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SIMPLE METHOD TO DETERMINE THE PERMITTIVITY IN SUBSTRATES USING A NANO VNA

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Abstract: This work shows the comparison of the NANO VNA with a professional laboratory VNA, for tests of radio frequency (RF) and microwave devices and components, with a focus on printed circuit board substrates. The tests were carried out for three substrates: FR4 (ε_r=4.4) TLY5 (ε_r=2.2) y RF35 (ε_r=3.5), obtaining a minimum error with both VNAs, so the use of the NANO VNA is a good option for students and professionals in the area of telecommunications engineering, especially because of its cost of less than 200 dollars compared to the professional VNAs of Thousands of dollars.
Keywords: Microstrip, NANO VNA, permittivity, radio frequency, substrate.

INTRODUCTION

In current electronic systems with a high density of components and a tendency towards miniaturization; the characteristics of the laminated substrates (Printed Circuit Boards) play an important role for their performance, especially in Radio Frequency (RF) and Microwave circuits (Zheng, Wang, Han, Wu, Mo and Tian, 2022). The substrates are made of different materials such as: glass, Teflon, mica, fiberglass and others, basically they are dielectric; Although some are metallic, fundamentally based on aluminium, the parameters that define them for their application and performance are the dielectric constant and the loss tangent (Courtney and Motil, 1999). The most common are those of fiberglass with different types of resin, their combination defines the mechanical and electrical properties, they are known as FR, which is fire retardant. For consumer circuit printed circuit boards, the FR4 type is normally used, it is waterproof so its electrical insulation is high and it has a high resistance/weight ratio (Clyde, 2001). Among the types of flat circuits, the most widely used in microwave electronics are microstrips. They are also circuits mostly used in the characterization of electromagnetic properties of materials, especially substrate materials (Chen, Ong, Neo, Varadan & Varadan, 2004).

Microwave permittivity measurement methods can be classified into resonant methods and non-resonant methods. The methods with better precision to determine the permittivity are the resonants, which are widely used for the characterization of low-loss dielectrics. The main disadvantage of these methods is that they can only be applied in bandwidths defined by the resonator (Ligthart, 1983). In the non-resonants are the transmission/reflection (T/R) methods. Narayanan (2014) found that these are easy to implement enabling broadband measurements, but are less accurate in determining substrate permittivity compared to resonant methods.

The non-resonant microstrip method mainly includes the transmission line method and the T/R method. For the case of the transmission line method, the sample under test is used as a substrate for the development of a segment of the microstrip transmission line, the electromagnetic properties of the substrate are obtained from the transmission and reflection properties of microtape (Ajmera, Batchelor, Moody, & Lashinsky, 1974). Calibration errors, connector non-reproducibility, and impedance mismatch influence the accuracy of T/R methods (Jarvis, Vanzura, & Kissick, 1990).

Baker-Jarvis, Vanzura, and Kissick (1990) mention that there are many techniques to measure the electrical characteristics of substrates, but Athey, Stuchly M. A. and Stuchly S. S. (1982) verify and all of them require sophisticated systems and high economic cost, Montoya and Gaviria (2013) found that, although they are simple methods using resonant techniques, a Vector Network Analyzer (VNA) is required at least.

Laboratory VNAs are devices with costs of several thousand US dollars, although there are some semi-portables that have minimized their cost. All this makes the characterization of substrates a selective job. However, with the new developments of the NANO VNA with costs less than 200 US dollars, this process can be carried out by students, technicians, engineers and even researchers, anywhere.

In this work, he demonstrates the use of a NANO VNA (3G Vector Network Analyzer SAA-2) that costs less than 100 US dollars in the characterization of substrates by means of a microstrip. To be clear about the process, first a theoretical development of the phenomenon that identifies the parameters of the substrate is presented, then three 50 Ω microstrips are built, one of which is simulated to verify its behavior and finally they are measured with a ZVB VNA model. -4 from Rohde & Schwarz and the NANO-VNA SAA-2. Figure 1 shows both Vector Network Analyzers and on one side a measurement pattern to observe the comparison of dimensions.

