An Undergraduate Microwave and RF Low-Profile Laboratory

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Abstract— **In this work, we present a complete set of undergraduate microwave and RF laboratory experiences, that have been designed to improve the students competences on the high-frequency design, analysis and characterization. The developed courses include one-port and two-port circuits' measurement and characterization with the current most used instruments: vector network analyzers, spectrum analyzers, noise figure analyzers and power-meters. The computer-aided design has not been overlooked: a *design-optimization-fabrication-measurement* process is proposed to improve the students' global vision of the subjects.**

Keywords-microwave circuits; antenna design; low-profile laboratory; computer-aided design and simulation; microstrip lines.

I. Introduction

Last decade has been characterized in education of electrical engineering for an overwhelming development of web-based software and/or CAD programs for low-cost simulations of technological phenomena [1,2]. Two positive consequences have been derived from this fact: firstly, budgets devoted to the acquisition of new laboratory equipment could be reduced -especially in recent engineering campuses-; and, secondly, subjects related to computer engineering have increased their presence in electric engineering syllabus. But also negative facts have appeared as drawbacks: on one hand, a high percentage of graduate students are not able to translate all the theoretical knowledge to real-world and, on the other hand, the academic formation in specialized areas of electrical engineering, such as high-frequency and microwaves, has decreased. This paper presents the development and adjustment of a low-profile laboratory for teaching high-frequency and microwave techniques in Electrical Engineering. As it was pointed-out in [3], special attention has to be paid to these laboratories, according to both the high cost of the electronic equipment and difficulties to achieve realistic designs and high-precision at these frequency ranges.

The high-frequency laboratory has to be useful for several courses of the Telecommunication and Electrical Engineering degree, all of them in the undergraduate last two semesters (the students are assumed to have a consistent knowledge of electromagnetic theory and analogical circuits and systems). The first of the courses to be taken is a basic introduction to microwave theory and techniques, including passive and active circuits design, as long as scattering (*S*) parameters analysis and measurement. Parallel to this subject, a second course is related to antenna theory, design and characterization, including radio-wave propagation theory. Finally, an advanced course on microwave circuit design, including circuit components of wireless transducers such as low-noise amplifiers (LNA), oscillators and mixers is also developed.

This paper is organized as follows. After this brief introduction, the two sets of experiences that have been developed for the laboratories are introduced in Sections II (microwave courses) and III (antennas and propagation course), respectively. Section IV discusses the competences that the students should develop after following the combined three proposed courses, and presents the main conclusions of this work.

II. Microwave Laboratory Experiences

The first three explained experiences (*II.A* to *II.C*) are oriented to the study of different characterization techniques and the involved instruments, while the last two ones (*II.D* and *II.E*) are useful to the microwave engineering process.

A. Two-port S Parameters Characterization with VNAs

One of the main parts of any elementary course on microwave circuits theory and design is the study of the *S* parameters [4], which overcome the problems that arise when applying the usual low-frequency characterization parameters (i. e., *Z*, *Y* or *H* parameters) to the microwave frequency range, where the voltage and current strongly depends on the reference position of the access transmission line. *S* parameters are based on power and phase measurements, which are measurable using standard coherent reception techniques. The students of Telecommunication and Electrical Engineering are used to these techniques and thus are able to fully understand the *S* parameters measurement.

In the laboratory, students learn how to use a *Vectorial Network Analyzer* (*VNA*), which is the most used instrument to characterize high-frequency circuits from a few *kHz* to over 100 GHz. To do so, it is essential to deal with two-port calibration techniques. Therefore, the students have to study and validate some of these techniques (such as *TOSM* – Thru/Open/Short/Match or *TRL – Thru/Reflect/Line*).

During the first of the courses developed on the microwave subject, the students characterize two-port passive networks,

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and study their properties taking into account the scattering parameters theory. In the second course, active devices (microwave amplifiers) are characterized using the *VNA*: the dependence of *S* parameters on the polarization is studied, and stability analyses are performed.

B. Microwave Characterization with Spectrum Analyzers

The use of *VNA* to characterize two-port or, in general, multiport circuits, is usually restricted to linear applications, as this equipment is based on the measurement of the circuit behavior at a single frequency, which is swept to perform broadband characterization.

