because any misalignments between the different parts may cause a relevant variation of the response. In addition, it must be highlighted that painting the structure has to be done with extreme care, as the surface must be homogeneously covered, with no air gaps or drops of paint remaining.

It must be noticed that metallization is not a problem when working with more expensive 3D printers, since they may work with metal directly and therefore the whole closed structure can be printed. However, the main goal of 3D printing in education is to obtain results at a low cost, following a home-made philosophy.

Finally, there are other issues that may cause results to be different from the expected ones. For instance, plastic characteristics may vary from one spool or supplier to another. As a result, the roughness of the walls or the ability of the plastic to absorb the paint may differ, as well as its resistance to humidity or temperature variations. A good practice is to maintain the same material supplier to try to reduce these variations to the minimum.

To sum up, the main benefits and limitations of low-cost additive manufacturing in the microwave field appear in Table 2.

## 3. Characterization of the manufacturing process for waveguide devices

In order to illustrate how 3D printing could be used at an academic level, several passive waveguide devices have been designed, manufactured and measured. The traditional manufacture of such devices would have cost thousands of dollars and it would have been unfeasible for students or regular university course budget.

All designs have been manufactured with a low-cost 3D printer (printing accuracy ±0.1 mm) and the material used was PLA. However, four important parameters have to be considered in first place

**Table 3.** Key aspects of 3D printing waveguide devices

| Key aspects |
|---|
| • Frequency (influenced by printing accuracy)<br>• Matching level (influenced by printing accuracy)<br>• Insertion losses (influenced by metallization)<br>• Structure: E-plane vs H-plane |

(Table 3). Two of them are already fixed by the aforementioned printing accuracy. Two sets of tests have been conducted with waveguide sections as benchmarks to determine the other two. The waveguide used was the standard WR75, whose usable frequency range goes from 10 to 15 GHz. In all cases, standard flanges have been printed along with the devices to attach the structure to the network analyzer.

### *3.1 Metal paint*

The first issue to address is the selection of the most adequate paint to metallize the devices. Two different commercial paints have been tested, which are supplied by RS [13] and Ferro [14] respectively. For both paints, conductivity is provided, although DC value is assumed, since there is no information about variations with frequency. RS paint is silver-loaded, but its theoretical conductivity is $\sigma$_nomRS = $10^5$ S/m, two orders of magnitude below silver. The paint supplied by Ferro has a nominal conductivity of $\sigma$_nomFERRO = 1.6–$5{\cdot}10^6$ S/m, due to its silver content as well.

Fig. 1 and Fig. 2 show the results obtained after measuring 3D printed 50-mm-long WR75 waveguides covered with RS and Ferro paints. From this set of proofs, it can be concluded that the RS paint, which costs $60 per 20 gr, is the most suitable one to metallize 3D printed devices working in Ku band. Both waveguides present a similar matching level (20–25 dB, maximum achievable with this technology), but the insertion losses for the second paint are better. However, losses are quite high due to the conductivity behavior at high frequencies, the paint absorption by the plastic or any misalignments of the structure.

