Cost-Effective Standing Wave Ratio Meter

Ana Đ. Ćupurdija, *Member, IEEE*, and Slobodan V. Savić, *Member, IEEE*

***Abstract*—This paper presents a cost-effective and compact realization of a standing wave ratio (SWR) meter designed with commercially available low-cost components. The SWR meter was tested by measuring voltage standing wave (VSW) and complex impedance with slotted coaxial transmission line, and both results were in good agreement with the simulated circuit results and measurements done on professional equipment - HP SWR meter and vector network analyzer (VNA). The proposed system presents an affordable and precise SWR meter, but also a valuable educational platform for understanding electromagnetic field distribution along transmission lines.**

***Index Terms*—complex impedance; electromagnetic waves; measuring instruments; slotted coaxial transmission line; standing wave ratio.**

I. Introduction

SINCE their discovery, electromagnetic (EM) waves never lost their significance and the functionality of many modern devices would be unimaginable without them. These devices include mobile phones, laptops, wireless devices, radar systems, etc. Bluetooth and the internet would not exist were it not for EM waves. Therefore, today they represent an irreplaceable means for information transmission and a physical phenomenon whose number of applications will only increase in the future [1].

However, when propagating through different mediums (air, water, dielectrics, ionosphere, etc.) or when guided with different guiding-structures (transmission lines or waveguides), EM waves form certain patterns [2] that are not always quite intuitive and can be hard to visualize, even for an experienced RF engineer. An excellent starting point for analyzing this phenomenon is the graphical representation of standing waves along transmission lines (TLs).

To provide a way for students to better understand the concepts of electromagnetic field distribution, we have designed and realized a compact and affordable standing wave ratio (SWR) meter. This prototype, along with slotted coaxial TL, presents a working principle of SWR measurements in a simple and easy-to-understand manner and also provides relatively precise measuring equipment.

The rest of the paper is organized as follows. In the second chapter, the theory of standing waves is briefly introduced, and the requirements for a functional SWR meter are discussed. In the third chapter, starting SWR meter model and its simulation results obtained via TINA simulator [3] are shown. In the fourth chapter, the design and realization of the SWR meter are presented, along with schematics and printed circuit board (PCB) layout. In the fifth chapter, voltage standing wave (VSW) measurements were done for a transmission line closed with different loads, and these results are compared with the results obtained with a professional SWR meter. In the sixth chapter, unknown load impedances are estimated from the SWR measurements and compared to the results obtained with AWR Design Environment [4] and vector network analyzer (VNA) measurements. Finally, in the seventh chapter, conclusions are drawn.

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II. Standing Waves Measurement Theory

Two-wire transmission line represents a pair of conductors carrying an EM wave. The theory of EM propagation along TLs is explained in detail in [2, 5].

When exciting a TL with a signal from a generator connected at its one end, voltage and current waves are formed along the TLs axis. In the steady state, when all excitations and all responses are single-frequency signals, on the transmission-line there are, generally, two waves traveling in opposite directions. These waves are progressive (traveling) waves, and their superposition forms the standing wave. The effective (rms) value of the standing wave is a function of the generator's power, the complex impedance of a load which ends TL on the other end, the characteristic impedance of the TL, and it (generally) changes along the TLs axis. When the TL is opened on its other end, all of the incident power is reflected from the open end. When the TL is ended with a lossy load, some of the excited power is dissipated in the load, making the reflected wave have less energy than the incident wave.

The parameter that integrally describes standing wave is SWR, defined as

$$SWR = \frac{U_{\max}}{U_{\min}}, \tag{1}$$

where $U_{\max}$ and $U_{\min}$ are the maximum and the minimum effective value of the VSW along TL's axis, respectively. The standing wave ratio can be in the range $[1, \infty)$. If SWR equals one, the load is matched to the TL, and there is no reflection. If SWR tends to infinity, all the energy of the incident wave is reflected.

