CALIBRATION OF MICROSTRIP AND STRIPLINE FIELD APPLICATORS USING TIME DOMAIN TECHNIQUES

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FIELD APPLICATORS FOR MATERIAL MEASUREMENTS

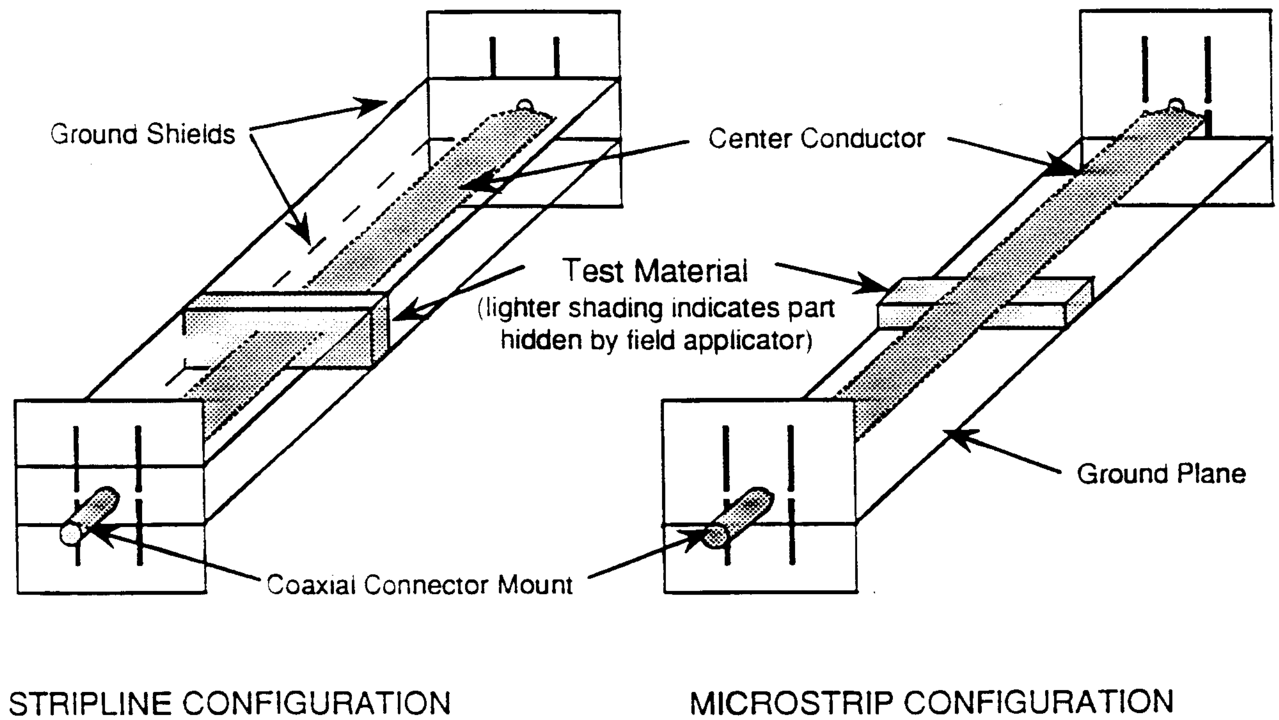


Figure 1. Configuration of stripline/microstrip field applicator.