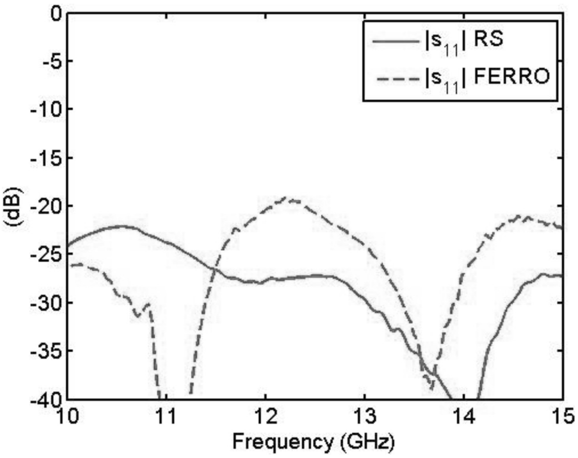

**Fig. 1.** Measured matching level of 3D printed 50-mm-long WR75 waveguide painted with RS and Ferro paint.

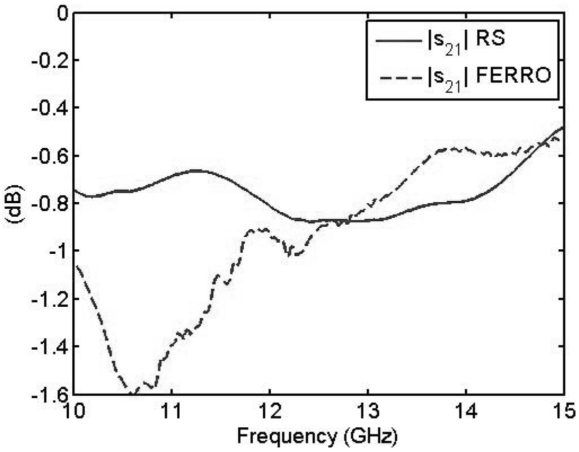

**Fig. 2.** Measured insertion losses of 3D printed 50-mm-long WR75 waveguides painted with RS and Ferro paint.

### *3.2 Structure division: E-plane vs H-plane*

Due to the need of metallizing the devices, their inner surface must be easily reachable by hand. In many cases, it implies that the design must be divided in separate parts. The main two possibilities are to consider H-plane or E-plane structures. The former consists in separating the structure in a body and a cover, whereas the second one is based on an E-plane approach and splits the structure into two identical halves. In order to determine the best approach, another set of proofs has been conducted.

Fig. 3 shows the CAD layout of a 40-mm-long WR75 section used as benchmark for both E-plane and H-plane divisions. Fig. 4 shows the insertion-loss level from the 40-mm-long waveguide sections. The H-plane structure presents higher losses due to the likely existence of a gap of air between the body and the cover, as well as the bending of the latter. On the contrary, E-plane structures present lower losses because they are less sensitive to assembling issues,

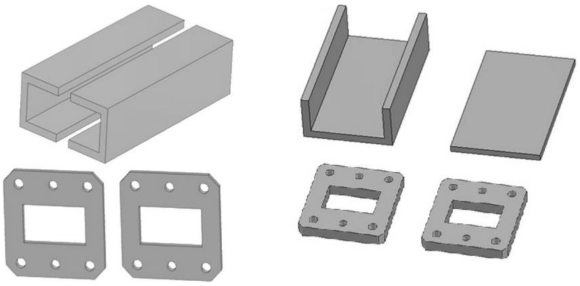

**Fig. 3.** Layout of 40-mm-long WR75 sections. Left: E-plane structure. Right: H-plane structure.

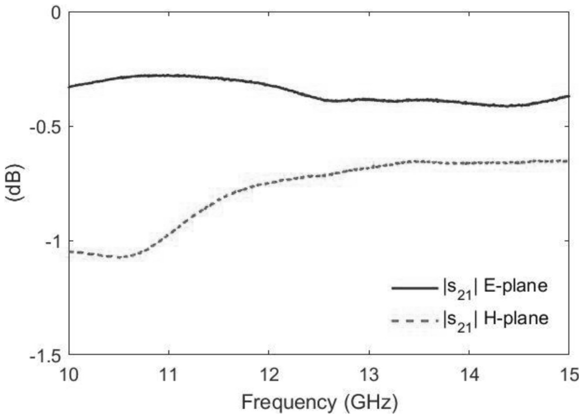

**Fig. 4.** Comparison of insertion losses for WR75 waveguide sections printed following E-plane and H-plane approaches.

due to the absence of currents along the cutting plane [15]. Consequently, dividing the structure into two halves results to be the best way to proceed in terms of insertion losses, although it must be kept in mind the need of a good alignment when assembling the device.