One way to measure SWR is to use slotted coaxial TL and measure EM field or voltage along TL's slot with a short probe. The probe should be long enough to detect high enough voltage, and short enough not to (locally disturb) the

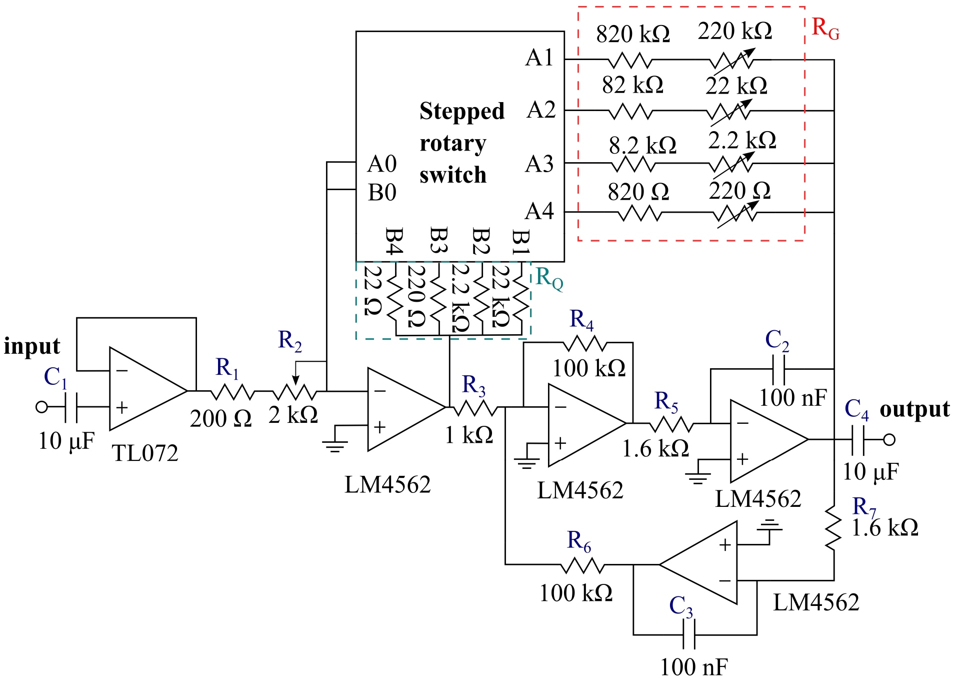

Fig. 1. SWR meter schematics.

EM field. The voltage measured with this probe is proportional to the electric field in the slotted coaxial TL and is connected to the square-law diode detector [6]. This diode is usually a germanium diode, which works in the quadrature region of the I-V (current-voltage) characteristics. Therefore, the signal obtained with this diode detector is proportional to the square of the VSW effective value. This signal is then further processed by the SWR meter. Keeping all of this in mind, we can define SWR meter functionalities and parameters of interest. Also, please note that in the measurement set up that we are using, shown in Fig. 5, incident voltage (field) is modulated with a signal of a fixed, preferably low, frequency (i.e., around 1 kHz), that represents an envelope of the high-frequency signal that form the standing wave. The incident signal is amplitude modulated because when working with an unmodulated signal, the output of the diode detector would be a DC voltage which is generally susceptible to high measurement errors due to the existence of the DC offset in systems. Since the amplitudes of the measured unmodulated signal are relatively small (about 1 mV), even a small DC offset could introduce significant measurement errors. By measuring the effective value of the detected 1 kHz envelope, the effective value of the high-frequency signal could also be measured. Expected values for the signals at the output of the probe are in the range 1-10 mV, so the designed SWR meter should have a significant gain. Based on all of this, we decided to design the SWR meter as an active bandpass filter, with the center frequency around 1 kHz. The proposed design has four gain stages (times 1, 10, 100, and 1000), while also having an option to fine-tune gain to any value in these ranges. Finally, the Q factor of the filter needs to be set accordingly, so the circuit can filter unwanted harmonics and harmonic components, but also not be too selective. The Q factor needs to be independent of the set gain, and the gain and the Q factor of the system should be independent of impedances connected at its input and output.

III. Simulation Results

The main part of the circuit (bandpass active filter) was designed starting from [7] and by using the operational amplifier LM4562. This chip is made by Texas Instruments, so simulation of the circuit was done in their TINA simulator [4]. The schematics used for simulation are shown in Fig. 1, while omitting the stepped rotary switch. This schematic is the main building block for the SWR meter.

The circuit shown in Fig. 1 is excited with an AC generator at 1 kHz. The gain is set with resistors R_1, R_2 and R_G, and is given by the formula

$$G = \frac{R_G}{R_1 + R_2}. \tag{2}$$

The Q factor is set with the resistors R_G and R_Q, given by the formula

$$Q = \frac{R_G}{R_Q}. \tag{3}$$

In the mentioned configuration, without the stepped rotary switch, the Q factor depends on the gain (since they have a common factor of the resistor R_G). This is not a desirable feature, hence, stepped rotary switch was introduced in the PCB design step. The circuit is intended to operate in a single-frequency mode, just like the professional HP SWR meter, which is used for comparison. This central bandpass frequency is set with capacitor C_2 and resistor R_5 (aka C_3 and R_7), given with the formula

$$f_c = \frac{1}{2\pi R_5 C_2} \tag{4}$$

Simulation results are shown in Table I, for four gain configurations. The resistor R_Q was changed along with R_G, so that the Q factor is constant, and is set to be around $Q = 45$. These results confirmed that the designed circuit works as expected, so we proceeded with the board design and fabrication.