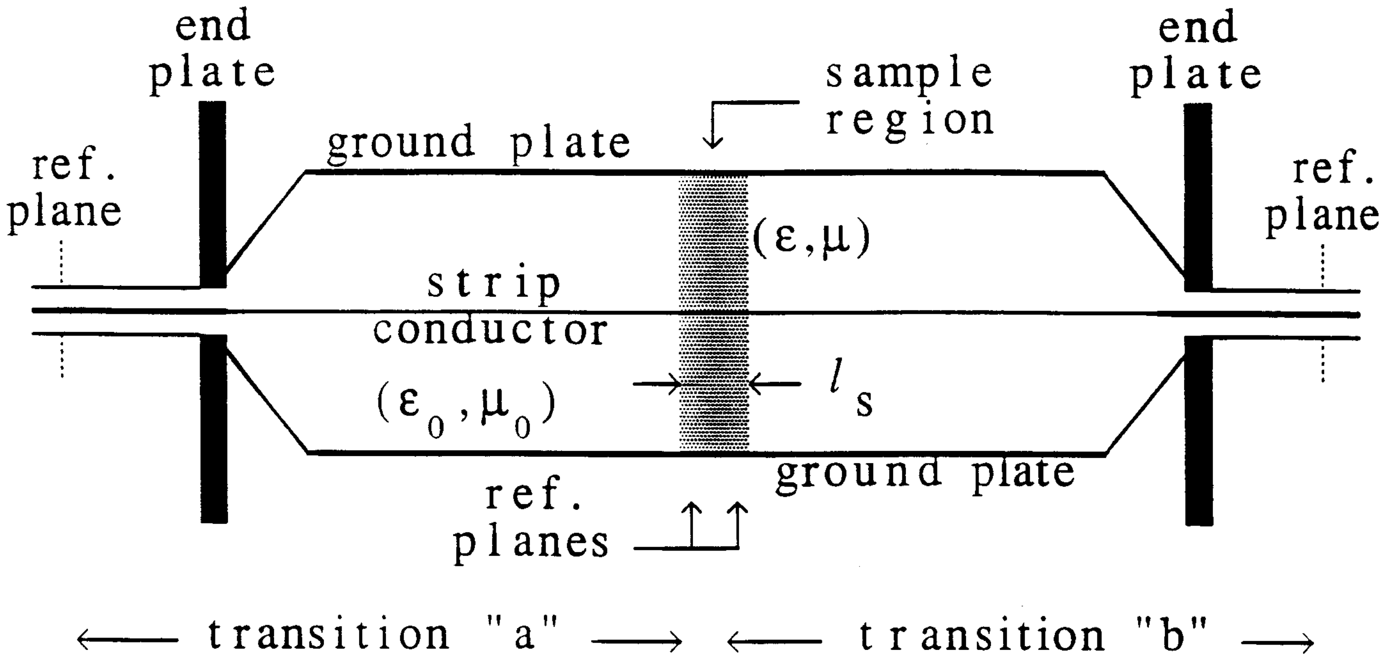


Figure 2. Field applicator configuration, with sample and transition regions identified.

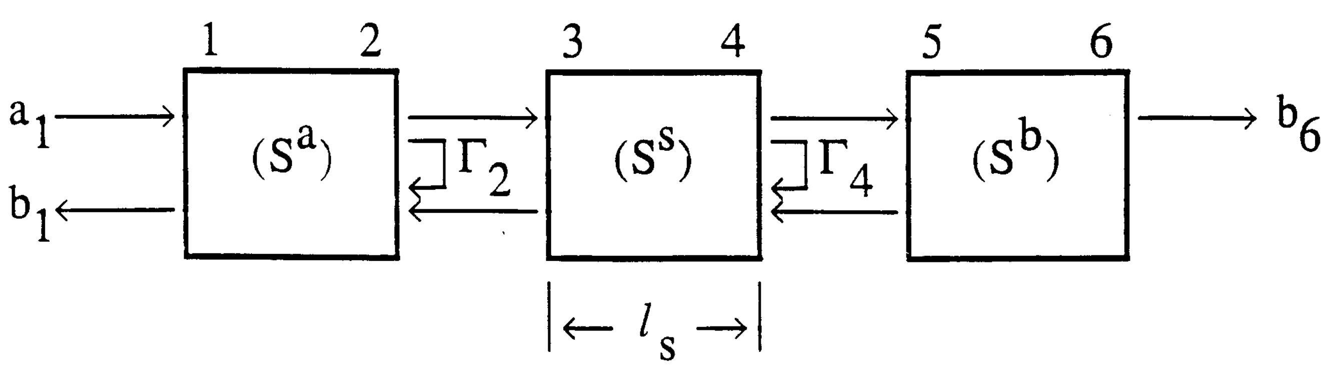


Figure 3. Equivalent two-port network configuration, including scattering parameter representations of transition and sample regions.

I. INTRODUCTION

Materials characterization requirements

- broadband frequency coverage from about 100 MHz-2 GHz
- material properties likely to be both dielectric and magnetic
- materials potentially anisotropic
- composite materials may be inhomogeneous on the small scale, but modeled as large-scale homogeneous

Field applicator requirements

- broadband measurements suggest TEM or quasi-TEM field applicator
- two complex measurements are required
- unidirectional electric and magnetic field polarizations desirable
- large sample volumes should be interrogated by the field applicator

II. FREQUENCY DOMAIN MATERIALS CHARACTERIZATION

Overview of Measurement Scheme

- measure terminal scattering parameters at coaxial ports of field applicator

- five applicator adjustments required (seven measurements)
  - S_{11} and S_{21} of empty applicator
  - S_{11} and S_{21} of applicator with sample present
  - three short circuit measurements at differing locations

- de-embed sample region S-parameters from those measured at the coaxial terminal ports

- calculate complex constitutive parameters (ϵ,μ) of sample material from de-embedded S-parameters
  - Nicholson-Ross-Weir method
  - samples must not be integer multiples of a half-wavelength thick

Conclusion

- frequency domain method yields accurate reliable results for most materials of interest when stripline applicator is used

- good results for microstrip applicator limited to measurement of low permittivity, low loss materials.