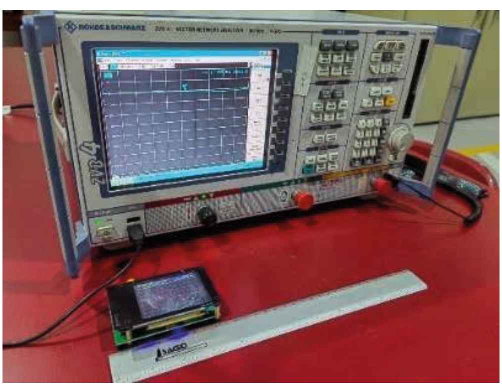

Figure 1. Size comparison of a Rohde & Schwarz brand VNA with respect to the NANO VNA

REFLECTION CANCELLATION METHOD

Because simplicity is sought in the procedure, the method to be used will be a T/R method presented by Pannell and Jervis (1981), where the reflection cancellation method is described.

A. METHOD OF ANALYSIS

In a transmission line the input impedance is determined by Cheng (1989):

$$Z_i = Z_0 \frac{Z_L + jZ_0 \tan \beta\ell}{Z_0 + jZ_L \tan \beta\ell}\ \Omega \qquad (1)$$

where: Z_0 is the characteristic impedance; Z_L is the load impedance; $\beta = 2\pi/\lambda = \omega/vp$ is the phase constant, being λ the wavelength, ω the frequency angular and vp phase velocity; ℓ is length of the line.

In homogeneous transmission lines $vp = f\lambda = c / \sqrt{\varepsilon_0}$ donde $c \approx 3x10^8\ m/s$, corresponds to the speed of light; $f(Hz)$ is the frequency, λ(m) is the wavelength and ε_r is the relative permittivity or dielectric constant. From (1) three cases can be analysed:

- If $Z_L = Z_0$, you have to $Z_i = Z_0$, indicates that there is a total coupling;
- If $Z_L=0$, you have to $Z_i = Z_0 \tan \beta\ell$, implies that the line is shorted to the load;
- If $Z_L = \infty$, you have to $Z_i = -jZ_0 \cot \beta\ell$, implies that the line is open-circuited at the load (Cheng, 1989).

According to the above, homogeneous transmission lines with load impedance equal to zero ($Z_L=0$ or short-circuited, presents its first resonance at the frequency corresponding to the length of the line equal to one quarter of the wavelength ($\ell=\lambda/4$). At this frequency the input impedance tends to infinity ($Z_i \rightarrow \infty$) and repeats every lambda means ($\lambda/2$) as shown in figure 2 with green color.

In the same way, homogeneous transmission lines with impedance of charge equal to infinity ($Z_L=\infty$) or in open circuit, presents its first resonance at the frequency that corresponds to the length of the line equal to one half of the wave length ($\ell=\lambda/2$). At this frequency the input impedance tends to infinity ($Z_i \rightarrow \infty$) and repeats every lambda means ($\lambda/2$) as shown in figure 2 with blue color.

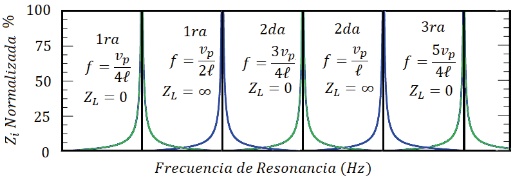

Figure 2. Normalized input impedance for shorted and open transmission lines

The characteristic impedance $Z_0(\Omega)$ of a microstrip is partially determined by the electrical permittivity $\in_r$ of the substrate material (Wheeler, 1965). This method is based on the fact that a mismatched section of transmission line of length ℓ appears to be a perfect match at frequencies such as $\frac{n\lambda}{2} = \ell$. This is due to the fact that the reflection coefficients at the ends of the unbalanced section have the opposite sign and, therefore, cancel. At other frequencies the line is out of tune. If the source frequency is adjusted, the line will appear equalized at frequencies such that $\ell = \frac{\lambda_1}{2}$, λ_2, $\frac{3\lambda_3}{2}$, ..., thus allowing to obtain $\lambda_1, \lambda_2, \lambda_3, \ldots$.

The phase velocity v_p is given by:

$$V_p = f\lambda = \frac{c}{\sqrt{\epsilon_{r\,eff}(f)}} \qquad (2)$$

where: c is the speed of light; f is the resonant frequency; λ is the wavelength of the source.