## 4. Designed waveguide devices: analysis of results

The tests previously carried out with waveguide sections were necessary to determine the best paint and structure division for further designs, four of them presented within this section intending to represent different aspects of the microwave field. Although they all are very common in microwave courses and therefore familiar to students, some of them are also very sophisticated and representative of the state of the art. There are two filtering structures, one directional coupler and one horn antenna with different geometries. WR75 waveguide has been used to implement all devices, since its usable frequency range goes from 10 to 15 GHz, the established upper limit for low-cost 3D printing technology. The widely-used mode-matching technique [16] has been employed for the full-wave design of the passive devices, whereas the Microwave Studio CST [17] has allowed the introduction of losses. According to the aforementioned tests, all of them have been metallized with RS paint. The ones which needed to be divided for the metallization process were separated into two halves, following the E-plane approach. Table 4 shows the different devices, the most sensitive part of the manufacturing process, the agreement between simulation and measurement and the easiness to use them in a basic microwave course.

### *4.1 Band-pass filter*

The first device is a band-pass filter, whose selective frequency response is based on the resonance phenomenon [15]. Since there is much energy involved, insertion losses are predictably higher than in high-pass or low-pass filters. In this particular case, a third-order Chebychev band-pass filter has been designed. Coupling between cavities is made by means of inductive irises. The central frequency is fc = 12 GHz and the bandwidth is 600 MHz. Specifications involve return losses, expected to be 23 dB. Fig. 5 shows the filter CAD layout and the final structure fully assembled and ready to be measured.

The measured response appears in Fig. 6 along with the simulation considering the effective conductivity. Both responses are very close, although the matching value is reduced in the 3D printed model. It is about 20 dB in the passband, which shows a good agreement with the tests conducted with empty waveguide sections. In addition, insertion losses are 1.32 dB at the central frequency.

### *4.2 Diplexer*

A diplexer is a passive microwave device more complex than the previous design, since it is formed by two filtering structures joined by a three-port junction. It allows the use of one single antenna for both transmission and reception, therefore it is widely used. In this case, real satellite-communication specifications for Ku band are used to design the diplexer. The two passbands are 11.9–12.2 GHz and 13.75–14 GHz. Specifications involve return losses and out-of-band rejection. The former is expected to be approximately 22 dB, whereas the latter is required to be at least 50 dB in the complementary bands.

Design requirements can be fulfilled by using different implementations. In this example, a high-pass and a low-pass filter are used, since implement-

**Table 4.** Summary of measured 3D printed devices

| Device | Sensitive part | Agreement simulation-measurement (✗ - ✓ - ✓✓) | Adequacy for a microwave course (✗ - ✓- ✓✓) |
|---|---|---|---|
| Filter | Irises | ✓✓ | ✓✓ |
| Diplexer | Low-pass filter corrugations | ✓ | ✓ |
| Coupler | Inner posts | ✓✓ | ✓✓ |
| Antenna | Smoothness of surface | ✓✓ | ✓✓ |