Disadvantages of Frequency Domain Technique

- shorts and sample materials must be carefully placed after repeated movement in order to obtain accurate results

- time consuming to make seven measurements

- making required five adjustments becomes cumbersome and of questionable accuracy for high temperature investigations

  - placement of samples and movement of shorts requires a minimum of five heating/cooling cycles

  - multiple heating/cooling cycles deform applicator and sample materials

  - multiple heatings and coolings limit the lifetime of applicator and sample materials

III. TIME DOMAIN MATERIALS MEASUREMENT

Overview

- measurements made in frequency domain at applicator terminals

- three applicator adjustments required (four measurements)
  - S_{11} of short circuit (provides phase reference plane)
  - S_{11}, S_{21} of sample **placed at same location as short**
  - S_{21} of empty applicator

- frequency domain measurements are transformed to time-domain (IFFT), windowed to remove extraneous reflections, and transformed back to frequency-domain (FFT), transmission mismatch effects are removed via calibration with short and empty applicator measurements

  - $S^p_{11\,short} = [S^a_{21}][S^a_{12}][-1]$ $\qquad C_R = [S^a_{12}][S^a_{21}]$
  - $S^p_{11} = [S^a_{12}][S^a_{21}]S_{11\,sample}$
  - $S^p_{21\,empty} = [S^a_{21}][S^b_{21}]e^{-jk_o l_s}$ $\qquad C_T = [S^a_{21}][S^b_{21}]$
  - $S^p_{21} = [S^a_{21}][S^b_{21}]S_{21\,sample}$

  two pairs of two equations in two unknowns which can be solved to determine S-parameters of the unknown sample

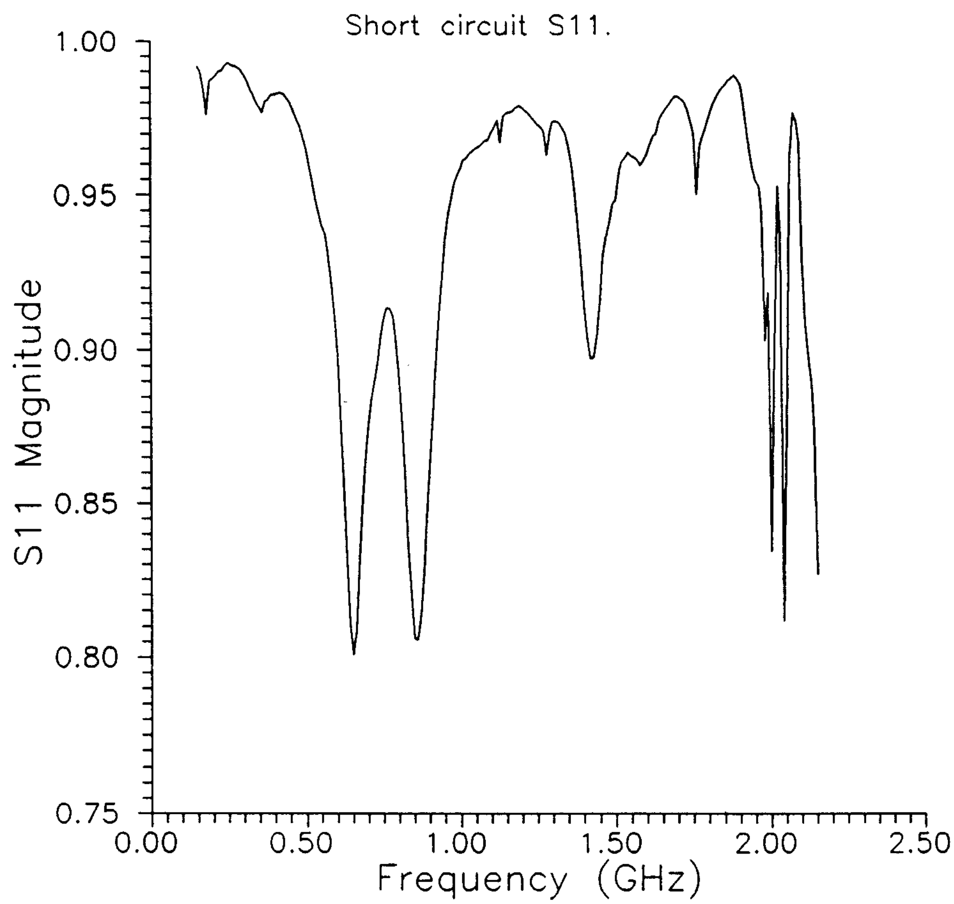
- complex constitutive parameters (ϵ,μ) of sample material determined from processed sample S-parameters