Thus, the effective permittivity is defined by Pannell and Jervis (1981):

$$\varepsilon_{eff}(f) = \left(\frac{c}{f\lambda}\right)^2 \qquad (3)$$

By measuring the input impedance of an open-circuited or shorted transmission line with an impedance analyzer or network analyzer, the dielectric constant of the material between the conductors of the line can be determined, knowing the frequency of first resonance (f_r) and line length (ℓ), with the following equation used by Pannell and Jervis (1981), and Rovensky, Pietrikova, Ruman and Kovac (2015):

$$\varepsilon_{eff} = \left(\frac{c}{2\ell f}\right)^2_{open} \qquad (4)$$

$$\varepsilon_{eff} = \left(\frac{c}{4\ell f}\right)^2_{short} \qquad (5)$$

B. EXPERIMENTATION

To validate the proposed method, we first proceeded to calculate the microstrips for a characteristic impedance of 50 Ω, with a substrate 0.05m wide and 0.1m long. The calculation was carried out with a web simulator (Chemandy Electronics, 2022), the parameters obtained are those shown in Table 1.

Substratum	t copper thickness (mm)	h substrate height (mm)	W track width (mm)	ε_r	ε_{eff}	Impedance (Ω)
FR4	0.035	1.58	3.01	4.4	3.33	49.84
TLY5	0.035	1.19	3.65	2.2	1.871	50.08
RF35	0.035	1.52	3.42	3.5	2.747	49.83

Table 1. Characteristics of the microstrips under test.

The response of the simulation with the ADS of the coupling (S11) and transfer (S21) of the microstrips FR4, TLY5 & RF35 in the frequency interval of 0.1 to 5 GHz are shown in figure 3, where it can be observed that the parameter S11 has levels less than -25 dB which implies that it is well coupled. Regarding parameter S21, it has an attenuation slope of 0.002 dB/GHz. This indicates that the microtapes have a good performance.

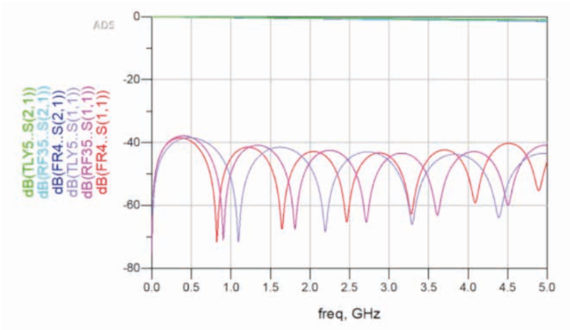

Figure 3. Simulation response of a 50 Ω microstrip with the three substrates used (FR4, TLY5 & RF35)

To check the data obtained by table 1 with respect to the characteristic impedance, the parameter S11 is plotted on the Smith chart (figure 4) where it can be seen that the response is at the midpoint of the chart and corresponds to $Z_0 = 50\Omega$. at a frequency range of 0.1 to 5 GHz.

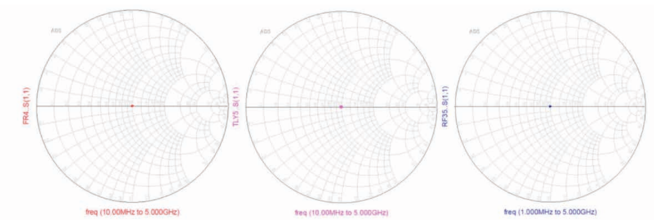

Figure 4. Simulation response of a 50 Ω microstrip with the three substrates used (FR4, TLY5 & RF35)

For the experimental part, three 50 Ω microstrips were built, which are the following:

The constructed microstrips that were tested are shown in Figure 5.

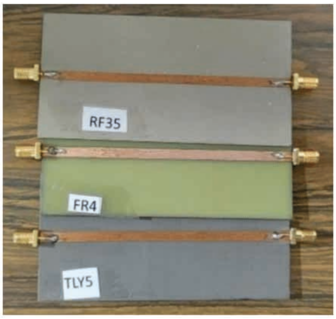

Figure 5. Microstrips used in tests

RESULTS AND DISCUSSION

Tests carried out with VNA ZVA R&S and NANO VNA-SAVER.

As the fundamental objective of the work is to show the performance of a NANO VNA, this was compared with a typical VNA in the laboratory, the characteristics are shown in tables 2, 3 and 4.

For the FR4 material, the following graph was obtained (figure 6) where the resonance frequency obtained in open mode is shown.