TABLE I
GAIN SIMULATION RESULTS

Resistor R_G	1 kΩ	10 kΩ	100 kΩ	1 MΩ
Theoretical gain	1	10	100	1000
Simulated gain	1.13	10.13	100.12	993.76

IV. SWR METER PROTOTYPE

Based on the schematics in Fig. 1, PCB layout was made and is shown in Fig. 2. The purpose of the buffer at the input stage is to make the input impedance of the circuit independent from the gain and Q factor. The output stage of the meter is not buffered. When the output current is below the maximum value stated in the datasheet (26 mA), practically there is no distortion in the output voltage. In order not to exceed the current limit, in the worst case scenario for output voltage of 1 V, the load impedance must be greater than 40 Ω, which is well below input impedances for all commercial multimeters.

The resistor R_2 is a potentiometer, so the gain can be fine-tuned to any value in the predefined ranges. Predefined ranges of 1, 10, 100, and 1000 are set using the stepped rotary switch, with three pins and four positions. This switch changes the resistors used for setting the gain (R_G in Fig. 1). Also, using this switch, the resistors used for setting the Q factor are simultaneously switched when setting the gain, so the Q factor would stay constant when the resistor R_G changes. For the measurements shown in Section V, the Q factor is set around $Q = 45$.

The branches with resistors used for gain setting contain one fixed resistor and one trimmer potentiometer. This way, even with component tolerances, the gain can be fine-tuned to exactly match the predefined values (1, 10, 100, and 1000). The made prototype has its stage for power supply (converting the AC voltage of 230V into ±5 V DC needed for the operational amplifiers) and also has added overcurrent protection, in a form of a fuse.

The final prototype is shown in Figs. 3 and 4, where it can be seen that the final prototype is compact and practical to use. With this design, we satisfied all of our requirements for a functional SWR meter, so we proceeded with the measurements.

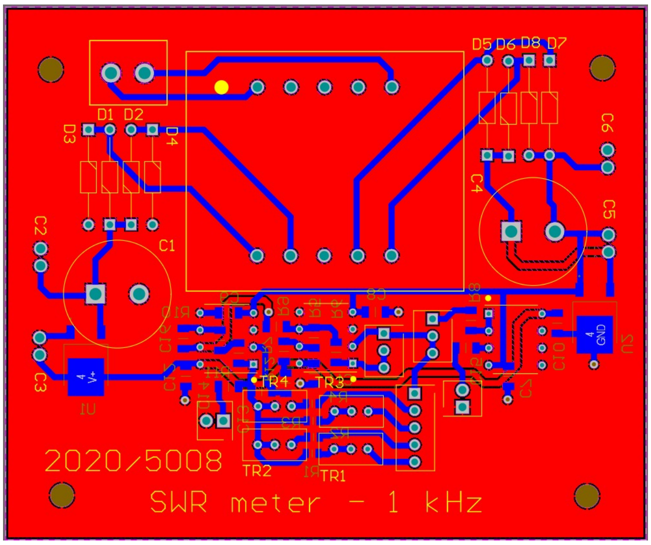

Fig. 2. Printed circuit board layout of the SWR meter.

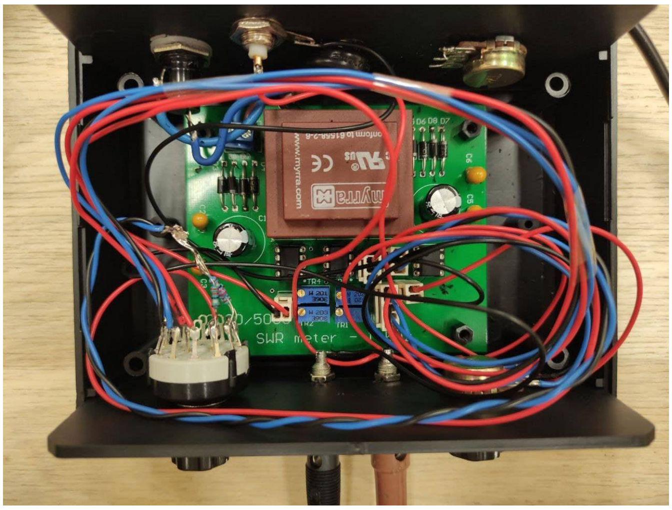

Fig. 3. The prototype of the SWR meter.