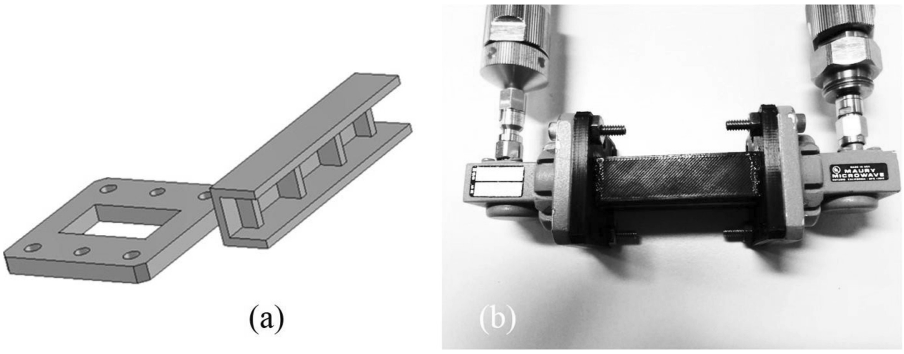

**Fig. 5.** (a) Band-pass filter CAD layout and (b) printed structure ready to be measured.

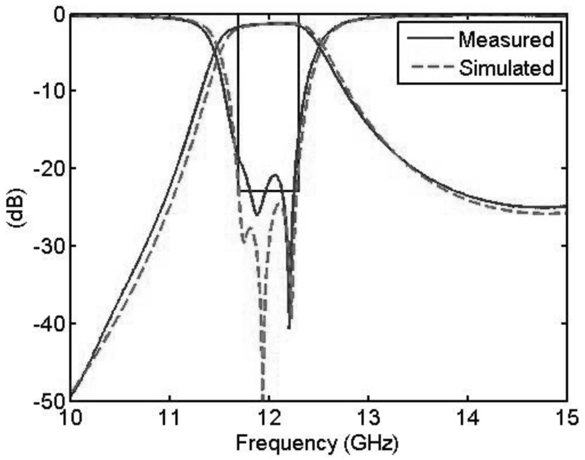

**Fig. 6.** Comparison between measured and simulated response for the band-pass filter in Fig. 5.

ing two band-pass filters instead would cause higher insertion losses.

Considering the printing accuracy, corrugations are the most sensitive part of the design, therefore they have been designed wider than in a usual low-pass waveguide filter. They are 4.5-mm wide and such decision has implied to use more sections to obtain the same filter response. Moreover, wider corrugations are painted more easily, which is another important aspect of the manufacturing process.

This kind of design decisions and trade-offs imposed by the manufacturing process also illustrate the advantages of including 3D printing in microwave education. Students can learn how reality affects a design process and how to handle manufacturing issues from the beginning.

Fig. 7 shows the different development stages of the diplexer: (a) the layout, (b) the CAD model ready to be printed, (c) one of the printed halves and (d) the device ready to be measured. Apart from the three-port junction to join both filters, a double bend has been designed to allow the WR75 flanges to be attached. Besides, a fastening piece has been printed to keep both halves as close as possible.

