Accurate Characterization and Measurement of Material

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Introduction

Material measurement is indispensable in the research and development of applications within the radio frequency (RF) and microwave frequency ranges. Fields such as PCB design, microwave circuit design, material science, biological research, automotive engineering, as well as metrology and research institutions require characterization of various materials. This is essential to better understand their impact on electromagnetic wave propagation for achieving desired designs, or to inspect manufacturing processes for quality control. Similar needs across diverse application areas create a continuous demand for the precise characterization and measurement of material dielectric properties.

Currently, the industry primarily utilizes instruments like Vector Network Analyzers (VNAs), Impedance Analyzers, and LCR meters, along with dedicated measurement fixtures and algorithm software, to achieve accurate measurement of parameters such as permittivity (dielectric constant) and permeability through various methods. Each method has its applicable domain, determined by several factors such as measurement frequency, expected values of εr and μr, measurement accuracy, material properties (e.g., isotropy and homogeneity), material form (e.g., liquid, powder, solid, thin film), sample size constraints, requirements for non-destructive or non-contact testing, and temperature range.

This article discusses the coaxial/waveguide transmission line method for material property measurement based on a Vector Network Analyzer, algorithms for converting S-parameters to permittivity and permeability, and demonstrates the broad applicability of the VNA as a high-frequency material characterization tool through a real-world case study, showcasing Siglent Technologies' material testing solution. Note: The conversion algorithms discussed herein are applicable only to solid material measurements.

Material Dielectric Properties

Generally, materials can be categorized as insulators (i.e., dielectrics), conductors, and semiconductors. A material is classified as a dielectric if it can store energy when an external electric field is applied. The electromagnetic energy stored and dissipated by a material is quantified by its permittivity and permeability, representing its insulating characteristics. Permittivity is a physical parameter describing the interaction between a dielectric and an applied electric field. The term "dielectric constant" commonly refers to the relative permittivity, or the ratio of absolute permittivity to the permittivity of free space.

$$\mathrm{K} = \varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \varepsilon_r' - j\varepsilon_r''$$

Where ε is the absolute permittivity, and εr is the relative permittivity. $\varepsilon 0$ is the permittivity of free space.

The dielectric constant k (also denoted as Dk or εr) is a complex number. Its real part $\varepsilon r'$ characterizes the amount of energy stored by the material under an applied electric field, while the imaginary part $\varepsilon r''$ characterizes the amount of energy dissipated. When depicted on a vector diagram, the ratio of the imaginary part to the real part of the permittivity is called the loss tangent or dissipation factor (also denoted as D or Df). This ratio gives the proportion of energy lost to energy stored, measuring the inherent electromagnetic energy dissipation of the Material Under Test (MUT). Its reciprocal is called the quality factor Q.

$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'} = D = \frac{1}{Q} = \frac{\text{Energy lost per cycle}}{\text{Energy stored per cycle}}$$

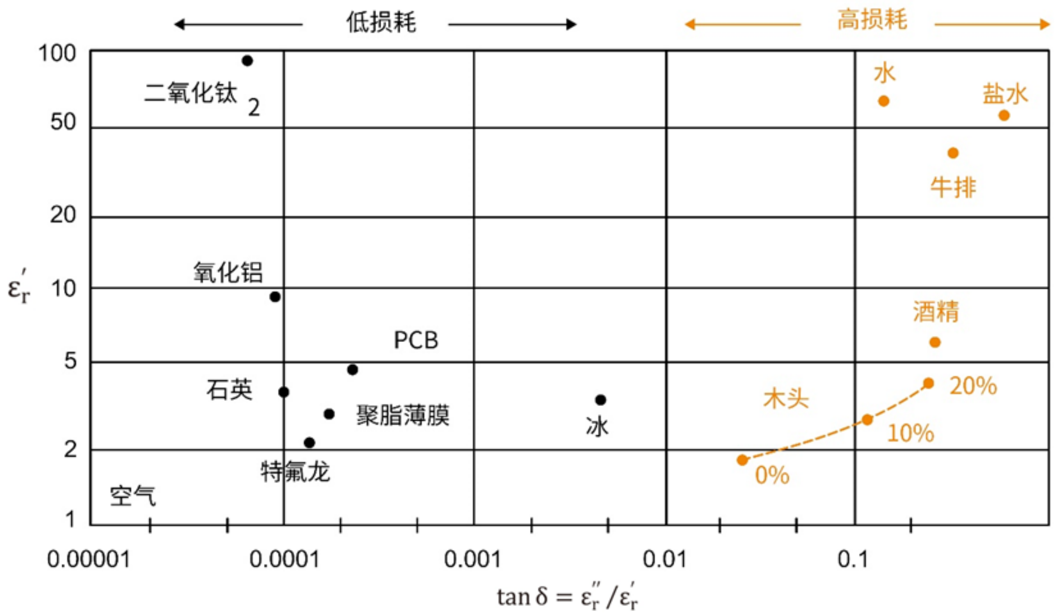
Magnetic materials are generally characterized by permeability, which measures their ability to interact with an applied magnetic field. The term "permeability" commonly refers to the relative permeability, or the ratio of absolute permeability μ to the permeability of free space μ_0.

$$\mu_r = \frac{\mu}{\mu_0} = \mu_r' - j\mu_r''$$

Where μ is the absolute permeability, and μ_r is the relative permeability. μ_0 is the permeability of free space.

$$\mu_0 = 4\pi \times 10^{-7} \mathrm{H/m}$$

Permeability is also a complex number. Its real part μ_r' characterizes the amount of energy stored by the material under an applied magnetic field, while the imaginary part μ_r'' characterizes the amount of energy dissipated. Similarly, the loss tangent for magnetic materials is defined as the ratio of the imaginary part to the real part of the complex permeability. Measurement of complex permeability is only applicable to magnetic materials. Some materials like iron (ferrites), cobalt, nickel, and their alloys exhibit significant magnetic properties, while most materials are non-magnetic with permeability very close to that of free space, typically considered μ_r = 1.



