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Method of measurement of radiofrequency and microwave electronic systems (2022)

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***Abstract*—In this work, a didactic laboratory method for measuring electronic radiofrequency and microwave systems, called RFLabKit, was developed. From the research of the state of the art of didactic laboratory solutions for radiofrequency, it can be concluded that there are no self-powered solutions through RF connections and usually require expensive professional measurement equipment. These solutions form the basis for building the requirements of this work. The solution design comprises three essential areas: hardware, communications and software. In the hardware project, several circuits are designed using software tools for simulating electronic circuits and radiofrequency circuits, and for electromagnetic simulation. The SoC microcontroller used in the solution is also analyzed and discussed. Four didactic demonstration modules were developed, PLL module (phase-capture loop), AMP module (amplifier), FIL module (filter) and DET module (RF logarithmic detector) and a software application called management system (SGE) was developed, for managing the modules, obtaining measurements and presenting results. The experimental results of the modular board are in concordance with those of the simulation, the PLL and DET modules were calibrated and the cascade connections of the various modules (PLL, FIL, AMP and DET), in different topologies, allowed the analysis of the solution's performance. The experimental results demonstrate the quality of the measurement method, proving the accuracy of measurements compared to those obtained by a VNA.**

***Index Terms*— calibration, didactic laboratory, measurement system, microwave, radio frequency, RF laboratory kit.**

I. INTRODUCTION

IN the field of radio frequency and microwave electronics teaching, practical learning takes place through software simulations or laboratory measurements of test circuits. Regarding the first case, the ADS program – PathWave Advanced Design System [1], which allows the simulation of numerous parameters of a circuit in an extensive way. With regard to laboratory measurements, given the high cost of equipment for high frequencies, they are often overlooked in the face of simulation, creating a gap in practical knowledge that is essential for learning engineering in these areas.

A. Problem

Learning radio frequency and microwave circuits, although well supported by theoretical foundations, from a perspective of extending to practical knowledge, requires the use of extremely sophisticated laboratory equipment. Since any of the more complex equipment is formed by a large set of simple modules, the principle of creating a fully modular measurement system, allows for a better adaptation of teaching to the complexity of laboratory experimentation.

B. Proposal

The challenge posed was to build a modular, uniform and low-cost concept for carrying out laboratory measurements of radiofrequency and microwaves, involving several typical circuits (especially amplifiers, filters, oscillators and detectors), performing different types of measurements without use of expensive measuring equipment and with the possibility of establishing wireless communications for centralizing information.

The implementation of the laboratory method is ensured by a program developed and installed in each module (firmware), and by a management application responsible for the remote control of each module, for automatically obtaining the diagram of the connections between the various modules, for the measurements of the modules and the presentation of measurement results, the latter constituting the main user interface (HMI).

This laboratory method was given the name of RFLabKit.

C. Original contribution

The following are considered as original contributions of this work:

1) Method of measurement of laboratory systems based on communication between measurement modules and a computer in order to simplify and automate the measurement process.
2) Circuit for automatic detection of the connection between the modules and a method for establishing the connection scheme, using a communication process between the modules.
3) Automatic measurement capability of RF/microwave systems without the need for calibration, since each module stores and disseminates information from measurements previously made, such as the s parameters of a two-port network as a function of frequency.

II. STATE OF THE ART

The didactic solutions researched (EDUCTIKA [2], EXSTO [3], MINI-CIRCUITS [4]) are based on RF connections and power connections of independent circuits, that is, in addition to having to carry out the connections by

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coaxial cables to form the didactic circuit, it is also necessary to connect the power of some components. EDUCTIKA, EXSTO didactic solutions do not include measuring equipment, so it is essential to purchase these professional equipment, which add a considerable additional cost.

The solution from the manufacturer MINI-CIRCUITS includes the vector analyzer in the didactic kit, therefore having a higher cost than the other solutions, however, it has a lower cost than what is necessary for a professional measuring equipment, although it is less accurate.

III. RFLabKit Design

In the system design, the didactic laboratory solution was divided into 3 blocks (Fig. 1), the management system (SGE), the modular measurement system (SMM) and the wireless communications system (SCW).

Fig. 1. General structure of the demo system.

The SMM is the modular solution that allows the assembling of a radiofrequency teaching circuit by connecting several didactic modules (e.g., amplifier, filter, oscillator, detector, coupler, etc.), by means of coaxial cables, which also supply these modules, constituting the experimental teaching base, which is controlled by the SGE.

The modules all have the same structure, with three ports with SMA connectors, differing only in the device under test (DUT), for example, amplifier, filter, oscillator, detector, coupler and others.

The module without the DUT, called modular board (Fig. 2), is divided into two areas, the test area associated with the DUT, mostly RF, and the control area comprising the interface, processing and communication.