The diplexer response is shown in Fig. 8 com-

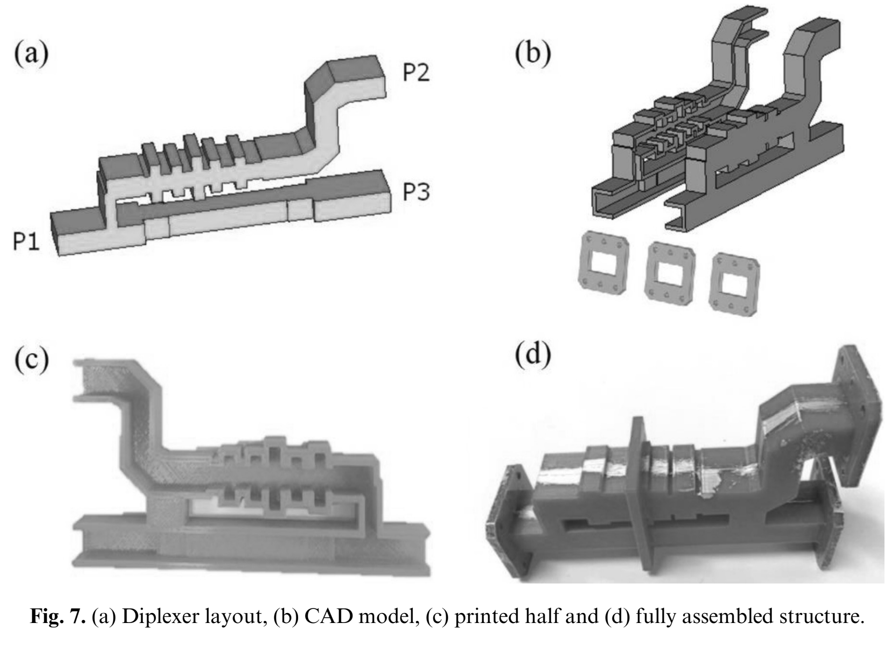

**Fig. 7.** (a) Diplexer layout, (b) CAD model, (c) printed half and (d) fully assembled structure.

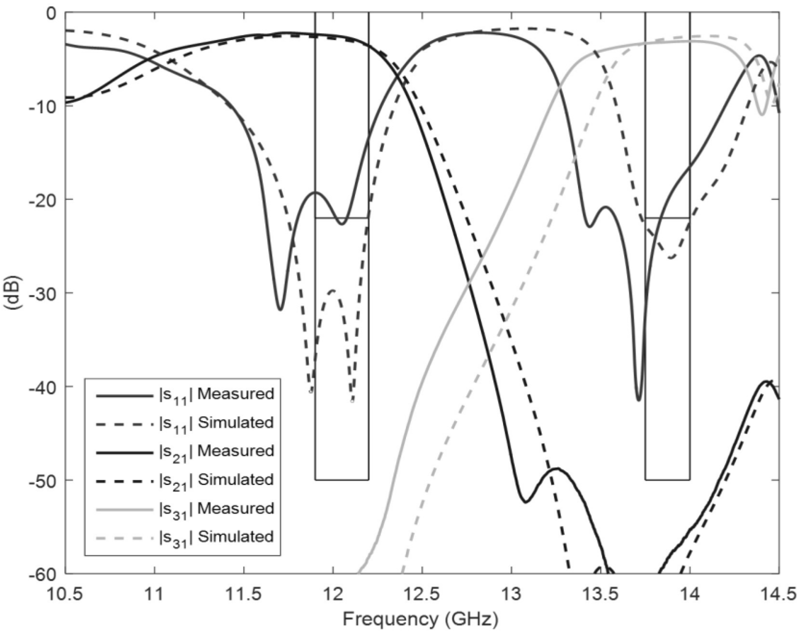

**Fig. 8.** Comparison between measured and simulated response for the diplexer in Fig. 7.

pared to a simulation including losses. The variability of paint is the main cause of the high insertion losses—up to 3.5 dB in the passband—. The matching value measured in both channels is approximately 20 dB, in accordance with the levels achievable with 3D printing. Besides, both responses have moved to lower frequencies as a result of possible printing inaccuracies. In the case of the low-pass filter, having made the corrugations wider has allowed to obtain a good transmission response which achieves the required levels of out-of-band rejection.

### 4.3 Branch-line coupler

Directional couplers are four-port devices which distribute the power at the input port between the two output ports [15]. They are basic devices in the microwave field and very familiar to students, specially 3-dB couplers, widely used in beam-forming networks, as input/output in balanced microwave amplifier circuits, as power dividers, etc. Particularly, branch-line couplers are formed by two shunt transmission lines connected by two secondary or branch lines. Their bandwidth is