  - Nicholson-Ross-Weir method

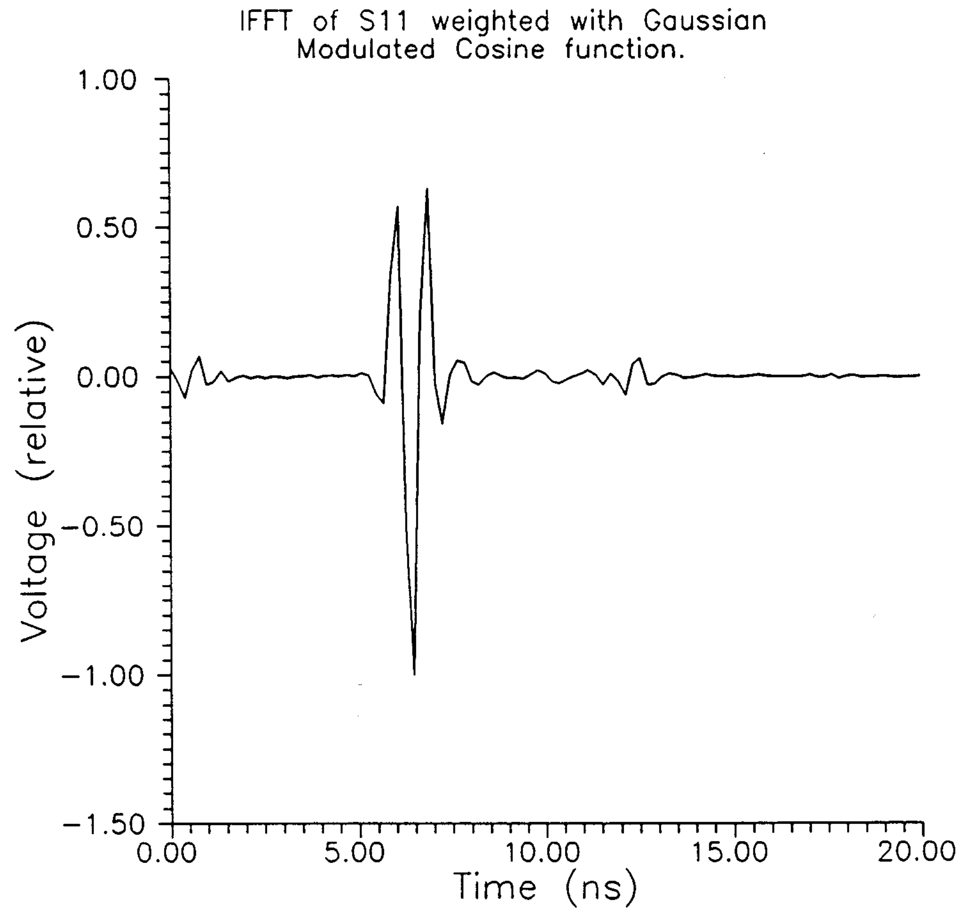
Signal Processing Scheme

i. determination of sample S_{11} parameter (S_{11}^{s}):

- terminal short circuit S_{11} measurement:



- apply weighting function to short circuit S_{11} measurement
- calculate IFFT of weighted short circuit S_{11}



- window out transition region effects
- calculate FFT of windowed time-domain data
- remove weighting function

remaining data is $R_1 = [S_{12}^a][S_{21}^a]S_{11short} = -[S_{12}^a][S_{21}^a]$