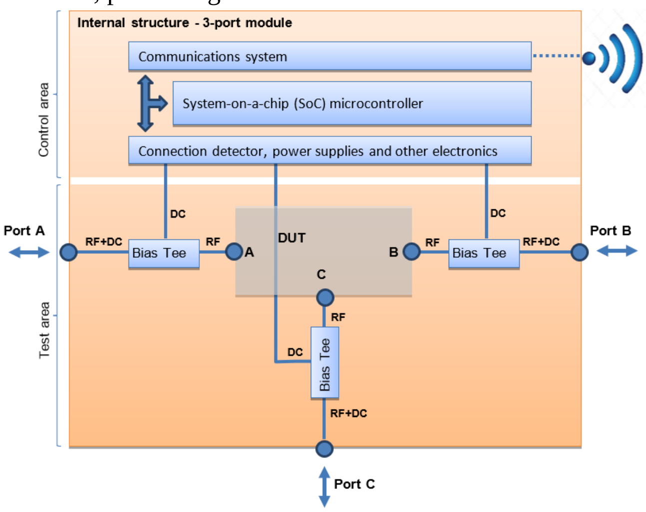

Fig. 2. Internal structure for a 3-port module.

SGE is a graphical application that runs on a PC and is responsible for the management, communication and presentation of results.

The System-On-Chip (SoC) microcontroller chosen for the modular board was the ESP32 [5], in addition to the common features of a microcontroller, such as I/O, DAC, ADC, serial communication and SPI, it has the ability to be programmed through a high-level language, such as the MicroPython [6] language which is the efficient implementation of the Python version 3 [7] language on a microcontroller, takes up few resources (e.g., memory and processing), and includes wireless communication (SCW). The advantage of using a high-level language is that they are easier to read, write, and maintain, so they are faster in firmware deployment.

The modular boards are powered by the same connection cable as the RF signal and the separation of the RF signal from the DC signal is carried out through a Bias Tee circuit. In the designing of this circuit, capacitors and coil were calculated to cover a working frequency band between 1GHz and 3GHz. The ADS program was used to simulate the circuit, however it was necessary to electromagnetically model the coil and the SMA sockets (external and internal) through the CST program [8].

Figures 3 and 4 represent the simulation results of the electric and magnetic fields of the CST program at the surface of the external SMA socket and internal SMA socket respectively, for the frequency of 2GHz, where the area of greatest impact of the discontinuity existing in the SMA sockets was identified, caused by the transition between the coaxial and the microstrip.

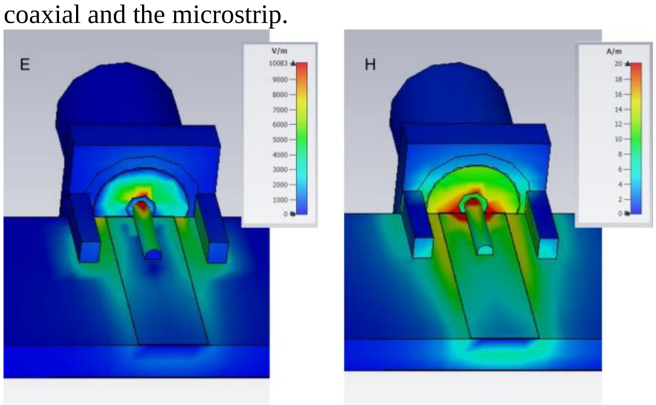

Fig. 3. Simulation results for the electric (E) and magnetic (H) surface fields for 2GHz.

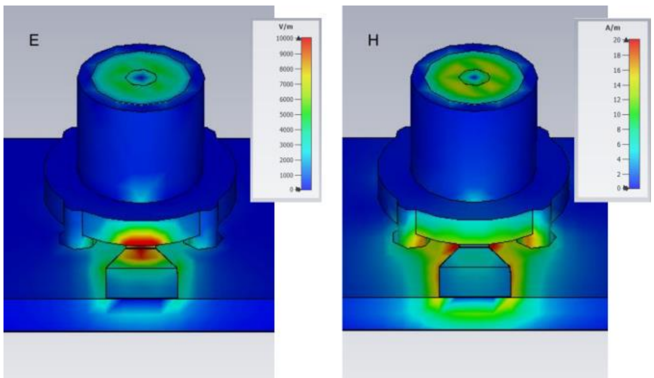

Fig. 4. Simulation results for the electric (E) and magnetic (H) surface fields for 2GHz.

The s parameters of the sockets were obtained through the CST simulation and it was concluded that the internal SMA socket has about twice the losses of the external SMA, this situation is justified by the fact that the internal socket has an angle of 90º with a the coaxial/microstrip.