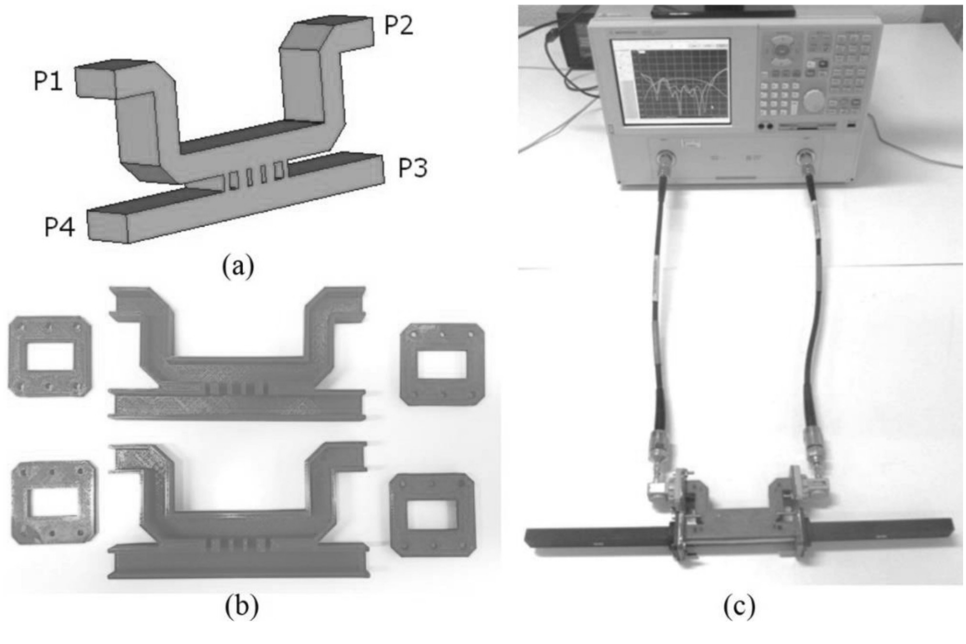

**Fig. 9.** (a) 3-dB branch-line coupler model, (b) printed pieces and (c) measurement arrangement for the assembled device.

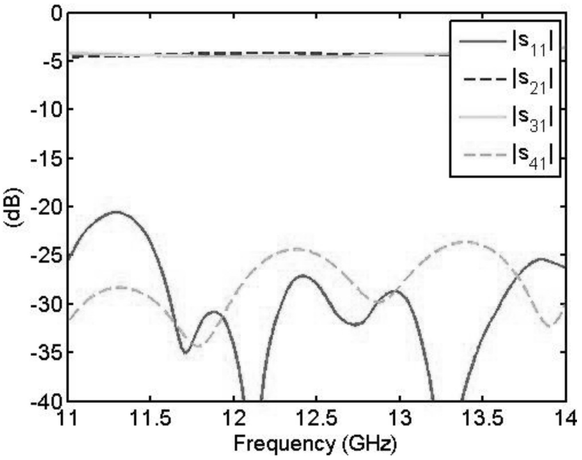

**Fig. 10.** Experimental results for the 3-dB branch-line coupler with five branches in Fig. 9.

relatively narrow, yet a broadband coupler can be obtained by cascading several sections.

A 3-dB branch-line coupler for Ku band has been designed. Seeking for a broad bandwidth, it presents five branches. Isolation and matching levels are required to be 25 dB in the working band. Fig. 9 shows the branch-line coupler from the simulation model to the measurement arrangement. Two double bends have been designed and added to the original branch-line coupler in order to be able to attach the standard WR75 flanges.

The experimental response is shown in Fig. 10. In terms of matching and isolation, the results are very satisfactory. The former is greater than 25 dB from 11.5 to 14 GHz, whereas the latter is better than 24 dB from 11 to 14 GHz.

Fig. 11 allows the evaluation of the behavior of the printed branch-line coupler in terms of power coupled to each output port. The experimental results are compared to a full-wave simulation including losses. They are higher in the coupled port (P3) than in the transmitted one (P2), although the latter has a double bend attached. This difference can be explained considering that the coupled signal passes through the branches to reach the output port. Besides, misalignments are likely to occur, especially in the small posts among the branches. They are the smallest and therefore most sensitive part of the design, as it happened with corrugations in the low-pass filter.