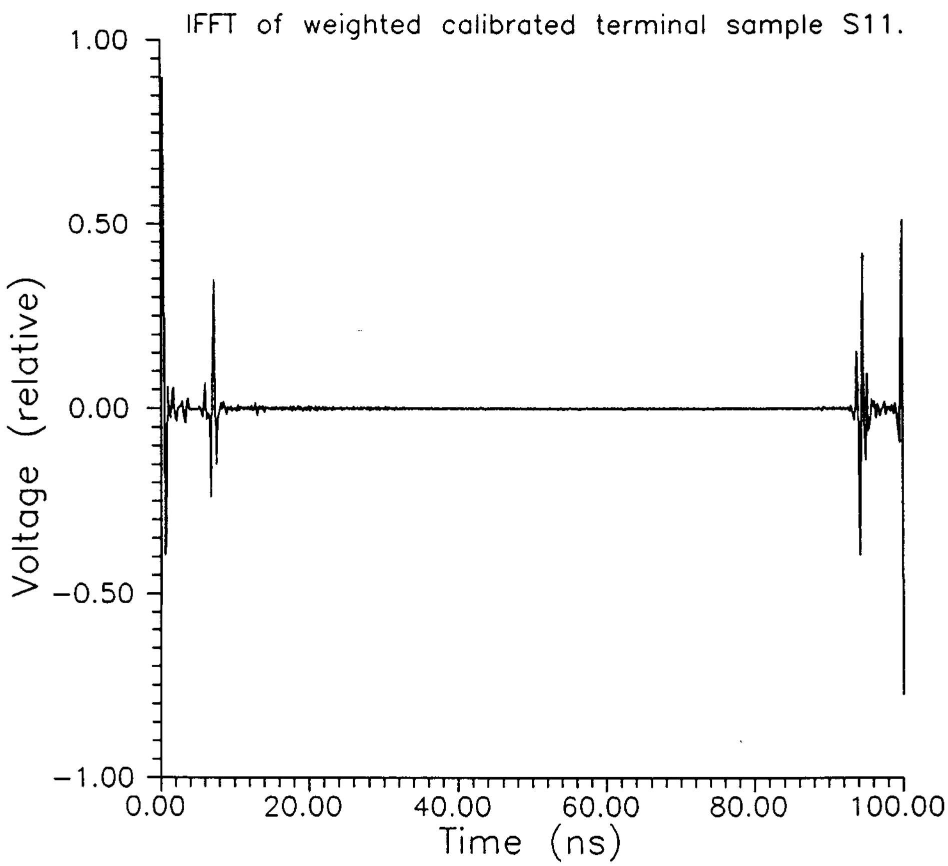
- scale amplitude of R_1 by factor of -1

remaining data is reflection calibration $C_R = [S_{12}^a][S_{21}^a]$

- divide terminal sample S_{11} measurement by reflection calibration C_R

- apply weighting function

- calculate IFFT of calibrated sample S_{11}



- window out transition region effects

- calculate FFT of windowed time-domain data

- remove weighting function

remaining data is desired sample region S-parameter S_{11}^{s}

ii. determination of sample S_{21} parameter (S_{21}^{s}):

- terminal empty applicator S_{21} measurement

$$S_{21}^{empty} = [S_{21}^{a}][S_{21}^{b}]e^{-jk_o l_s}$$

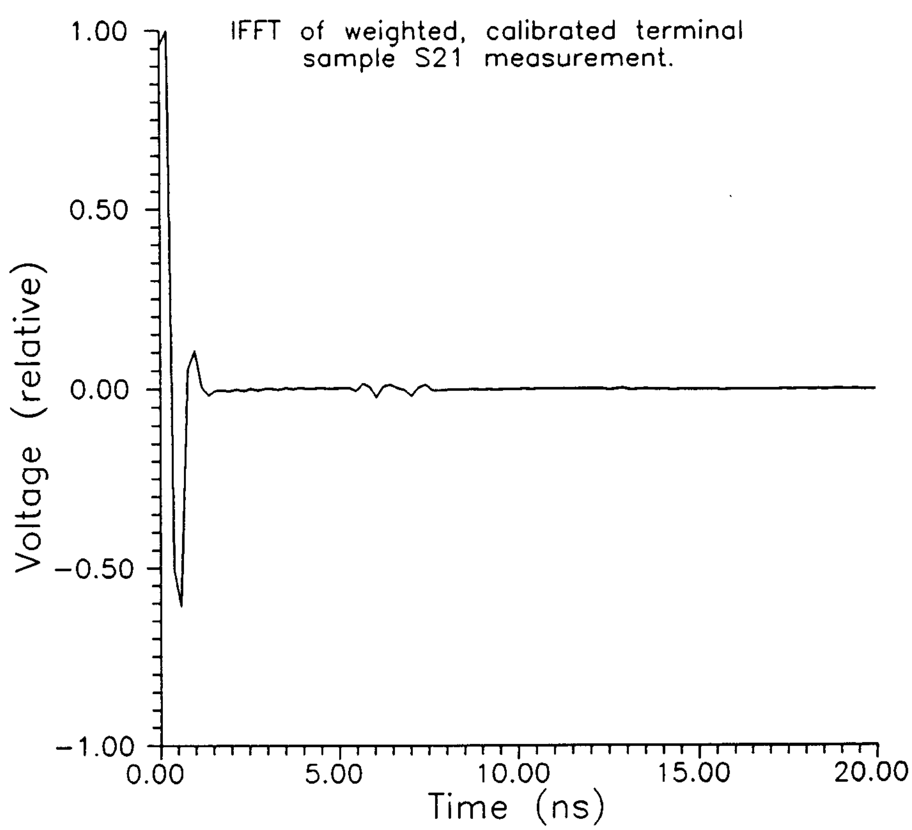
- divide terminal empty applicator S_{21} measurement by phase factor $e^{-jk_o l_s}$