Fig. 5 shows the results of the simulation of the magnetic field of the CST program at the surface of the transverse plane to the coil, for the frequency of 2GHz.

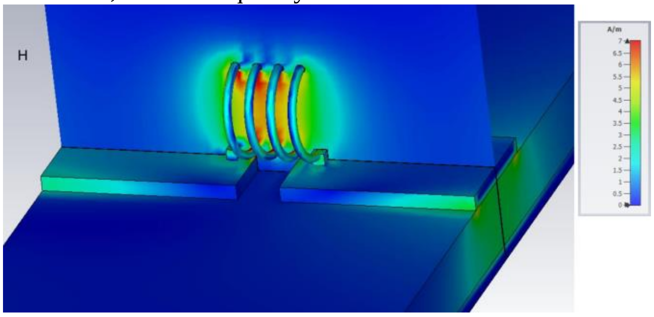

Fig. 5. Simulation results for magnetic field (H) to 2GHz transverse plane surface.

In the analysis of the s parameters of the coil obtained through the CST program, it is concluded that the coil cannot be modeled by a simple inductance in the ADS, being inductive up to the resonant frequency and capacitive from there. Again, these parameters were used in the ADS simulation.

The presentation by SGE of the scheme of the didactic circuit diagram with modules is performed automatically. On the modular board, a circuit was designed that works like a switch that, when opened, causes a small voltage drop between two ports (e.g., PortA/PortB). The SGE, through an algorithm, sends a command to the module to open the switch and the other modules that are connected to this port detect this small voltage drop, the algorithm processes this information and builds with the other modules the scheme of the didactic circuit in an automatic way.

Were designed 3 fixed voltage sources (3.3V, 5V and 12V) with switching regulators DC-DC, and 2 variable voltage sources (0V to 20V) controlled by the SoC microcontroller through DAC. Finally, were designed the Reset circuit of the SoC microcontroller, the power failure detector (burnout) and the LED circuits.

After having designed and dimensioned the modular board, 4 boards were produced: PLL module (phase capture loop, Fig. 6), AMP module (amplifier, Fig. 8), FIL module (filter, Fig. 7) and DET module (logarithmic RF detector).

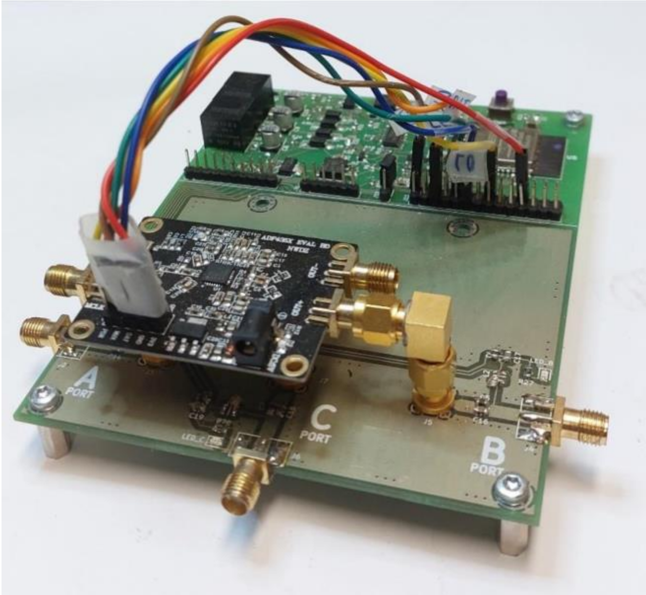

Fig. 6. Photo of the PLL module.

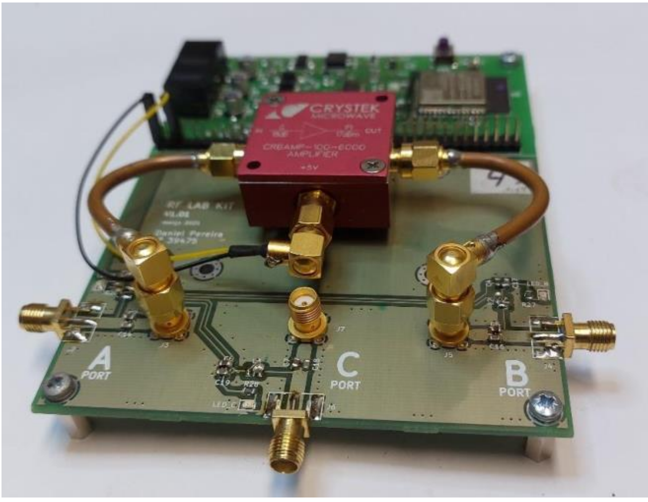

Fig. 7. Photo of the AMP module.