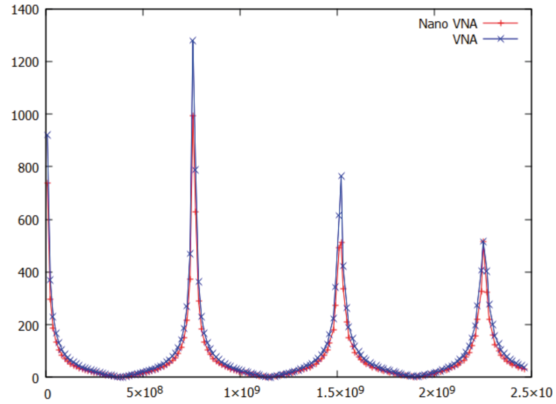

Figure 6. Measurement of the impedance parameter versus frequency (in open mode) with FR4

The blue lines correspond to the VNA samples from the Rohde & Schwarz laboratory. By way of comparison, the same measurement was performed with the NANO VNA, obtaining red traces as a result. Where it was possible to visualize that there is a difference in the resonance frequency value equal to 29.9 MHz.

In order to verify these measurements, the same measurement was carried out, but now in short mode, to confirm the calculation of $\ell = \frac{\lambda}{4}$ (figure 7), in the same way, it was measured with the two VNA.

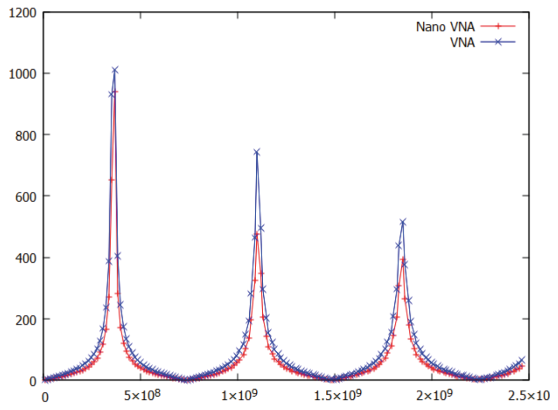

Figure 7. Measurement of the impedance parameter with respect to frequency (in short mode) with FR4

Here there was a discrepancy due to the measurement method and configuration of the NANO VNA, which is why a difference in the resonance frequency of 2.64 MHz was obtained. This made the measurement more effective and got even closer to the value of the VNA.

Table 2 shows the values of the effective relative permittivity (ε_{eff}) calculated with the measured resonance frequencies and the error regarding the relative permittivity of the FR4 substrate.

Using equation (4) it is obtained:

$$\epsilon_{eff}(f) = \left(\frac{3x10^8\, m/s}{787.4MHzx0.2m}\right)^2 \approx 3.629$$

Relative Effective Permittivity of FR4:

ε_{eff}=3.33

	ε_{eff}	error regarding ε_{eff}
NANO VNA	3.629	8.98%
VNA	3.921	17.74%

Table 2. Standard deviation of the measurements with FR4.

The next substrate tested was TLY5, with which the following responses were acquired in the measurement. Figure 8 shows the resonance frequencies detected with both vector network analyzers.

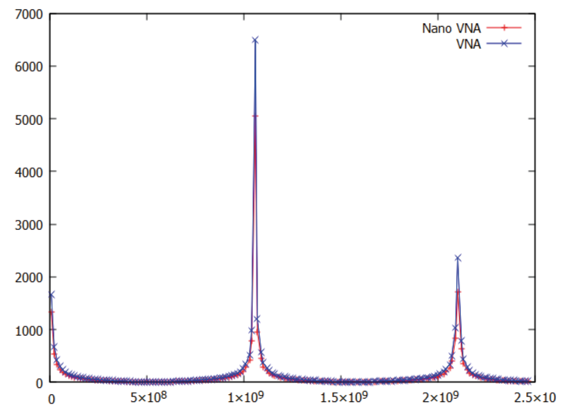

Figure 8. Measurement of the impedance parameter versus frequency (in open mode) with TLY5

As can be well observed, the trace generated by the VNA of the laboratory had a higher peak than that of the NANO VNA, this difference was identified as 0.5 MHz and is in open mode.

To verify this data, we now proceeded to measure now in closed mode with which a difference of 1.7 MHz was acquired as shown in figure 9.