V. MEASUREMENTS ON A SLOTTED COAXIAL TRANSMISSION LINE

The first measurement to test the functionality of the SWR meter was made with an oscilloscope, where the input and the output voltages are observed to set the desired gain to 1, 10, 100, and 1000 with trimmer resistors. The effective value of input voltage is set so that the output can be easily visible on the oscilloscope for a given measurement, but also to prevent the operational amplifiers from entering the saturation. The gain was then fine-tuned to the wanted values with trimmer resistors.

After setting the gains to the desired values, measurements on the TL were done. The used TL is a slotted coaxial TL having $Z_c = 50\,\Omega$ characteristic impedance with a probe that could be moved longitudinally along TL's axis. This way the effective value of VSW is measured along TL's axis. The slotted TL we are using has a ruler along its axis, so we will use this ruler for measuring distance along TL's axis. The probe position is controlled with a mechanical knob. The line was excited with a sine wave at 1.4 GHz, modulated with a sine at 900 Hz. This signal was generated by a software-defined radio (SDR) device. The frequency of the envelope at 900 Hz was chosen because, due to the component tolerances, the central frequency of the filter was not exactly 1 kHz. Central frequency was determined by changing the envelope frequency and observing when the maximal gain occurs.

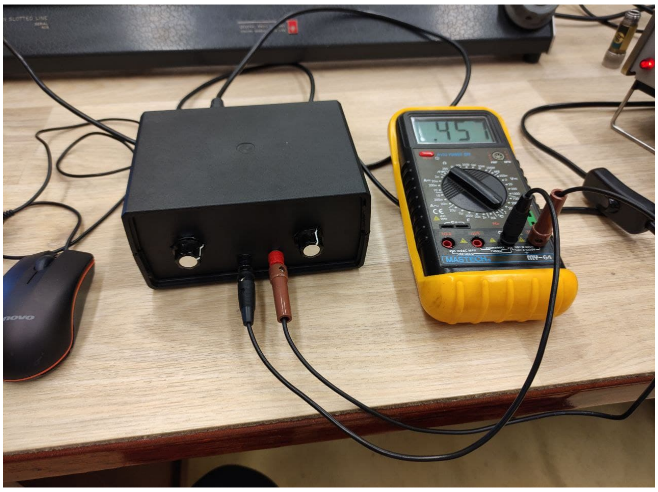

Fig. 4. The prototype of the SWR meter is enclosed in a box and connected to the voltmeter.

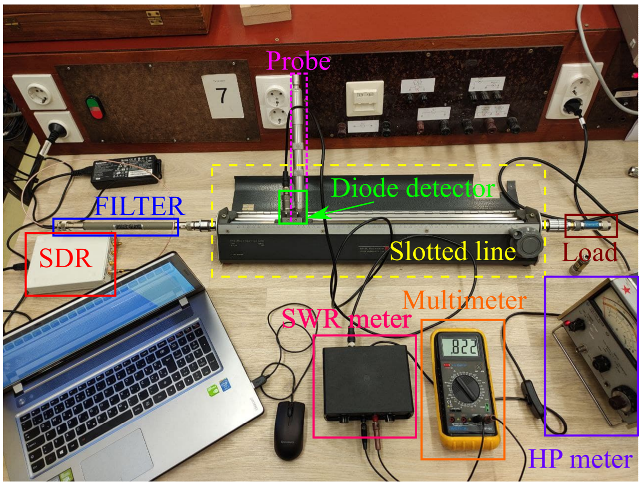

Fig. 5. Complete measurement setup.

To suppress any unwanted signal, at the input of the TL, a coaxial filter was placed, with a cut-off frequency at 2.2 GHz. The effective value of the output voltage of the realized SWR meter is measured with a multimeter, as shown in Figs. 4 and 5. The measurements were done by moving the probe in steps of 5 mm and measuring the VSW effective value in 81 data points. The measurements were done in the distance range from 15 cm to 55 cm at the TL ruler. The same procedure was done when TL was opened at its other end, and when it was terminated with the 6 dB and with the 10 dB loads. These loads are realized as coaxial (6 dB and 10 dB) attenuators, opened at their second end. The SWR meter gain for the measurements is set so that the peak of the VSW corresponds to the effective value of 1 V measured with the multimeter.