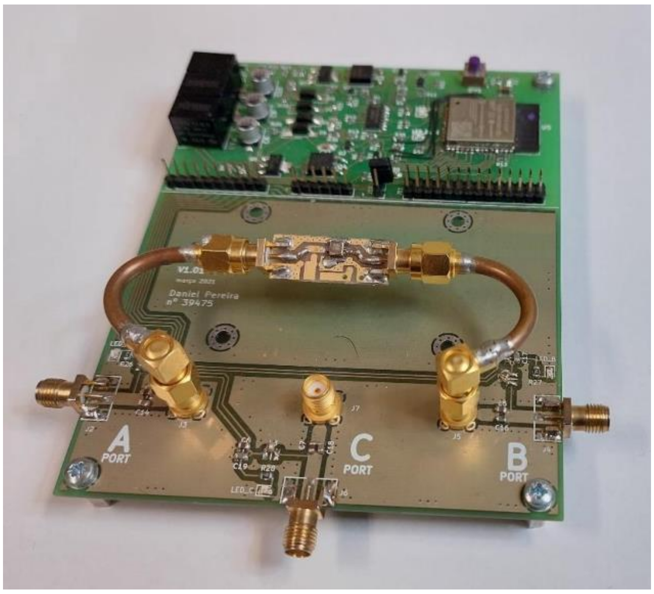

Fig. 8. Photo of the FIL module.

IV. Experimental Results

To measure the Bias Tee of the modular board, the VNA (Vector Network Analyzer) model PicoVNA 106 [9] (300kHz to 6Ghz), from the manufacturer Pico Technologies [10] was used. VNA port 1 was connected to the board's external SMA (RF+DC) socket and VNA port 2 was connected to the board's internal SMA (RF) socket, as shown in Fig. 9.

Fig. 9. Modular board Bias Tee measurement assembly.

Fig. 10 shows a match between the theoretical and experimental results, obtaining in the measurements a maximum loss of 0.65dB in the 508MHz to 3GHz band, when in the simulation this value was 0.52dB, i.e., a difference of 0.13dB.

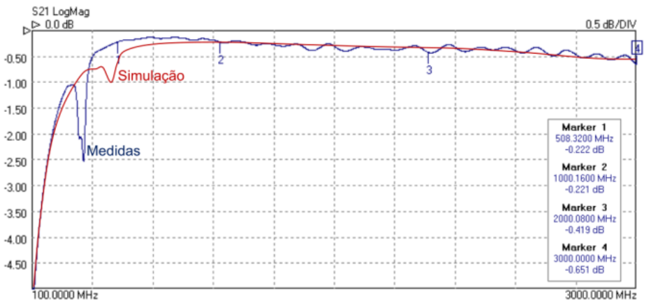

Fig. 10. Measurements and simulation of modular board gain (|s21|) in external/internal port A.

Fig. 11 and Fig. 12 show the reflection coefficients measured by the VNA, respectively of the input (s11) and the output (s22), in comparison with the simulated ones, concluding that the maximum reflection factors measured at the input and output are in agreement with those of the simulation, less than -14dB.

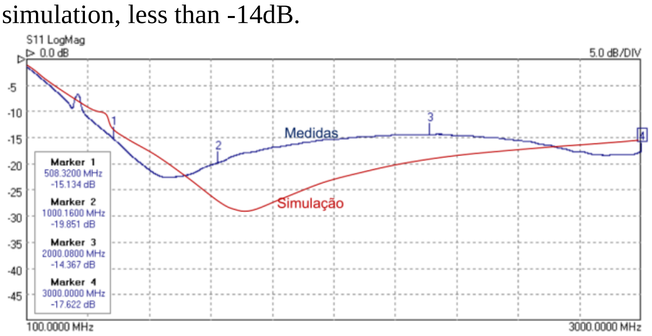

Fig. 11. Measurements and simulation of the modular board input reflection factor (|s11|) in the external/internal port A.

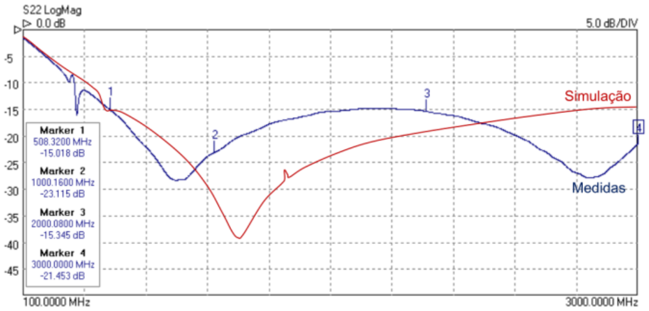

Fig. 12. Measurements and simulation of the modular board output reflection factor (|s22|) in the external/internal port A.