remaining data is transmission calibration $C_T = [S_{21}^{a}][s_{21}^{b}]$

- divide terminal sample S_{21} measurement by transmission calibration C_T

- apply weighting function

- calculate IFFT of calibrated sample S_{11}



- window out secondary reflections
- calculate FFT of windowed time-domain data
- remove weighting function

remaining data is desired sample-region S-parameter S_{21}^{s}

C. Determination of Material Constitutive Parameters from Measured Sample-Region S Parameters

i. Nicholson-Ross-Weir Method

Sample-region parameters to processed S- parameters

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

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

$$\Gamma = \frac{Z_c^s - Z_c^e}{Z_c^s + Z_c^e} = \text{interfacial reflection coefficient} \tag{3}$$

$$T = \exp(-j\beta l_s) = \text{transmission propagation factor} \tag{4}$$

$Z_c^{e,s}$ = characteristic impedances of empty and sample regions

β = propagation phase constant of sample region

Equations (1) and (2) can be solved to yield

$$\Gamma = K \pm \sqrt{K^2 - 1} \tag{5}$$

$$T = \frac{\left(S_{11}^s + S_{21}^s\right) - \Gamma}{1 - \left(S_{11}^s + S_{21}^s\right)\Gamma} \tag{6}$$

$$K = \frac{\left(S_{11}^s\right)^2 - \left(S_{21}^s\right)^2 + 1}{2S_{11}^s} \tag{7}$$

Equating measured $\beta_m(\omega)$ and $\Gamma_m(\omega)$ to corresponding theoretical values leads to a pair of equations which can be solved for complex ϵ and μ.

$$\beta(\epsilon, \mu, \omega) - \beta_m(\omega) = 0 \tag{8}$$

$$\Gamma(\epsilon, \mu, \omega) - \Gamma_m(\omega) = 0 \tag{9}$$

stripline: TEM-mode operation leads to

$$\beta = k = \frac{\omega}{c}\sqrt{\epsilon_r \mu_r}\ , \qquad Z_c = \eta f_g = \eta_0 \sqrt{\frac{\mu_r}{\epsilon_r}} f_g \tag{10}$$

f_g = purely geometrical factor

$$\Gamma = \frac{\sqrt{\dfrac{\mu_r}{\epsilon_r}} - 1}{\sqrt{\dfrac{\mu_r}{\epsilon_r}} + 1} \quad \text{... provides} \quad \frac{\mu_r}{\epsilon_r} = \left(\frac{1+\Gamma}{1-\Gamma}\right)^2 = X \tag{11}$$

$$\ln(T) = -j\beta l_s \quad \text{... provides} \quad \epsilon_r \mu_r = -\left[\frac{c}{\omega l_s}\ln(T)\right]^2 = Y \tag{12}$$

consequently: for the TEM stripline mode

$$\epsilon_r = \sqrt{\frac{Y}{X}}\ , \qquad \mu_r = \sqrt{XY} \tag{13}$$

ii. Pucel-Masse Method (Microstrip)

- for microstrip-mode operation the values yielded by the NRW method are effective permittivity and effective permeability

- many forms for the determination of effective permittivity exist. One such form has been presented by Pucel and Masse

$$\epsilon_{eff}(\epsilon_r) = \epsilon_r \left(\frac{C-D}{C} \right)^2 \tag{14}$$

where

$$C = \frac{W}{2h} + \frac{1}{\pi} \left[\ln 2\pi e \left(\frac{W}{2h} + 0.94 \right) \right] \tag{15}$$

$$D = \frac{\epsilon_r - 1}{2\pi\epsilon_r} \left\{ \ln \left[\frac{\pi e}{2} \left(\frac{W}{2h} + 0.94 \right) \right] - \frac{1}{\epsilon_r} \ln \left(\frac{e\pi^2}{16} \right) \right\} \tag{16}$$

- For microstrip substrates with magnetic characteristics ($\mu_r \neq 1$), Pucel and Masse apply duality to define an effective microstrip permeability

$$\mu_{eff}(\mu_r) = \mu_r \left(\frac{C}{C - D'} \right)^2 \tag{17}$$

where

$$D' = \frac{1 - \mu_r}{2} \left\{ \ln\left[\frac{\pi e}{2} \left(\frac{W}{2h} + 0.94 \right) \right] - \mu_r \ln\left(\frac{e\pi^2}{16} \right) \right\} \tag{18}$$