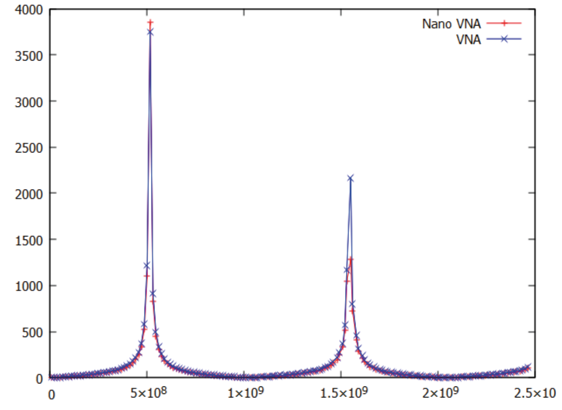

Figure 9. Measurement of the impedance parameter with respect to frequency (in short mode) with TLY5

Table 3 shows the values of the effective relative permittivity (ε_{eff}) calculated with the measured resonance frequencies and the error regarding the relative permittivity of the TLY5 substrate.

Using equation (4) it is obtained:

$$\epsilon_{eff}(f) = (\frac{3x10^8\, m/s}{1.0565GHzx0.2m})^2 \approx 2.015$$

Effective Relative Permittivity of the TLY5:

$$\varepsilon_{eff}=1.871$$

	ε_{eff}	Error respecto ε_{eff}
NANO VNA	2.015	7.69%
VNA	2.017	7.8%

Table 3. Standard deviation of the measurements with TLY5.

Finally, the RF35 material was also subjected to the aforementioned measurements. Figure 10 shows the values and as a difference in resonant frequency of 0.88 MHz for the open mode case.

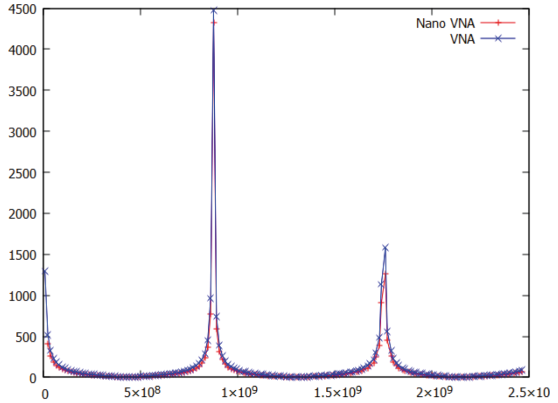

Figure 10. Measurement of the impedance parameter versus frequency (in open mode) with RF35

For the short case there was also a difference of 0.88MHz as can be seen in figure 11.

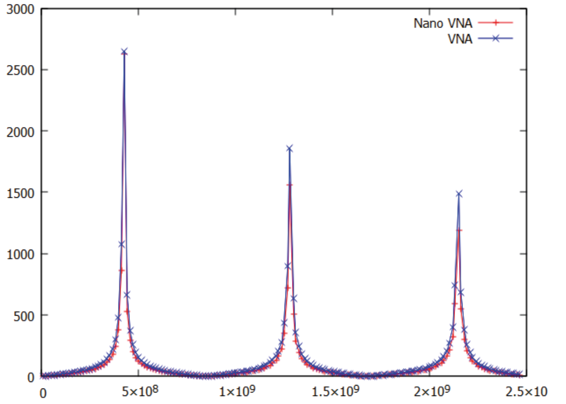

Figure 11. Measurement of the impedance parameter versus frequency (in short mode) with RF35

Table 4 shows the values of the effective relative permittivity (ε_{eff}) calculated with the measured resonance frequencies and the error regarding the relative permittivity of the RF35 substrate.

Using equation (4) it is obtained:

$$\epsilon_{eff}(f) = (\frac{3x10^8\, m/s}{877.1MHzx0.2m})^2 \approx 2.924$$

Effective Relative Permittivity of RF35:

$$\varepsilon_{eff}=2.747$$

	ε_{eff}	Error regarding ε_{eff}
NANO VNA	2.924	6.44%
VNA	2.93	6.66%

Table 4. Standard deviation of the measurements with RF35

CONCLUSIONS

The results obtained in the different tests demonstrate that the NANO VNA is a feasible instrument for the characterization of RF and Microwave components and devices. The main advantages are its low cost, as mentioned above, the use of PC software that facilitates data acquisition, its portability and safety against electrostatic discharges; so it can be handled without much caution. Its practicality and adaptability is recommended for the development of didactic or professional work; mainly for students, hobbyists, engineers and people who start in the field of radio frequency. This being its main advantage and for which this article is written.

The disadvantage is its low sensitivity (-70 dBm) and its set of loads that are not calibrated. Better measurement performance can be achieved by minimizing the error if the charges are calibrated.

The method used for the characterization of the substrates is adequate when the length is known, since it is a parameter that defines the resonance frequency in the series impedance.

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