For the calibration of the PLL module the scheme in Fig. 13 was used. The PLL board has two outputs, out+ and out-, which were found to have signals with very close powers as long as both have a 50Ω load. The external Port B of the PLL module was connected to the Agilent N9320B spectral analyzer [11], the internal Port B of the PLL module was connected out+ of the PLL board, and the out- output of the PLL board was connected to a 50Ω load.

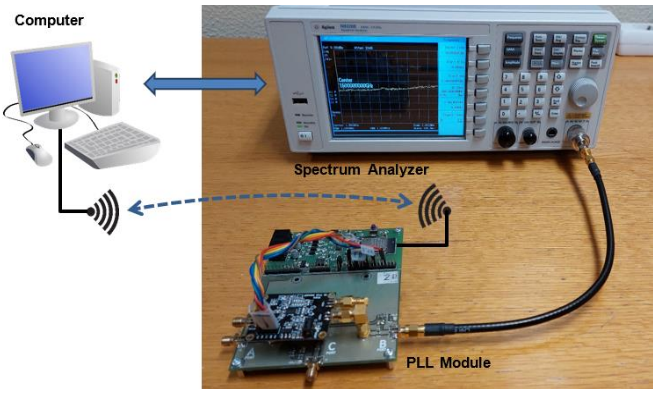

Fig. 13. Calibration circuit of the PLL module.

In the DET calibration, the PLL module was used to generate the signal and the spectrum analyzer to measure, since the PLL will work as a generator in the measurement system. Fig. 14 illustrates the connection scheme for the calibration measurements.

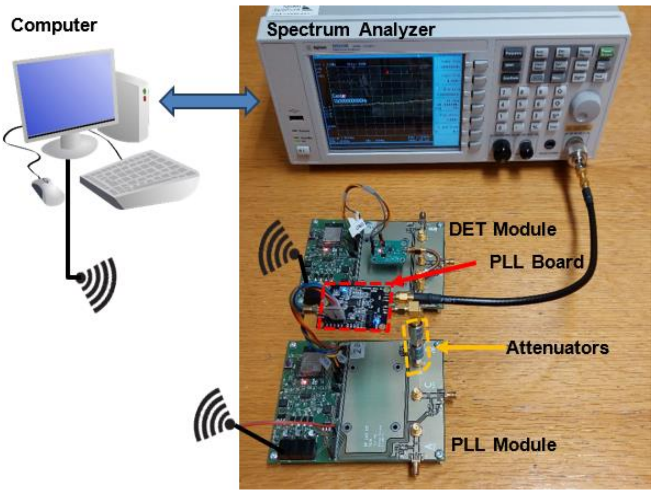

Fig. 14. Det module calibration connection scheme.

A calibration of the variable power supply was also performed, varying the DAC word from 0 to 255 and measuring the power output voltage, using the multimeter BK

Precision 2138E [12].

The result of these calibrations was saved in the module's firmware, and this information is made available by communication to the SGE right after the module is powered up.

In order to characterize the performance of the system in terms of operating speed, the following operating times were analyzed:

- Average start-up time of the module is 14s, however the time of the PLL module is slightly higher (200ms), given that the initial configuration of the PLL is more complex.
- Average detection time of the modular circuit scheme, the measured results are presented in Table I, there is a detection time of 2.3s for a module and an approximately linear increase as a function of the number of modules ($t \approx 1.9n + 0.6$).

TABLE I
AVERAGE FREQUENCY SCAN TIME

Circuit	Number of modules	Average time [s]
PLL	1	2.3
PLL + DET	2	4.3
PLL + FIL + DET	3	6.4
PLL + AMP + FIL + DET	4	7.8

- Average frequency sweep time, by number of samples (number of averages ADC takes to improve accuracy) and number of points (one for each frequency) are shown in Table II. It is verified that each sample is measured in approximately 178µs, it is verified that each sample is measured at approximately 178µs, there is a compromise between the number of points/samples and the total measurement time, 201 points with 100 samples should be chosen when a quick measurement is required, and 201 points with 10000 samples for a measurement with reasonable precision.

TABLE II
AVERAGE FREQUENCY SCANNING TIME

Samples	Number of points (mm:ss)				
	21	51	201	501	1001
10	00:03	00:03	00:09	00:21	00:39
100	00:03	00:05	00:14	00:35	01:04
1 000	00:06	00:10	00:37	01:31	03:00
10 000	00:29	01:09	04:29	11:07	22:10

Fig. 15 represents the RFLabKit scheme for the demonstration of the measurement method of the FIL module, with indication of the ports and their connections.