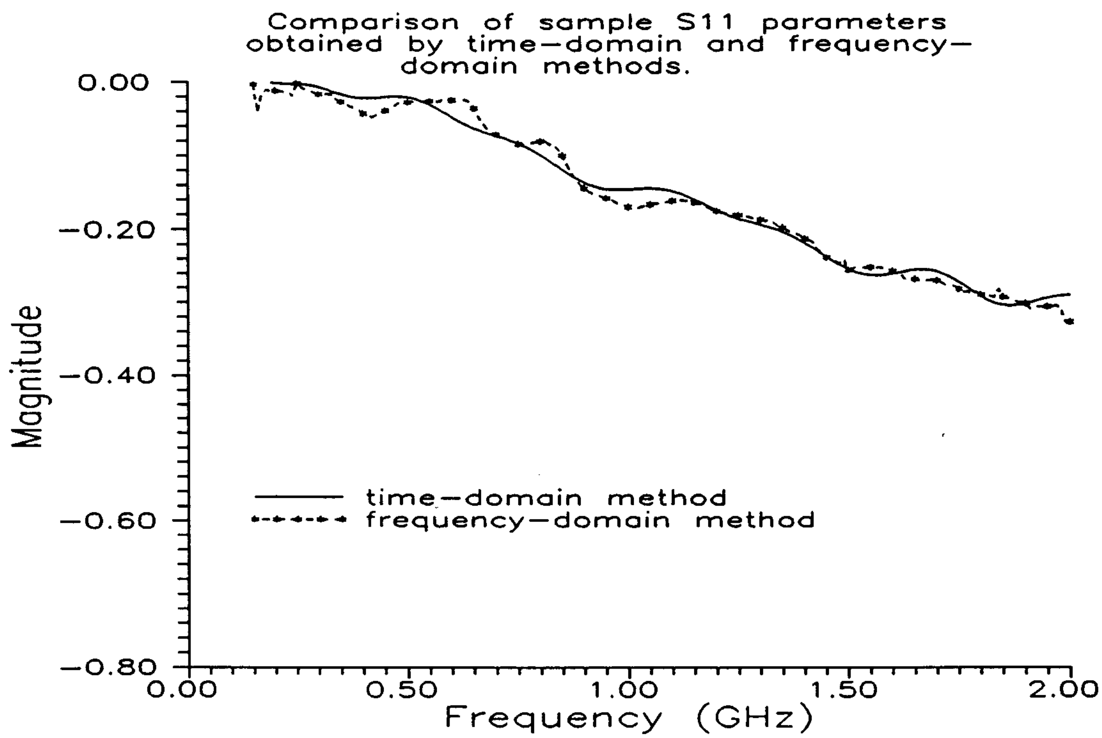
- Relative permittivity and relative permeability are determined from root searches of

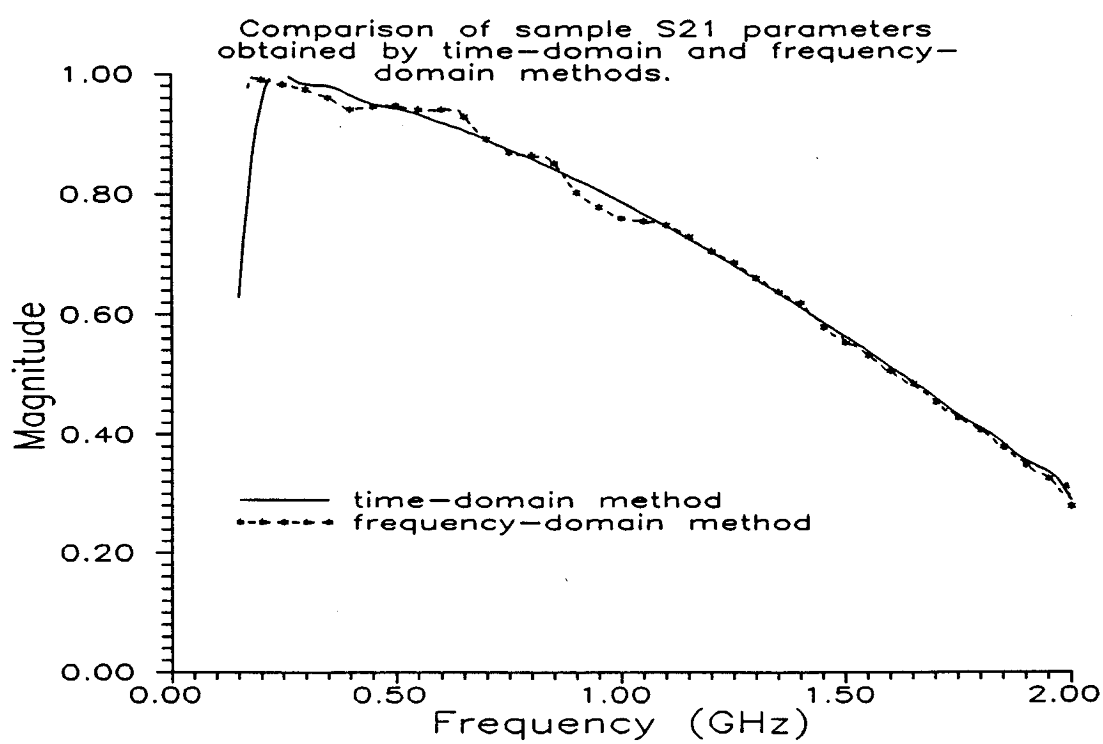
$$\mu_{eff}^{m} - \mu_{eff}(\mu_r) = 0$$