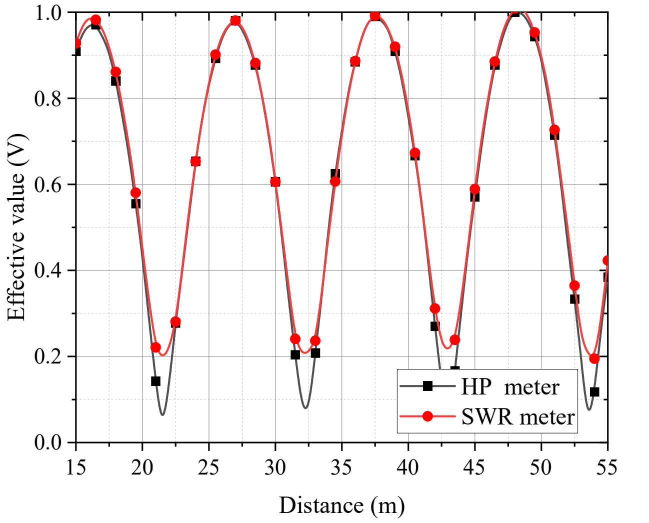

Fig. 6. Comparison of the VSW measurement obtained with designed and professional SWR meter for open-ended transmission line.

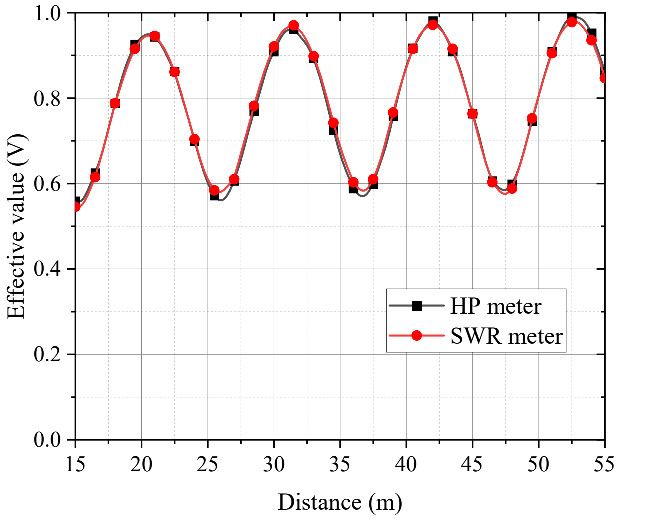

Fig. 7. Comparison of the VSW measurement obtained with designed and professional SWR meter when the transmission line is closed with the 6 dB load.

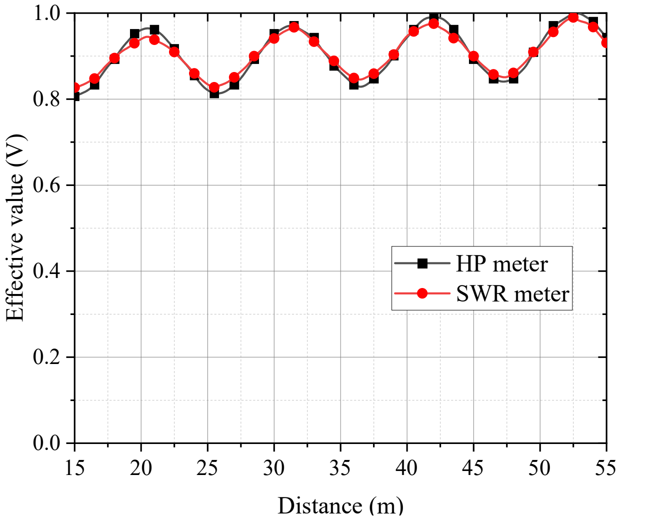

Fig. 8. Comparison of the VSW measurement obtained with designed and professional SWR meter when the transmission line is closed with the 10 dB load.

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For the obtained results to be double-checked, the same set of measurements was done with the professional Hewlett-Packard 415E SWR meter. The entire measurement setup is shown in Fig. 5. The obtained VSW curves for the case of the unloaded TL are shown in Fig. 6, while the obtained curves for cases of 6 dB and 10 dB loads are shown in Figs. 7 and 8, respectively. In the case of the unloaded line, the proposed SWR meter does not have such deep minimums as the professional one. Additionally, for this case, VSW should be equal to zero at its minimum. This is not being the case in Fig. 6 due to, among other, finite number of measuring points along TL's axis. Nevertheless, these two sets of results are in good agreement, and even better when TL is closed with loads (Figs. 7 and 8).