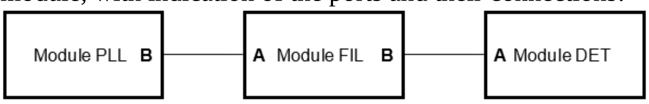

Fig. 15. FIL measurement assembly (PLL+FIL+DET).

The SGE was configured to generate the sweep of frequencies between 1475MHz to 1675MHz, without attenuation (0dB), PLL power -10dBm, 1001 points and 10000 samples.

Fig. 16 plots the filter frequency response measured by RFLabKIT, Network Analyzer (VNA) and manufacturer data.

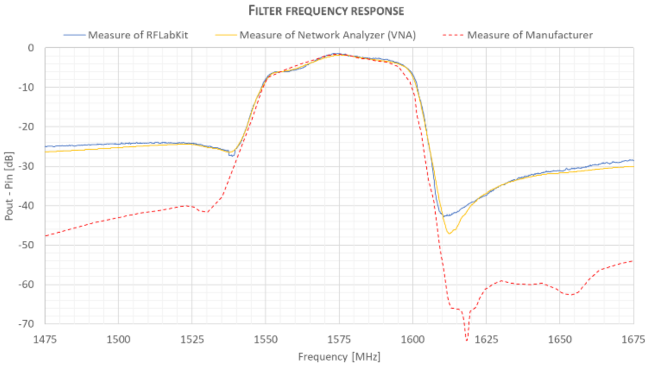

Fig. 16. Filter frequency response graph.

It was concluded that the measurement of RFLabKit gave a result very close to the measurement with the VNA, confirming the accuracy of the measurement system performed. Regarding the filter manufacturer's data, there is also agreement with the measurements in the pass band, with a reasonable difference in the attenuation band (between 20 and 25dB), and this difference must be associated with the fact that the board on which it is mounted the GPS filter does not have the same quality as the measurement mounting system used by the manufacturer to obtain its measurements.

Fig. 17 represents the RFLabKit scheme for the demonstration of the measurement method in the AMP module.

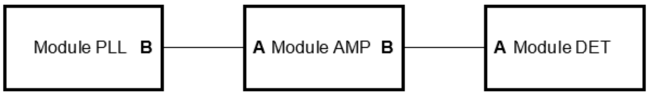

Fig. 17. AMP measurement assembly (PLL+AMP+DET).

The SGE was configured to generate sweep frequencies between 1475MHz to 1675MHz, attenuation 24dB, PLL power -10dBm, 1001 points and 10000 samples.

Fig. 18 illustrates the filter frequency response graphs measured by RFLabKIT, Network Analyzer (VNA) and Manufacturer.

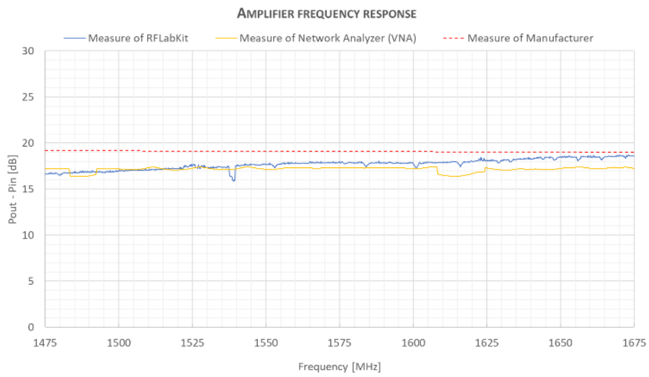

Fig. 18. Amplifier frequency response graph.

The result of the measurements is consistent with the conclusions obtained in the previous paragraph for the AMP, in which the measurements in RFLabKit are very close to those performed by the VNA and the data presented by the manufacturer is slightly better (with a maximum difference of 1.5dB).

Fig. 19 represents the scheme of RFLabKit to demonstrate the measurement method in the FIL module in a cascade with the AMP module.

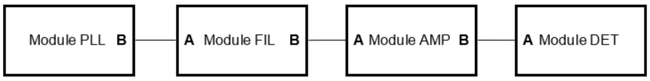

Fig. 19. Fil measurement assembly plus AMP (PLL+FIL+AMP+DET).

The SGE was configured to generate sweep frequencies between 1475MHz to 1675MHz, attenuation 12dB, PLL module power -7dBm, 1001 points (or a step of 200kHz) and 10000 samples per point.

Fig. 20 illustrates graphs of the filter frequency response measured by RFLabKIT and Network Analyzer.