3. Transmission Line Method

The Transmission Line Method requires placing the MUT within a section of rectangular waveguide or coaxial transmission line. A calibrated network analyzer is then used to measure the reflection characteristic S11 and transmission characteristic S21 of the line under high-frequency signal excitation. Algorithms are subsequently applied to convert the S-parameters to permittivity and permeability. This method assumes the propagation of only the fundamental waveguide mode (i.e., TE mode in waveguides and TEM mode in coaxial lines). The test sample must be precisely machined according to standard waveguide dimensions and must fill the fixture's cross-section without air gaps against the walls. If gaps exist between the sample edges and the inner walls of the waveguide measurement fixture upon insertion, measurement deviations will be introduced. Therefore, the key to the transmission line method lies in the ability to fabricate MUTs with flat, perpendicular end faces relative to the long axis and a known thickness >20--360λ. Coaxial transmission lines can cover a relatively wide frequency range up to 18 GHz, but toroidal sample preparation is relatively difficult. Waveguide transmission lines can extend the testing frequency into the millimeter-wave band, and rectangular samples are easier to machine. However, because waveguide transmission lines themselves have segmented frequency coverage, the frequency coverage for material testing using waveguides is also segmented. The typical error for measuring permittivity and permeability with the transmission line method is less than 5%, and the error for the dissipation factor is generally less than 10%. Another consideration is the attenuation caused by conduction or radiation losses in the transmission line fixture. Given a common loss tangent value of 0.01, materials with $\tan\delta<0.01$ are not characterizable with this method.

Transmission Line Method Overview

S-Parameters	**S11, S21**
Measured Parameters	Permittivity, Permeability
Sample Preparation	1) Material structure is uniform 2) Insertion loss introduced along the sample length should not be excessive. The insertion loss in dB should be at least 20 dB less than the measurement system's dynamic range in dB. 3) Sample must be machinable into the required shape (toroidal or rectangular). No gaps should exist between the MUT edges and the fixture inner walls. Surfaces should be smooth, and both end faces must be perpendicular to the transmission line axis. Carefully measure the fixture's cross-sectional dimensions before machining to define achievable tolerances. 4) Sample length is frequency-dependent. It must not be too long, exceeding the standard waveguide depth, nor too short. The phase change introduced along the sample length at the lowest measured frequency point should be significantly greater than the phase uncertainty of the network analyzer.
Advantages	1) Wide measurable frequency range, suitable for anisotropic materials 2) Suitable for medium to high loss samples 3) Can measure complex relative permittivity and permeability of the MUT
Limitations	1) Measurement accuracy affected by air gap effects 2) Waveguide transmission line results only cover a segmented frequency range 3) Reduced accuracy when sample length is an integer multiple of the material's half-wavelength 4) Low-frequency limit constrained by practical sample length; starting frequency typically above 100-500 MHz

S- Parameters	S11, S21
	5) Limited low-loss resolution; not suitable for low-loss materials, liquids, thin films, etc. 6) High sample fabrication requirements. Material must be machinable to required dimensions, and machining accuracy directly impacts results, especially for toroidal samples (often destructive).

4. Conversion Algorithms

Several algorithms exist for converting S-parameters to permittivity and permeability, each with its own advantages and limitations. Specific methods are suitable for specific materials. For accurate measurement of dielectric properties, users need to know the appropriate measurement and conversion method. The NRW algorithm is fast and non-iterative, but its accuracy degrades when the MUT dimensions correspond to integer multiples of the half-wavelength at the measurement frequency. This is often unavoidable, especially during broadband measurements, and discontinuities may occur for low-loss materials. The NIST Iterative algorithm, while more complex than NRW, helps overcome issues related to sample dimensions and is suitable for long samples and characterizing low-loss materials. The Non-Iterative method introduces effective electromagnetic parameters and is only applicable for permittivity calculation under the condition of permeability $\mu r=1$.

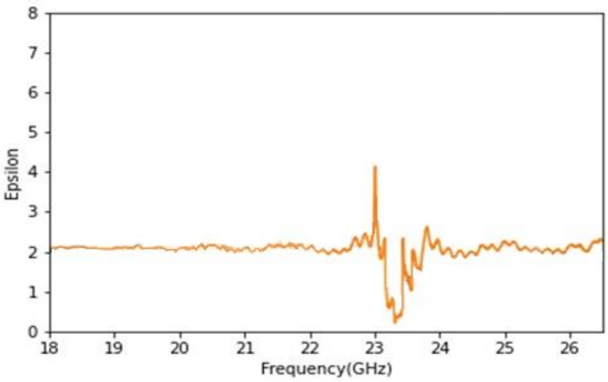
Conversion Algorithms Overview

Materials	Length	Magnetic Properties	Measurement Methods	Conversion Methods	S-Parameters	Dielectric Properties	Speed	Accuracy
Lossy solids	Short	non-magnetics	TR	NRW	S~11~, S~21~, S~12~, S~22~ or S~11~, S~21~	ε_r , μ_r	Fast	Medium
Lossy solids	Short	magnetics	TR	NRW	S~11~, S~21~, S~12~, S~22~ or S~11~, S~21~	ε_r , μ_r	Fast	Medium
Low loss solids	Long	non-magnetics	TR	NIST Iterative	S~11~, S~21~, S~12~, S~22~ or S~11~, S~21~	ε_r , $\mu_r = 1$	Slow	Good
Low loss solids	Long	non-magnetics	TR	New Non-Iterative	S~11~, S~21~, S~12~, S~22~ or S~11~, S~21~	ε_r , $\mu_r = 1$	Fast	Good

4.1 Nicholson-Ross-Weir (NRW)

4.1.1 Algorithm Overview

The NRW method calculates permittivity and permeability directly from S-parameters. It requires measurement of all four S-parameters (S~11~, S~21~, S~22~, S~12~) or the pair (S~11~, S~21~) of the MUT. When the sample is a low-loss material and its length is an integer multiple of the half-wavelength at the measurement frequency, this algorithm may produce deviations due to phase ambiguity issues. Therefore, using short samples is recommended. Typically, the optimal sample thickness for this method is λ~g~/4. The following graph shows the permittivity measurement of Polytetrafluoroethylene (PTFE) using the NRW method in the SNA5000A material measurement mode.