However, this involves that non-linear effects, such as harmonic appearance or intermodulation products, are not observable without specific modules or instruments that, in most cases, are quite expensive [5].

One of the possible alternatives is the development of home-made control software to perform non-linear measurement with *VNAs*. However, a simpler approach is to make use of a high-frequency signal generator and a spectrum analyzer, each of them connected to one of the ports of the device under test (*DUT*). In this way, the power at the input and output planes is known. This technique, apart from allowing the students to learn how to use both instruments, gives them the idea of the basis of the *VNA*, as they measure a magnitude proportional to the transmission *S* coefficient. Moreover, the necessity of a calibration tool will arise in a natural way, since the students identify the frequency-varying probe loss (here, low quality probes and connectors are used to enhance this fact).

C. Noise Measurement and Characterization

Noise is a fundamental parameter on telecommunication systems, but undergraduate students do not usually have the opportunity to handle with real noise measurements. This is the reason why a *noise figure analyzer* has been included in the high-frequency laboratory.

During the second course on high-frequency circuits, the student has the opportunity to measure real circuits noise figure, including passive and active devices, and comparing the results with those expected from the theory.

D. CAD Design of High-Frequency Passive and Active Circuits

The main objective of this work is to show a set of experiences that allow the students to have a comprehensive formation on high-frequency design and characterization. In this context, we do think that computer-aided design is extremely useful for circuit design and optimization and therefore should be considered in any high frequency laboratory.

There are several commercial tools able to simulate RF and microwave circuits. Most of them allow the integration of 3D or 2.5D electromagnetic simulations within block system design, where simple models for each circuit part are used. Common examples of this kind of packages are *Agilent Advanced Design System* (*ADS*) [6], *AWR Corp. Microwave Office* [7] or *Ansoft Designer* [8]. However, their correct use calls for an intense training that is not achievable in a one semester course. Moreover, only some of these codes are available in student versions, and these versions are usually truncated so that most of their functionality is missing.

As the solution of the Maxwell equations via numerical methods is necessary in the antenna design and optimization process, the CAD-aided design in the microwave laboratory has been centered on the model-based simulation of planar transmission lines. One good code based on transmission line models is *PUFF* [9]. This code was developed in the last 80's and it has been used for more than one decade in the academic environment. Its main advantages over the professional tools are:

1. It is more intuitive, as it allows the students to *see* the circuit they are simulating, in contrast to other model-based simulators.
2. Implemented models are simple but enough accurate for an introductory course.
3. It is a low-cost tool, in contrast with most of the commercial codes.

Following its example, we have developed *MWSim* [10], a model-based simulator. Its main differences with the *PUFF* code are: *i)* an updated to current standards graphic user interface, *ii)* a larger variety of microstrip models, performing more accurate results and allowing the comparison with other commercial tools, *iii)* an input/output format fully compatible with standard *Touchstone* (which allows the use of embedding and de-embedding techniques with VNA measurements and with electromagnetic simulators) and *iv)* it includes the possibility of exporting files into *Gerber* format [11]. The last option is of special importance as the students are able to export the geometry file of the designs and fabricate them using automatic milling machines, which is the objective of the experience IIE.

The students of the advanced course are encouraged to work with this tool and also with evaluation/student versions of commercial tools in order to compare the obtained results. With these comparisons, a twofold objective is tackled. First, the students get a better understanding and critical assessment on the models validity. And second, the use of the evaluation versions of commercial tools might be useful in their future professional life.

E. Microwave Passive Device Fabrication and Characterization

The engineering process in the designed laboratory does not stop on the design, simulation and optimization steps. In order to give the students the opportunity to build their prototypes, and characterize them by using the techniques they have already studied in experiences *II.A* to *II.C*, they are allowed to export the geometry of their designs into standard Gerber files, which can be fabricated using a milling machine. Thus, the laboratory has been equipped with the *LPKF* Protomat S62.