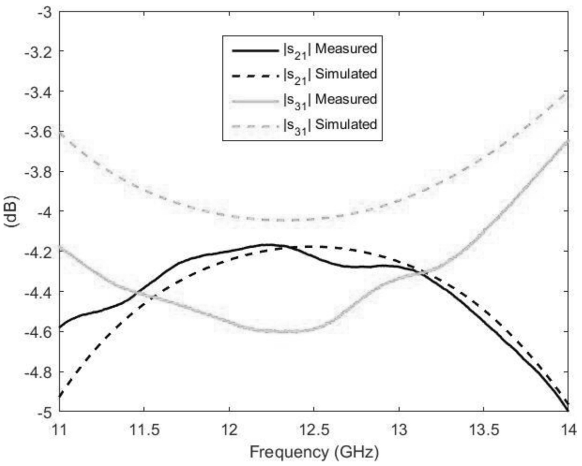

**Fig. 11.** Comparison between measured and simulated responses for the transmitted and coupled ports of the 3-dB branch-line coupler in Fig. 9.

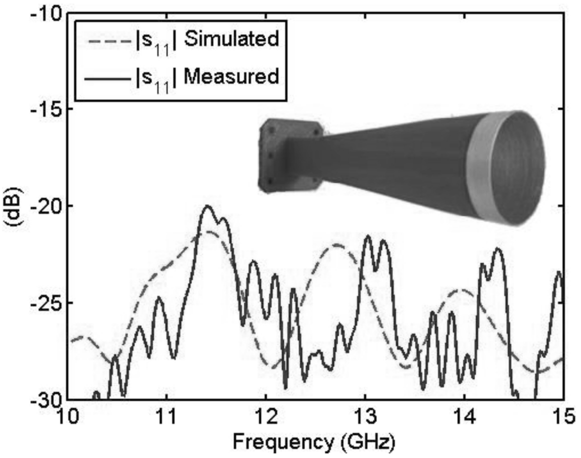

**Fig. 12.** Comparison between measured and simulated reflection response for the conical horn antenna. Top right inset, the printed and metallized structure.

### *4.4 Conical horn antenna*

The last design is a horn antenna [18]. These devices have a widespread applicability. For instance, horns are widely used in radio astronomy or communication applications, as feed elements for reflector antennas or as standard calibration antennas. They are typically formed by a waveguide flared to a larger opening.

In this case, the input is a standard WR75 flange, whereas the aperture is circular. It works in Ku band, being the directivity value 15 dB at 12.5 GHz. However, the easiest parameter to measure in a microwave course is the reflection coefficient. It appears in Fig. 12 compared to the simulated response with the effective conductivity. The experimental results fit the expected matching value, in spite of the ripple caused by minor reflections. The printed design can be seen there as well. Its most remarkable feature when compared with previous devices is that it is single piece. Its inner surface is reachable by hand, and therefore it is not necessary to print it in separate parts, which is an advantage to avoid misalignments. Besides, the antenna is formed by one single layer of plastic, except for the waveguide flange at the input, resulting in a very light structure—barely 15 gr.

## 5. Conclusion

This work shows the benefits of using low-cost 3D printing in microwave education through the explanation of several examples in waveguide technology. They prove how common, but in some aspects very sophisticated, microwave devices can be within the reach of students or small labs without great resources. Besides, the main limitations of 3D printing when applied in the RF field, i.e. printing accuracy and metallization, are completely overcome by its main advantage: it enables students to perform a whole design process, including the manufacturing and measurement of their own devices.

Four passive waveguide devices working in Ku band—a filter, a diplexer, a coupler and a horn antenna—have been designed, manufactured and measured, using a low-cost 3D printer based on FFF. They all have been printed with PLA and subsequently metallized using metal paint. Manufacturing decisions, like the most adequate paint or the best way of dividing the printed structures to paint them, have been taken by performing several sets of proofs with empty waveguide sections in advance.

Experimental results obtained show good agreement with the simulated responses, which validates the whole process. Moreover, the experience developed during such a project is priceless, since it includes design decisions, geometric constraints and several trade-offs, which may vary from one device to another. Further work will consist in dealing with printing accuracy and metallization, while trying to keep the cost low.

The benefits of active approaches to engineering education, such as Project Based Learning or hands-on experiences, have been clearly stated during the past years. Low-cost additive manufacturing provides a new tool to complement the education of future electrical engineers, in this case in the microwave field.

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