As can be seen from the figure, the NRW method produces discontinuous jumps at integer multiples of the sample's half-wwavelength. This occurs because at points corresponding to half-wavelengths, S~11~ becomes very small, and the VNA has significant uncertainty when measuring the phase of a small S~11~, ultimately causing frequency jumps. This situation can be improved by reducing the sample length, but it is difficult to determine the appropriate sampling length when the sample's εr and μr are unknown.

NRW Algorithm Advantages and Limitations

ADVANTAGES	LIMITATIONS
1) Fast calculation speed 2) Applicable to waveguides and coaxial lines	1) Discontinuities at frequencies corresponding to integer multiples of half-wavelength 2) Algorithm performance affected by material length; suitable only for short materials 3) Not suitable for low-loss materials

4.1.2 Calculation Steps

Based on the measured S-parameters S_{11} and S_{21} of the sample under test, the steps to calculate the complex relative permittivity and complex relative permeability are as follows: First, calculate the intermediate variables x and Γ, then calculate intermediate variables T and Λ, and finally compute εr and μr.

After obtaining S_{11} and S_{21} from VNA measurements, solve for the reflection coefficient Γ and transmission coefficient T using the following formulas.

$$S_{11} = \frac{\Gamma(1 - T^2)}{1 - \Gamma^2 T^2} \tag{1.1}$$

$$S_{21} = \frac{T(1 - \Gamma^2)}{1 - \Gamma^2 T^2} \tag{1.2}$$

Combining the above equations, calculate the intermediate variable x, and solve for Γ and T:

$$x = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \tag{1.3}$$

$$\Gamma = x \pm \sqrt{x^2 - 1} \tag{1.4}$$

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \tag{1.5}$$

Calculate the intermediate variable Λ, and finally compute the complex relative permeability μr and complex relative permittivity εr:

$$\frac{1}{\Lambda^2} = \left(\frac{\varepsilon_r * \mu_r}{\lambda_0^2} - \frac{1}{\lambda_c^2}\right) = -\left(\frac{1}{2\pi L}\ln\left(\frac{1}{T}\right)\right)^2 \tag{1.6}$$

$$\mu_r = \frac{1 + \Gamma}{\Lambda(1 - \Gamma)\sqrt{\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}}} \tag{1.7}$$

$$\varepsilon_r = \frac{\lambda_0^2}{\mu_r}\left(\frac{1}{\lambda_c^2} + \frac{1}{\Lambda^2}\right) \tag{1.8}$$

In calculating Λ, phase ambiguity is involved. When the material length increases by an integer multiple of the wavelength, the phase of the transmission coefficient T does not change, as shown below:

$$\ln\left(\frac{1}{T}\right) = -\ln(|T|) - j\varphi + j2\pi n \tag{1.9}$$

After calculating T, the value of n in the above equation cannot be determined. Two methods can be used to resolve this.

The first method uses group delay, as the delay through the material is a function of its total length. After obtaining εr and μr, compare the measured actual group delay with the calculated theoretical group delay to find the correct n.

The calculated theoretical group delay is:

$$\tau_{cal} = L\frac{d}{df}\sqrt{\frac{\varepsilon_r\mu_r f^2}{c^2} - \frac{1}{\lambda_c^2}} = \frac{L}{c^2}\frac{f\varepsilon_r\mu_r + f^2\frac{1}{2}\frac{d(\varepsilon_r\mu_r)}{df}}{\sqrt{\frac{\varepsilon_r\mu_r f^2}{c^2} - \frac{1}{\lambda_c^2}}} \tag{1.10}$$

The measured actual group delay is:

$$\tau_{meas} = -\frac{1}{2\pi}\frac{d\,\phi}{df} \tag{1.11}$$

$\tau meas$ (can be directly obtained from the VNA) (11)

$\tau meas$ can be directly obtained from the vector network analyzer, while τcal varies with n.

When $\tau cal{-}k{-}\tau meas \approx 0$, then n = k is the correct solution.

The second method uses initial guesses for $\varepsilon r*$ and $\mu r*$ in the sample to estimate n via λg.

$$\frac{1}{\Lambda} = j\left(\frac{\gamma}{2\pi}\right), \quad \text{其中}\ \gamma = j\frac{2\pi}{\lambda_0}\sqrt{\varepsilon_r^*\mu_r^* - \left(\frac{\lambda_0}{\lambda_c}\right)^2} \tag{1.12}$$

$$\mathrm{Re}\left(\frac{1}{\Lambda}\right) = \frac{1}{\lambda_g} \tag{1.13}$$

Solve for λg using the above equation to determine n.

4.1.3 Simplified Calculation Steps

When the sample under test is known to be non-magnetic (μr=1), the NRW algorithm can be simplified. The complex relative permittivity εr can be obtained directly from equations (1.6) and (1.7), and this method is not affected by phase ambiguity.

Substituting μr=1 into equation (1.7) and rearranging gives,

$$\frac{1}{\Lambda}=\frac{1-\Gamma}{1+\Gamma}\sqrt{\frac{1}{\lambda_0^2}-\frac{1}{\lambda_c^2}} \tag{1.14}$$

Combining equation (1.6) and (1.14) gives,

$$\frac{1}{\Lambda^2}=\left(\frac{1-\Gamma}{1+\Gamma}\right)^2\left(\frac{1}{\lambda_0^2}-\frac{1}{\lambda_c^2}\right)=\left(\frac{\varepsilon_r}{\lambda_0^2}-\frac{1}{\lambda_c^2}\right) \tag{1.15}$$

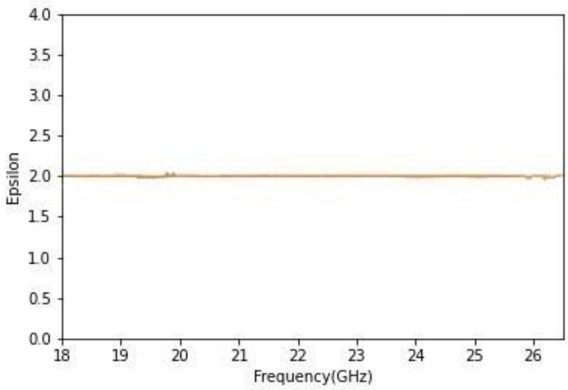
Solving yields,

$$\varepsilon_r=\left(\frac{1-\Gamma}{1+\Gamma}\right)^2\left(1-\frac{\lambda_0^2}{\lambda_c^2}\right)+\frac{\lambda_0^2}{\lambda_c^2} \tag{1.16}$$