VI. Load Impedance Calculation

The impedances of used loads (6 dB and 10 dB) are firstly estimated based on the fact that these loads are matched coaxial attenuators opened at their second end. Based on this, a simple model for the calculation of their input impedance is assembled in the AWR Design Environment, as shown in Fig. 9. The load which complex impedance we want to measure, labeled as "LOAD" at Fig. 5, is modeled as two short TLs with ideal (matched) attenuator between them. The same model is used for 10 dB load, with a loss parameter of the ATTEN element from Fig. 9 set to 10 dB. The length of used short TLs is estimated experimentally.

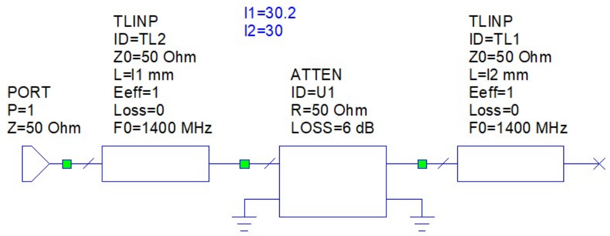

Fig. 9. The simple model of used loads made in the AWR Design Environment.

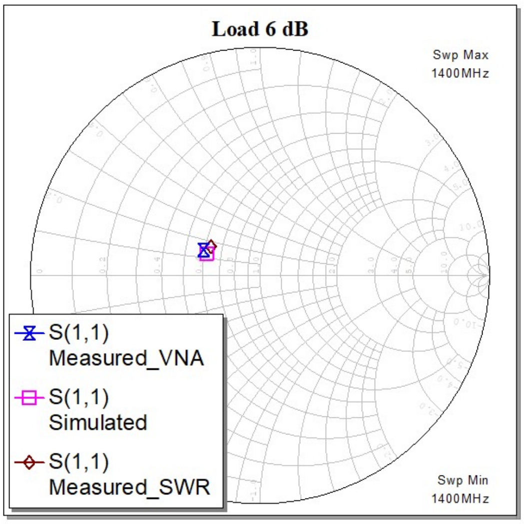

Fig. 10. Smith chart for the 6 dB load.

From the given SWR measurements, using the Smith diagram, load impedances are calculated as described in [5, 8] and compared to the impedances of the loads obtained via simulation and via measurements done on the N5227a Agilent VNA. The results are shown in Figs. 10 and 11 for 6 dB and 10 dB loads, respectively. From these figures, it can be noticed that the obtained results of the load impedances are in excellent agreement for all three sets of results. Therefore, we conclude that the designed SWR meter can be used for the precise determination of unknown impedances.

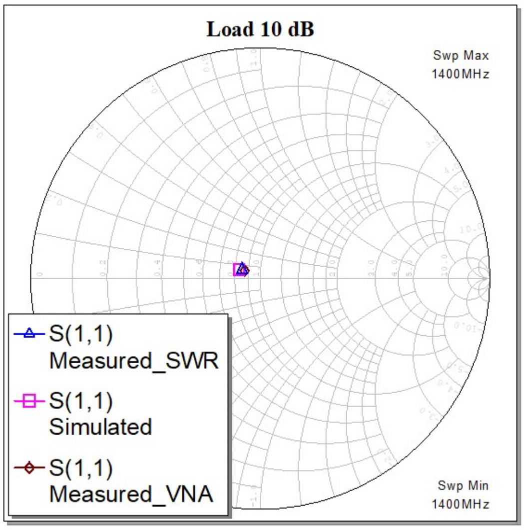

Fig. 11. Smith chart for the 10 dB load.

VII. Conclusion

A compact and affordable prototype for the SWR meter was proposed and realized. Simulation and measurement results are proven to fit well. The realized circuit acts as an active filter with four gain stages (1, 10, 100, and 1000), and the gain can also be fine-tuned to any value in these ranges.

Standing wave ratio measurements were done on a slotted coaxial transmission line for two different loads, and measurements obtained with the designed SWR meter are compared to those obtained with the professional HP SWR. These two sets of measurements are in good agreement. From the measured standing wave curves, load impedances are calculated and they are in excellent agreement with the results obtained with AWR Design Environment and professional VNA.

The realized device can be used to better understand and visualize the EM waves distribution on TLs but also could be a usable piece of equipment for microwave laboratories which is a good alternative to much more expensive professional equipment. Further improvements would include adding a tunable Q factor functionality to the device. This will be part of the authors' further efforts.

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