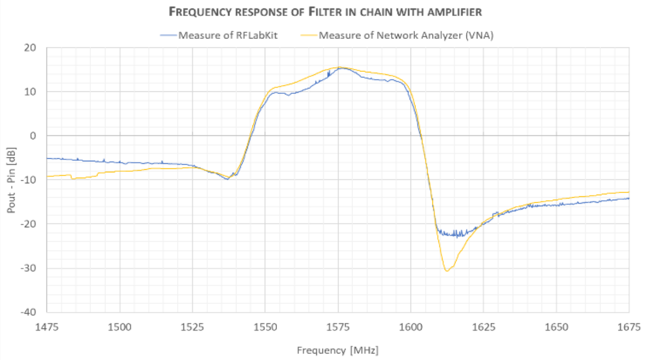

Fig. 20. Frequency response graph of amplifier in cascade with amplifier.

It is concluded, again, that the RFLabKit measurement gave a very approximate result to the measure with the VNA.

V. CONCLUSIONS

The objective of this work was to develop a method for measuring electronic radiofrequency and microwave systems for a didactic laboratory solution, which was called RFLabKit. The following original contributions are considered in this work: the method of measurement of laboratory systems based on communication between measurement modules and a computer in order to simplify and automate the measurement process; circuit for automatic detection of the connection between the modules and a method for establishing the connection scheme, using a communication process between the modules; and automatic measurement capability of RF/microwave systems without the need for calibration, since each module stores and disseminates information from measurements previously made, such as the s parameters of a two-port network as a function of frequency.

In order to achieve the objective mentioned above, in Chapter 2, we started by carrying out a state-of-the-art research in order to analyze and discuss the various existing didactic laboratory solutions, reaching the conclusion that the solutions are difficult to find, most of the solutions do not include measuring equipment has to be purchased separately and are presented as high-cost solutions.

In Chapter 3, the development of the laboratory solution was planned, for this, we started by identifying the requirements and proceeded to the design of the system.

In the development of the modules, the main elements were analyzed and discussed: SoC microcontroller, Bias Tee circuit, connection circuit between ports, fixed and variable power supply circuits, reset circuit, power failure detection circuit and LED circuits.

The ESP32 microcontroller SoC was chosen because it has built-in Wi-Fi communication and allows it to be programmed through a high-level language, such as the MicroPython language [6] which is the efficient implementation of Python version 3 [7] in a microcontroller and takes up few resources (e.g., memory and processing).

In the design of the Bias Tee circuit element, the radiofrequency circuit simulation tool ADS [1] was used, however it was necessary to electromagnetically model the coil and the SMA sockets (external and internal) through the CST program [8], to get the respective s parameters. In the electromagnetic simulation, it was concluded that the area of greatest impact of the discontinuity existing in the SMA chips is the one caused by the transition between the coaxial and the microstrip. It was also verified that the internal socket has about twice the losses of the external socket, as it has a coaxial/microstrip transition with an angle of 90º. Regarding the coil, it was concluded that it cannot be modeled by a simple inductance in the ADS, as it is inductive up to the resonant frequency (2.08GHz) and capacitive from there.

Four demonstration modules were built: phase-looked loop module (PLL), amplifier module (AMP), filter module (FIL) and RF logarithmic detector module (DET). This part of the work was very motivating, as it allowed the acquisition of practical skills, particularly, in the design of the project, in the choice of components, in the design of the printed circuit (PCB design and routing), and in the assembly and soldering of the components.

In Chapter 4, the Bias Tee circuit was analyzed and experimentally discussed, in comparison with the results obtained in the simulation. It was concluded that the simulation performed in the ADS (with the parameters obtained from the sockets and the coil in the electromagnetic simulation with the CST) is in agreement with the experimental results.

In the calibration of the PLL module, it was verified that there is an attenuation of 6dB in the power in the module compared to information given by the manufacturer, so the powers indicated by the manufacturer are for the differential output. Regarding the DET calibration, it was concluded that it has a dynamic range of approximately -51dB, which is a reasonable dynamic range for the developed system.

An analysis of the performance of the system with the demo modules was carried out, concluding that the registration of the modules in RFLabKit, after being turn on, occurs in about 14 seconds; the schema detection time by the management system (SGE) is linearly dependent on the number of modules, with approximately 2 seconds per module (7.8 seconds for 4 modules); and finally the frequency sweep time depends on the number of points and the number of samples per point (averaging for greater precision), being a good compromise between precision and speed the option of 201 points with 100 samples per point, and 201 points with 10000 samples for a more accurate measurement.

Finally, the experimental operation of the measurement method was analyzed and discussed, first by measuring the cascade of PLL+FIL+DET modules, secondly with the cascade of PLL+AMP+DET modules and thirdly with the cascade of PLL+FIL+AMP+DET modules, having verified that the results obtained experimentally are very close to those obtained by means of a VNA equipment.

TABLE III shows the main characteristics of the present work, in comparison with the didactic laboratory solutions resulting from the evaluation of the state of the art.