4.2 NIST Iterative

4.2.1 Algorithm Overview

The NIST Iterative method uses the Newton-Raphson root-finding technique for calculation and is applicable only to permittivity calculation. It requires measurement of all four S-parameters (S~11~, S~21~, S~22~, S~12~) or the pair (S~11~, S~21~) of the MUT. If an appropriate initial estimate for the material's permittivity is set, this method can iterate to an accurate result. When the sample thickness is an integer multiple of the half-wavelength (nλ~g~/2), this method does not produce inaccurate peaks like the NRW method. It is suitable for measuring long samples and low-loss materials. The NIST iterative calculation steps involve first setting an initial value for the sample's permittivity at selected frequency points, then using the measured S-parameters and an iterative algorithm to obtain the final permittivity value. The following graph shows the permittivity measurement of PTFE using the NIST iterative method in the SNA5000A material measurement mode.



As shown, this method yields stable permittivity from S-parameters, allows measurement of samples of arbitrary length, and minimizes the instability present in the NRW method by setting μr=1. However, under this setting, only non-magnetic materials can be measured.

NIST Iterative Algorithm Advantages and Limitations

ADVANTAGES	LIMITATIONS
1) Smooth permittivity results, no discontinuities 2) Accurate calculation results 3) Can use samples of arbitrary length 4) Suitable for both low-loss and high-loss materials	1) Applicable only to permittivity measurement 2) Requires initial estimate for permittivity; inappropriate choice may lead to iteration failure

4.2.2 Calculation Steps

Before measurement, initial values for complex relative permittivity and complex relative permeability must be selected. As the operational equations have multiple solutions, the rationality of the root values must be considered to obtain an appropriate one. Basic considerations: If a solution leads to unstable root values, it should not be selected; if the chosen root causes severe fluctuations or a sudden jump to another root's result during iterative computation, the chosen root is likely incorrect, and the initial value should be reselected.

The reflection coefficient is calculated as follows,

$$\Gamma = \frac{\frac{\gamma_0}{\mu_0} - \frac{\gamma}{\mu}}{\frac{\gamma_0}{\mu_0} + \frac{\gamma}{\mu}} \tag{2.1}$$

The propagation constant in air $\gamma 0$ and in the material γ can be determined by:

$$\gamma_0 = \mathrm{j}\sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{2\pi}{\lambda_c}\right)^2} \tag{2.2}$$

$$\gamma = \mathrm{j}\sqrt{\frac{\omega^2 \mu_r \varepsilon_r}{c^2} - \left(\frac{2\pi}{\lambda_c}\right)^2} \tag{2.3}$$

$$\mathrm{c} = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \tag{2.4}$$

Combining (2.3) and (2.4), and substituting $\mu r{=}1$ gives,

$$\gamma = \mathrm{j}\sqrt{\varepsilon_r \varepsilon_0 \mu_0 \omega^2 - \left(\frac{2\pi}{\lambda_c}\right)^2} \tag{2.5}$$

Substituting $\mu r{=}1$, calculate reflection coefficient Γ and transmission coefficient T,

$$\Gamma = \frac{\frac{\gamma_0}{\mu_0} - \frac{\gamma}{\mu}}{\frac{\gamma_0}{\mu_0} + \frac{\gamma}{\mu}} = \frac{\gamma_0 - \gamma}{\gamma_0 + \gamma} \tag{2.6}$$

$$\mathrm{T} = \mathrm{e}^{-\gamma L} = e^{-jL\left(\sqrt{\varepsilon_r \varepsilon_0 \mu_0 \omega^2 - \left(\frac{2\pi}{\lambda_c}\right)^2}\right)} \tag{2.7}$$

Solving either of the following two equations can determine the complex relative permittivity,

$$F(\varepsilon_r) = S_{11}S_{22} - S_{21}S_{12} - \left[e^{-2\gamma_0(L_{air}-L)}\right]\frac{T^2-\Gamma^2}{1-\Gamma^2T^2} \quad (2.8)$$

$$F(\varepsilon_r) = \frac{S_{21}+S_{12}}{2(1-\Gamma^2T^2)} - T(1-\Gamma^2)e^{-j\gamma_0(L_{air}-L)} \quad (2.9)$$

After calculating the real and imaginary parts of $F(\varepsilon r)$ based on the set initial complex relative permittivity value, compute the Jacobian matrix J,

$$F(\varepsilon_{r1}) = f_1(\varepsilon', \varepsilon'')$$

$$F(\varepsilon_{r2}) = f_2(\varepsilon', \varepsilon'')$$

$$J = \begin{pmatrix} \frac{f_1(\varepsilon'+h,\varepsilon'')-f_1(\varepsilon'-h,\varepsilon'')}{2h} & \frac{f_1(\varepsilon',\varepsilon''+h)-f_1(\varepsilon',\varepsilon''-h)}{2h} \\ \frac{f_2(\varepsilon'+h,\varepsilon'')-f_2(\varepsilon'-h,\varepsilon'')}{2h} & \frac{f_2(\varepsilon',\varepsilon''+h)-f_2(\varepsilon',\varepsilon''-h)}{2h} \end{pmatrix} \quad (2.10)$$

where ε', ε'' represent the real and imaginary parts of complex relative permittivity, and h represents an infinitesimal value.