As the objective of the exercise is not to obtain professional prototypes, but to provide the students a general overview of the design to fabrication and characterization process, these designs are fabricated on Double-Sided Standard FR4 PCBs, which are quite cheap and allow well-working designs up to a few GHz [12]. Moreover, in this range of frequencies high-frequency milling tools are not necessary, and therefore the milling process becomes cheaper.

Fig. 2 shows a microstrip circuit (branch-line coupler) that was simulated with *MWSim*, exported to Gerber and fabricated using the milling machine. Although the objective of this paper is not to introduce the results of the comparison between measurements and simulated data, it is worth to say that a very good agreement is usually found between them [10]. From a didactic point of view, this helps the students to understand how the abstract concepts they theoretically study can be translated into practical circuits, which they can fabricate and measure.

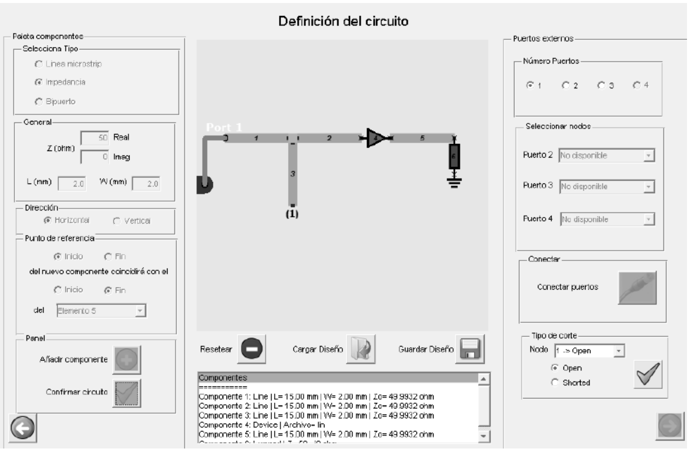

Figure 1. MWSim simulator: front-end user interface.

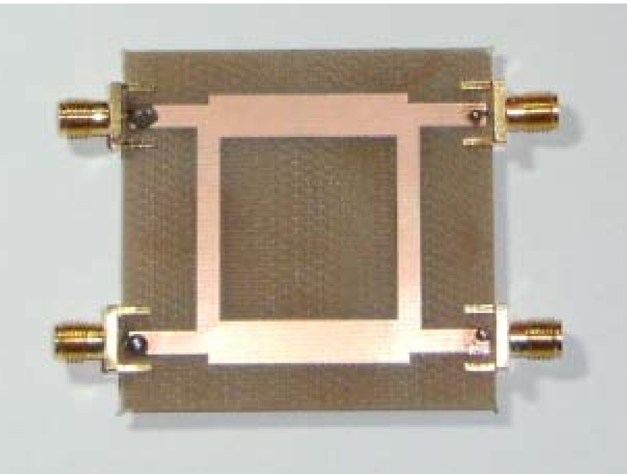

Figure 2. Microstrip circuit (branch-line copuler) designed with *MWSim* and fabricated with a milling machine using a double-side PCB and low-frequency mill tools.

III. ANTENNAS AND PROPAGATION EXPERIENCES

Experiences in this field are strongly related with those from Section II. Most of the experiments are performed in parallel with those described in Sections *II.A*, *II.B* and *II.D*, although more emphasis is made in the measurement and validation of one-port devices. Further, radiowave propagation and derivation of antenna parameters, and in some way the CAD design of antenna, constitute the new set of practical knowledge acquired by the students in this subject.

A. High-frequency Laboratory Equipment for One-port Measurements

Experiments related to this objective are focused in the use of the *Vectorial Network Analyzer* in one-port mode as well as the use of a *Spectrum Analyzer* with internal tracking generator as Scalar Network Analyzer. Additional efforts are made in this stage to perform measurements of the time-domain impulsive response of the antennas, as an alternative way to characterize the broadband and ultrawideband devices, matter of hot interest in the industry industry in applications related to both goniometry and impulsive radar fields [13]. Figure III shows a picture of the control panel of home-made software based on *LABVIEW* [14] and designed for time-domain characterization purposes.