It verified that RFLabKit represents an advantageous and innovative solution, highlighting the fact that it fits into emerging technologies with greater expression, such as the IoT; allow automatic detection of the schematic; and ensure the power supply to the modules through the coaxial connections.

TABLE III
COMPARISON BETWEEN RFLABKIT AND SOLUTIONS SEARCHED IN THE STATE OF THE ART

Features\Solutions	RFLabKit	Edukita	Exsto	Mini-Circuits
Operation frequency	1 a 3GHz	DC a 3GHz	DC a 3GHz	100MHz a 6GHz
Technology	Wi-Fi, IoT, MQTT	Microstrip	Microstrip	Coaxial modular coupler
Mounting	Modular	Microstrip	Microstrip	Modular
Type of modules	Passive and active circuits	Passive and active components	Passive and active circuits	Passive components in the VNA and passive and active circuits in the DUT
Modules connections	Coaxial	Magnetic puzzle	Coaxial	Coaxial
Type of connectors	SMA	Don't have	SMA	SMA
Measurement equipment	Yes	Not included	Not included	Yes
Software	Yes	-	-	Yes
Calibration Kit	Self-calibrated	-	-	Yes
DUT power supply	Internal (fixed or variable)	External	External	External
Circuit detection	Automatic	-	-	-

VI. Future Work

In order to take advantage of the development of this project, it is worth highlighting the possibility of its evolution in future projects:

- The modular board Bias Tee circuit can be designed for a higher band, for example up to 6GHz.
- The SGE software can also have the capability to simulate the didactic circuit, assembled with the modules, through the s parameters saved in the modules, without the need to perform a measurement, in this case the comparison between the simulation and the experimental results was obtained.
- Construction of a set of modules and respective software to measure reflection coefficients (parameters $|S_{11}|$ and $|S_{22}|$).
- Construction of new didactic test modules, for example, low pass filter, high pass filter, mixer, power amplifier, coupler, power divider and others.
- Development of a set of dynamic didactic laboratory guides in which the application SGE guides the student in carrying out the work. These guides should focus on certain topics, such as measuring the gain of an amplifier or filter, measuring the 1dB compression point of a power amplifier, or measuring a mixer.

VII. References

[1] Keysight Technologies, "PathWave Advanced Design System (ADS) | Keysight," Keysight Technologies, [Online]. Available: https://www.keysight.com/zz/en/products/software/pathwave-design-software/pathwave-advanced-design-system.html. [Accessed 2022].

[2] Elliptika, "Welcome to Eductika by Elliptika | Eductika by Elliptika," Elliptika, 2008. [Online]. Available: https://eductika.com/. [Accessed 2022].

[3] "Exsto | Bancadas Didáticas, Cursos e Soluções para Empresas," Exsto Tecnologia, [Online]. Available: https://exsto.com.br/. [Accessed 2022].

[4] Mini-Circuits, "Mini Circuits - Global Leader of RF and Microwave Components," Mini-Circuits, [Online]. Available: https://www.minicircuits.com/. [Accessed 2022].

[5] Expressif, "ESP32-WROOM-32D (4MB) Espressif Systems | RF/IF and RFID | DigiKey," Expressif, [Online]. Available: https://www.espressif.com/sites/default/files/documentation/esp32-wroom-32d_esp32-wroom-32u_datasheet_en.pdf. [Accessed 2022].

[6] George Robotics Limited, "MicoPython," George Robotics Limited, [Online]. Available: https://www.micropython.org. [Accessed 2022].

[7] Python Software Foundation, "Python.org," Python Software Foundation, [Online]. Available: https://www.python.org. [Accessed 2022].

[8] Dassault Systems, "CST STUDIO SUITE Student Edition | 3DEXPERIENCE Edu," Dassault Systems, [Online]. Available: https://edu.3ds.com/en/software/cst-studio-suite-student-edition. [Accessed 2022].

[9] Pico Technology, "PicoVNA 6 GHz and 8.5 GHz Vector Network Analyzers," Pico Technology, [Online]. Available: https://www.picotech.com/vector-network-analyzer/picovna/picovna-series. [Accessed 2022].

[10] Pico Technology, "PC Oscilloscope, Data Logger & RF Products | Pico Technology," Pico Technology, [Online]. Available: https://www.picotech.com/. [Accessed 2022].

[11] Keysight Technologies, "Datasheet N9320B RF - Spectrum Analyzer (BSA)," Keysight Technologies, [Online]. Available: https://www.keysight.com/zz/en/assets/7018-02996/data-sheets/5990-8119.pdf. [Accessed 2022].

[12] BK Precicion, "Manual - BK Presicion 2831E," [Online]. Available: https://bkpmedia.s3.amazonaws.com/downloads/manuals/en-us/5491B_manual.pdf. [Accessed 2022].