Update the permittivity estimate using Newton's method:

$$\varepsilon_{n+1} = \varepsilon_n + J^{-1}\varepsilon_n \quad (2.11)$$

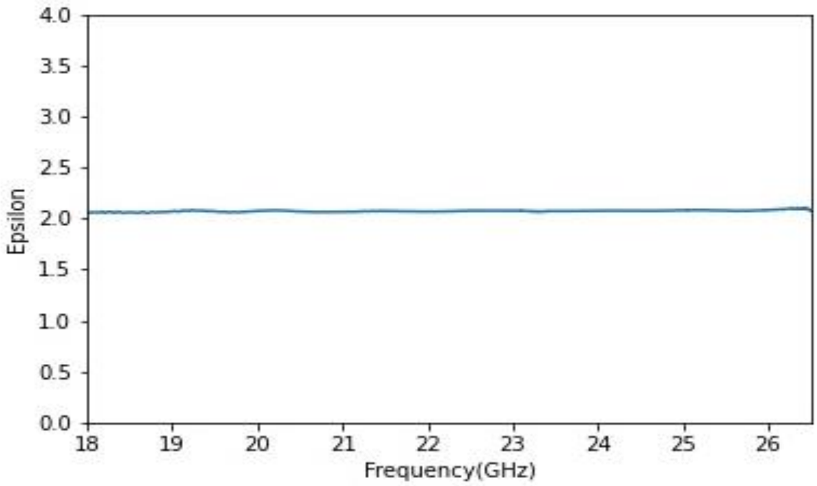
After obtaining $\varepsilon n+1$, check if the convergence condition is met. If satisfied, stop iteration; otherwise, continue.

$$max\left[|(\varepsilon_r')_{n+1} - (\varepsilon_r')_n|,\ |(\varepsilon_r'')_{n+1} - (\varepsilon_r'')_n|\right] < a \quad (2.12)$$

4.3 New Non-Iterative

4.3.1 Algorithm Overview

The Non-Iterative method is very similar to the NRW method, but it introduces effective electromagnetic parameters and is only applicable for permittivity calculation under the condition μr=1. It uses all four S-parameters (S~11~, S~21~, S~12~, S~22~) or just the two S-parameters (S~11~, S~21~) of the MUT. The advantage of this method is that it remains stable over the entire frequency range for any sample length, without discontinuities at frequencies corresponding to integer multiples of the sample's half-wavelength. Compared to the NIST Iterative method, it does not require an initial estimate for permittivity, and its calculation speed is very fast, with accuracy comparable to the iterative method. The following graph shows the permittivity measurement of PTFE using the new non-iterative method in the SNA5000A material measurement mode.



Compared with the NRW and NIST iterative methods, this method shows no discontinuities at frequencies corresponding to integer multiples of the half-wavelength within the sample, and the obtained permittivity accuracy is comparable to the iterative method.

New Non-Iterative Algorithm Advantages and Limitations

Advantages	***Limitations***
1) Smooth, stable complex relative permittivity results, no jumps 2) Accurate calculation 3) Can use samples of arbitrary length 4) Fast, non-iterative, no initial estimate needed	1) Applicable only to permittivity measurement

4.3.2 Calculation Steps

The method for calculating the reflection coefficient Γ and transmission coefficient T is the same as in NRW, formulas as per (1)-(5) in section 4.1.2.

$$x = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \tag{3.1}$$

$$\Gamma = x \pm \sqrt{x^2 - 1} \tag{3.2}$$

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \tag{3.3}$$

After solving for Γ and T, calculate the intermediate quantity $\frac{1}{\Lambda^2}$,

$$\frac{1}{\Lambda^2} = \left(\frac{\varepsilon_r * \mu_r}{\lambda_0^2} - \frac{1}{\lambda_c^2}\right) = -\left(\frac{1}{2\pi L}\ln\left(\frac{1}{T}\right)\right)^2 \tag{3.4}$$

$$\lambda_{og} = \frac{1}{\sqrt{\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}}} \tag{3.5}$$

(Alternatively derived from equations involving S11, S21) (3.5)

Define effective electromagnetic parameters *εeff* and *μeff*:

$$\mu_{eff} = \frac{\lambda_{og}}{\Lambda}\left(\frac{1+\Gamma}{1-\Gamma}\right) \tag{3.6}$$

$$\varepsilon_{eff} = \frac{\lambda_{og}}{\Lambda}\left(\frac{1-\Gamma}{1+\Gamma}\right) \tag{3.7}$$

Finally, calculate complex relative permittivity and complex relative permeability:

$$\mu_r = \mu_{eff} \tag{3.8}$$

$$\varepsilon_r = \left(1 - \frac{\lambda_0^2}{\lambda_c^2}\right)\varepsilon_{eff} + \frac{\lambda_0^2}{\lambda_c^2}\frac{1}{\mu_{eff}} \quad (3.9)$$

The new non-iterative algorithm is only applicable for μr=1. Substituting gives a simplified expression for εr:

$$\varepsilon_r = \left(1 - \frac{\lambda_0^2}{\lambda_c^2}\right)\varepsilon_{eff} + \frac{\lambda_0^2}{\lambda_c^2} \quad (3.10)$$

4.4 Air Gap Compensation Method

When a gap exists between the sample surface and the waveguide surface inside a waveguide transmission line, a capacitive series circuit model can be established. This model is used to correct the calculated permittivity and permeability. Applying this correction assumes the air gap is very small and the sample's permittivity value is within a small to medium range.

The sample's real relative permittivity is corrected as follows:

$$\varepsilon'_{rc} = \varepsilon'_r \frac{d(1+\tan^2\delta)[b-(b-d)\varepsilon'_r(1+\tan^2\delta)]}{[b-(b-d)\varepsilon'_r(1+\tan^2\delta)]^2 + b^2\tan^2\delta} \quad (4.1)$$

Where:

d — Height of the sample under test, in meters (m);

b — Height of the waveguide fixture's inner wall, in meters (m);

The sample's dielectric loss index is corrected as follows:

$$\varepsilon''_{rc} = \varepsilon''_r \frac{btan\delta}{b-(b-d)\varepsilon'_r(1+\tan^2\delta)} \quad (4.2)$$

The sample's real relative permeability is corrected as follows:

$$\mu'_{rc} = \mu'_r \frac{b}{d} - \frac{b-d}{d} \quad (4.3)$$

The sample's magnetic loss index is corrected as follows:

$$\mu''_{rc} = \mu''_r \frac{\mathrm{b}}{\mathrm{d}} \quad (4.4)$$

5. Material Measurement Example

A typical measurement system for the transmission line method consists of a Vector Network Analyzer, a coaxial or waveguide transmission line fixture, and a material measurement software option for calculating permittivity and permeability. The calibration type is TRL, and calculations can use the Non-Iterative, NIST Iterative, or NRW algorithms. The procedure involves placing a test sample inside the waveguide measurement fixture, connecting both ends of the fixture via waveguide-to-coaxial adapters to the calibrated network analyzer, measuring S11, S22, S21, and S12 parameters, selecting appropriate data processing methods, and substituting S-parameter values to calculate permittivity and permeability, thus completing the material measurement. To achieve accurate results, the analyzer and adapters should be adequately warmed up before measurement.