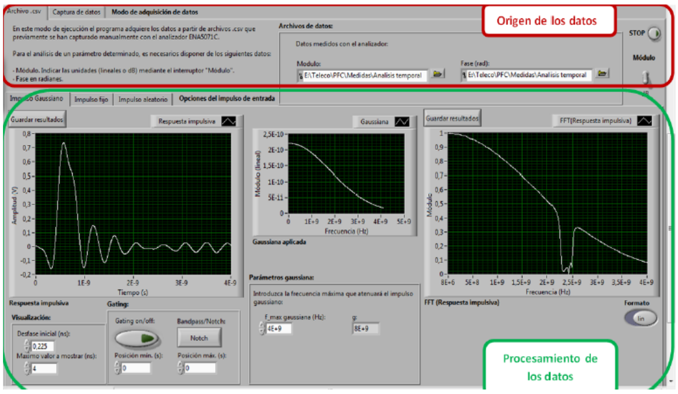

Figure 3. Software tool for the measurement of time-domain impulsive responses.

B. Practical Measurements of Antenna Parameters and Propagation Effects

Simple transmit/receive configurations can illustrate basic effects -mainly associated to antenna properties and radiowave propagation- which are involved in real-world wireless communications. Most of the available educational kits at affordable prices are devoted to this purpose, being the dimension of the laboratory a critical parameter in this choice. In our case a commercial X-Band antenna kit was chosen, being able to illustrate the effects in a real anechoic chamber related with the positioning and calibration of the system.

C. *Mesurements of In-site Radiowave Spectrum*

Acting as a complementary experience to *III.B*, the students should be set to perform in-site electromagnetic radiation measurements. Then, the first step is to guide them into the identification of radiowave signals for a specific place, which is done not only by looking at specific ranges of electromagnetic spectra, e. g. WiFI 802.11 emissions, but also by consulting the public information provided by Spanish Government related to the allowance of the emissions for the different TV and radiochannels [15]. Once done, they further compare measurements by using calibrated professional equipment for radiowave measurements and radioelectrical planning, and by using a set-up of laboratory equipment for non-calibrated measurements of radio and microwave spectra – basically a log-periodic array of antennas connected to a spectrum analyzer. Excellent agreement is achieved for identification purposes, but some considerations about the level of the received signals are arisen from the use of non-calibrated equipment.

D. *CAD of High Frequency Wireless Communications*

This experience presents different alternatives to the computer-aided design of antennas. Rather than focus in aspects related to particular software, these experiences are oriented to show the theoretical basis of commercial packages [16], and the limitations presented for carrying out the designs to prototypes. Hence, special attention is paid to the physical geometry of the antenna as a major factor for the choice between the high-number of CAD for antenna design, and some time is devoted to the limited number of wireless and radiopropagation tools available in the market.

E. *Fabrication and Measurement of Antennas*

As a final step, the manufacturing of planar and microstrip antennas, as well as the measurement of their radiation parameters, can be made by employing high-frequency milling machine and SMD tools, starting from CAD student's simulations. This stage is understood as a final evaluation of the maturity of the student, and lead to results as shown in Figure 4.

Figure 4. Example of a 2.4 GHz patch antenna.

IV. Discussion and Conclusions

The experiences that have been presented in Sections II and III have been developed during various semesters, and a continuous effort is being made to provide the students the best possible education in the subjects related to microwave and radiofrequency guided and wireless communications. Working together, efforts have been summed to have a laboratory as functional as possible.

The laboratory contains a couple of two-port VNAs, with their corresponding calibration kits and RF probes, six couples of microwave generators and spectrum analyzers, a noise figure analyzer, a milling machine, and a PC for every student.

With this equipment, during two semesters, the students are able to work in the laboratory under an expert supervision. These are the main abilities they acquire during this period:

1. Operation of specific high-frequency equipment. Specifically, they learn how to use the VNAs to characterize both multiport circuits and monoport ones (antenna), including the appropriate calibration techniques for each of them.
2. Simulation of microwave guided and wireless circuits, including both commercial and home-made simulators, and making use of both electromagnetic simulation schemes and model-based tools.
3. In-depth knowledge of the full "design to characterization" RF engineering process, including the simulation, optimization and fabrication steps.

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