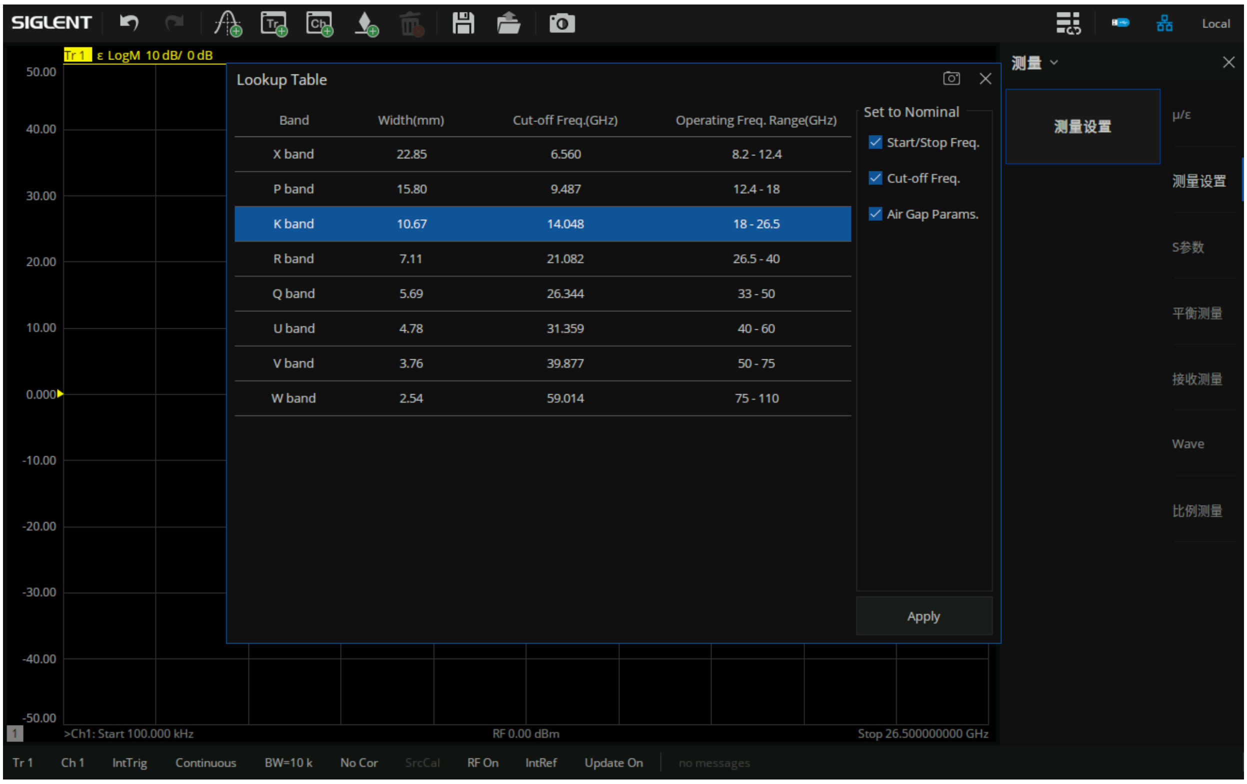
5.1 Measurement Conditions

Measurement Item	***Details***
Measurement	Siglent Technologies Vector Network Analyzer SNA5032A

Instrument	
Measurement Material	Polytetrafluoroethylene (PTFE)
Measurement Fixture	Coaxial cable, Waveguide fixture
Measurement Objective	Measure the permittivity of PTFE using a rectangular waveguide holder

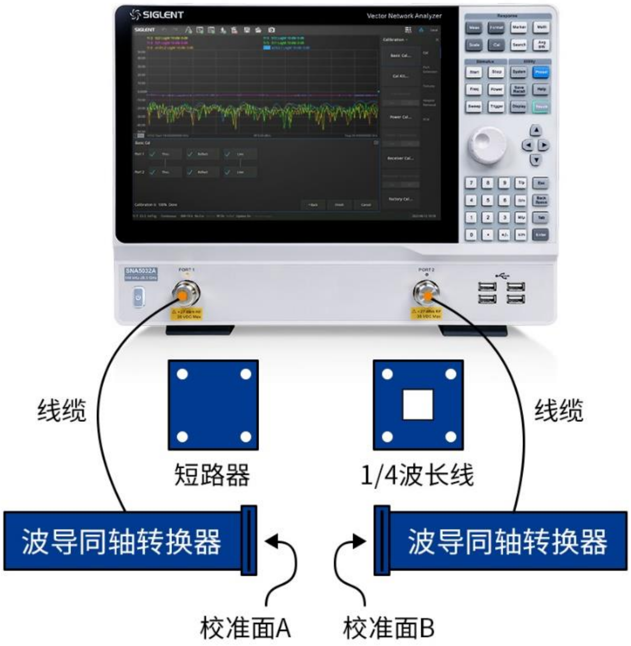
5.2 Fixture Parameter Setup

Before measurement, a series of instrument settings must be configured based on measurement conditions (measurement mode, sweep frequency range, IF bandwidth, number of points, etc.). Click Meas > Mode > MATERIAL to enter the material measurement mode and display the configuration dialog. Use Quick Setting to rapidly set relevant parameters based on waveguide fixture information. Click Lookup... to select and set waveguide fixture parameters. According to the current test conditions, select the K-band waveguide type, click Apply to apply the waveguide configuration, which automatically sets the network analyzer's current frequency range. Return to the main configuration interface to complete pre-configuration.

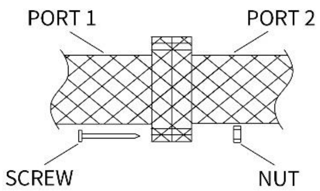


5.3 Waveguide TRL Calibration

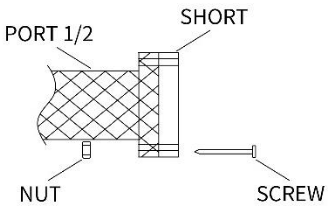
After connecting the network analyzer to the waveguide-to-coaxial adapters, perform calibration to extend the calibration plane to the adapter ends. Siglent Technologies provides a waveguide calibration kit covering 18GHz-26.5GHz, enabling Thru-reflect-Line (TRL) calibration. All error terms in the measurement setup error model can be determined through three simple connection types, as shown. For TRL calibration: connect short circuits at calibration plane A and B to complete the Reflect calibration; connect a 1/4-wavelength offset line between planes A and B to complete the Line calibration; directly connect planes A and B to complete the Thru calibration. Complete each calibration step individually to finalize the full TRL calibration.



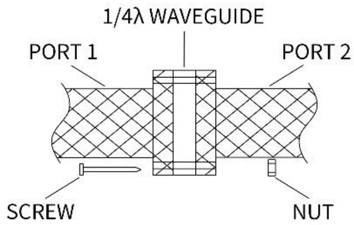
Waveguide Calibration Connection Diagram



Thru



Reflect

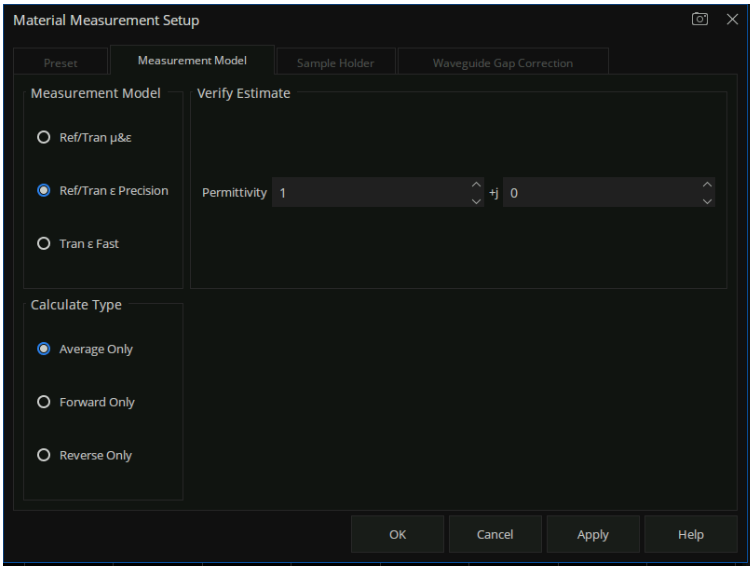


Line

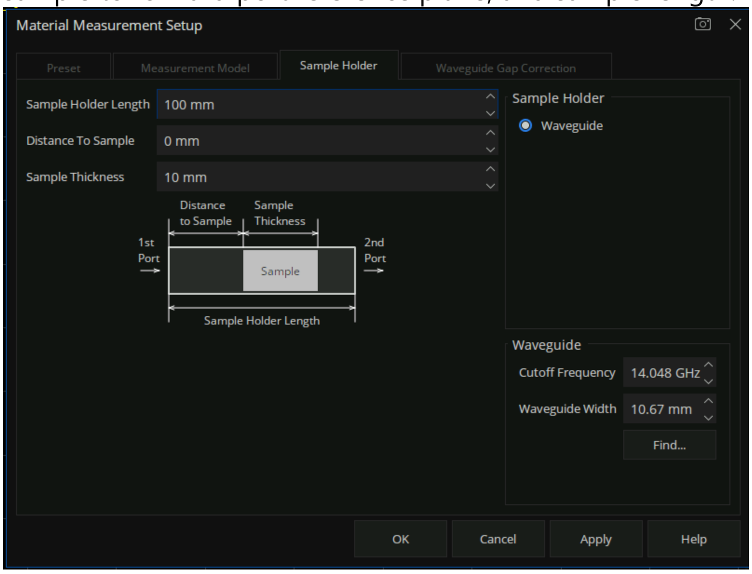
5.4 Material Measurement Setup

1. **Configure Measurement Model**: Select an appropriate measurement model based on material type and measurement objective, and configure current sample data. In this example, the Ref/Tran ε Precision measurement model based on the NIST iterative method is selected. A

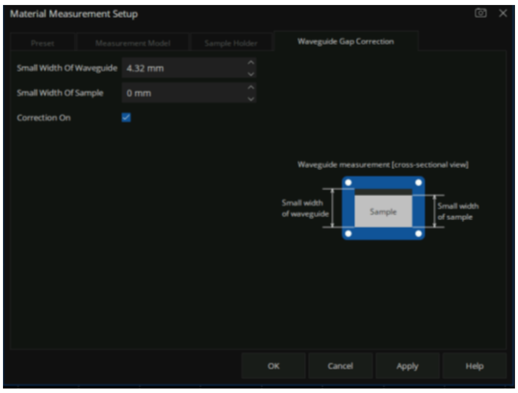
suitable initial permittivity value is preset for model iteration based on the current material properties.



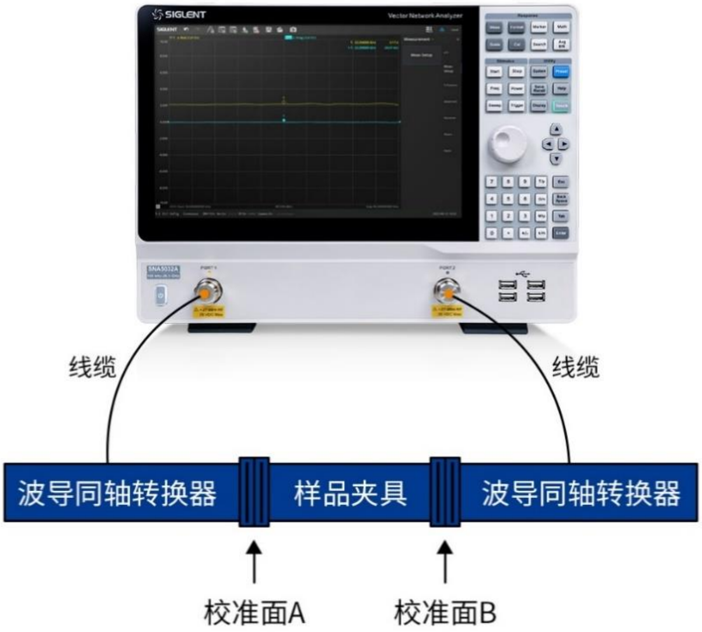
2. **Configure Sample Fixture Parameters**: Configure waveguide fixture length, distance from sample to forward port reference plane, and sample length.



3. **Configure Gap Compensation**: If a gap exists between the sample and waveguide, configure gap compensation. Set sample height and waveguide cross-section height. Check Correction On to correct calculation results based on waveguide and sample height information.

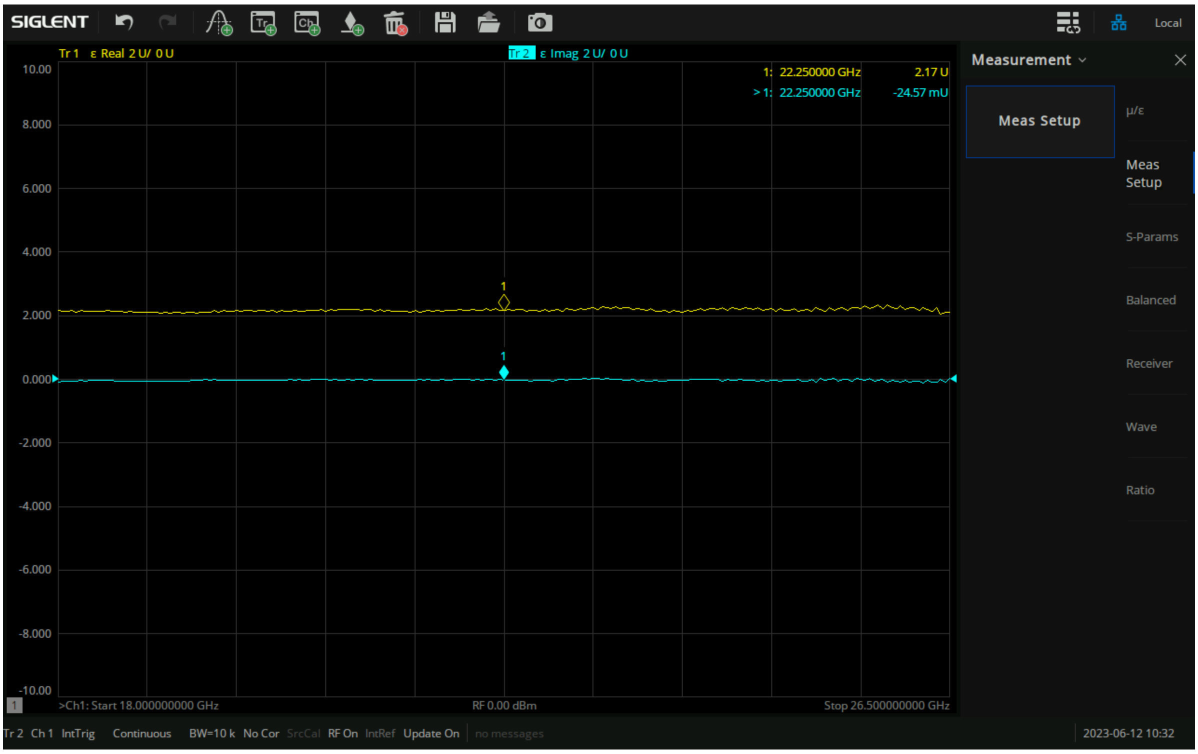


5.5 Sample Parameter Measurement



Material Measurement Connection Diagram

After completing all configurations, begin measuring the permittivity of PTFE. Insert the sample into the waveguide from the port, taking care to avoid damaging the sample. Once inserted, one surface of the sample should be flush with the waveguide reference plane. Set the measurement mode to ε and data format to real part. The measurement result is shown below. To measure permeability, set the Measurement Model to Ref/Tran μ&ε, set the measurement mode to μ, and data format to real part.



6. Summary

Siglent Technologies' comprehensive material measurement solution, including the SNA Series Vector Network Analyzers, MT Material Measurement Analysis Software, and KWR42A Waveguide Calibration Kit, helps users efficiently and accurately characterize and measure material dielectric properties. The SNA Series VNAs combine excellent measurement integrity with cost-effectiveness. Guided measurement wizards assist users through the measurement process. Results can be plotted in various formats (εr, μr, $\tan\delta$, $\varepsilon r''$, $\varepsilon r'$, $\mu r'$, $\mu r''$, $\tan\delta\mu$), aiding in better analysis. This solution is well-suited for laboratory, research institution, and educational environments.

关于鼎阳

鼎阳科技（SIGLENT）是通用电子测试测量仪器领域的行业领军企业，A股上市公司。

2002年，鼎阳科技创始人开始专注于示波器研发，2005年成功研制出鼎阳第一款数字示波器。历经多年发展，鼎阳产品已扩展到数字示波器、手持示波表、函数/任意波形发生器、频谱分析仪、矢量网络分析仪、射频/微波信号源、台式万用表、直流电源、电子负载等基础测试测量仪器产品，是全球极少数能够同时研发、生产、销售数字示波器、信号发生器、频谱分析仪和矢量网络分析仪四大通用电子测试测量仪器主力产品的厂家之一，国家重点“小巨人”企业。同时也是国内主要竞争对手中极少数同时拥有这四大主力产品并且四大主力产品全线进入高端领域的厂家。公司总部位于深圳，在美国克利夫兰、德国奥格斯堡、日本东京成立了子公司，在成都成立了分公司，产品远销全球80多个国家和地区，SIGLENT已经成为全球知名的测试测量仪器品牌。

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