$$\epsilon_{eff}^{m} - \epsilon_{eff}(\epsilon_r) = 0$$

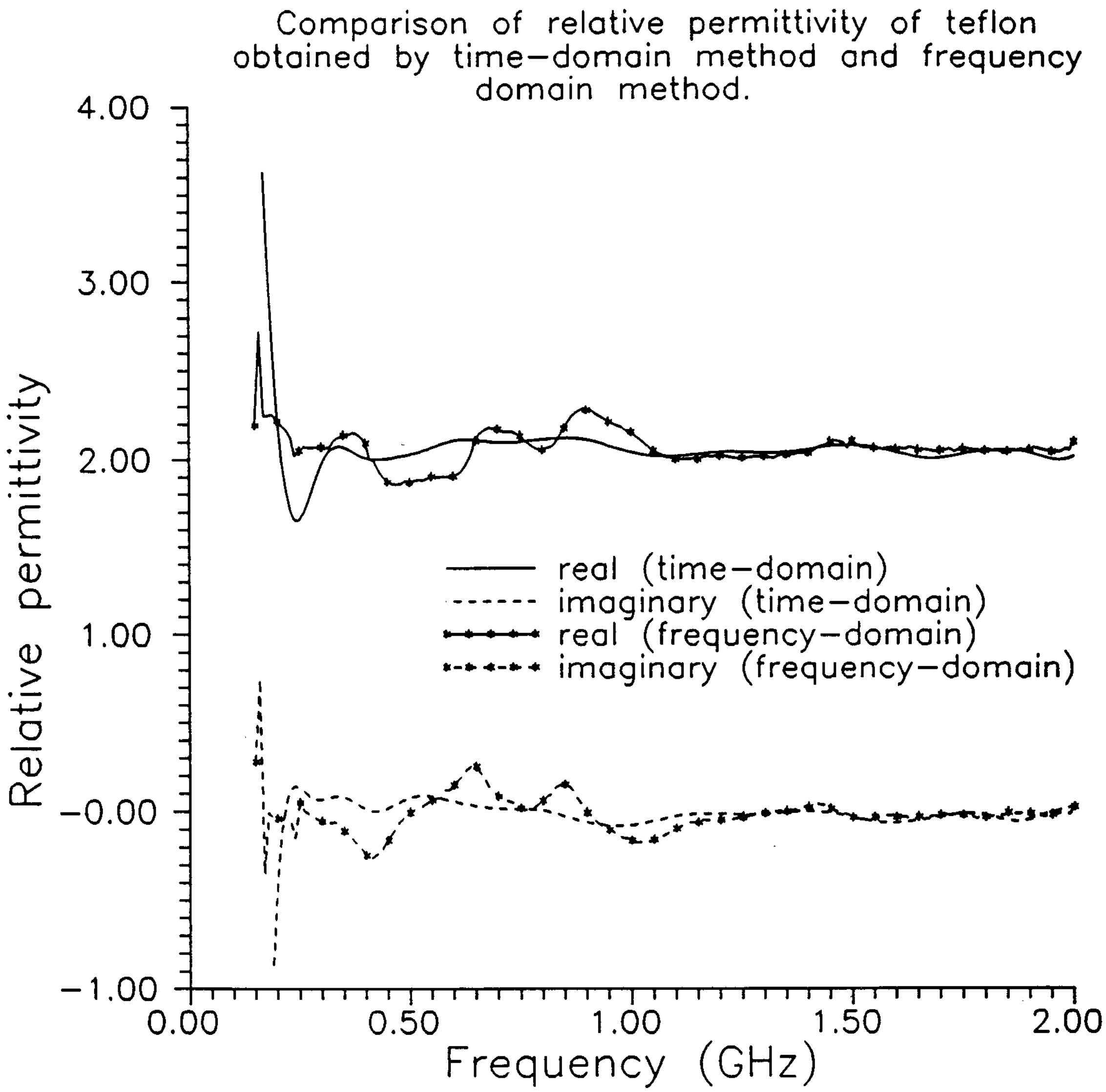
IV. COMPARISON OF TIME-DOMAIN AND FREQUENCY DOMAIN-RESULTS (STRIPLINE)

teflon data

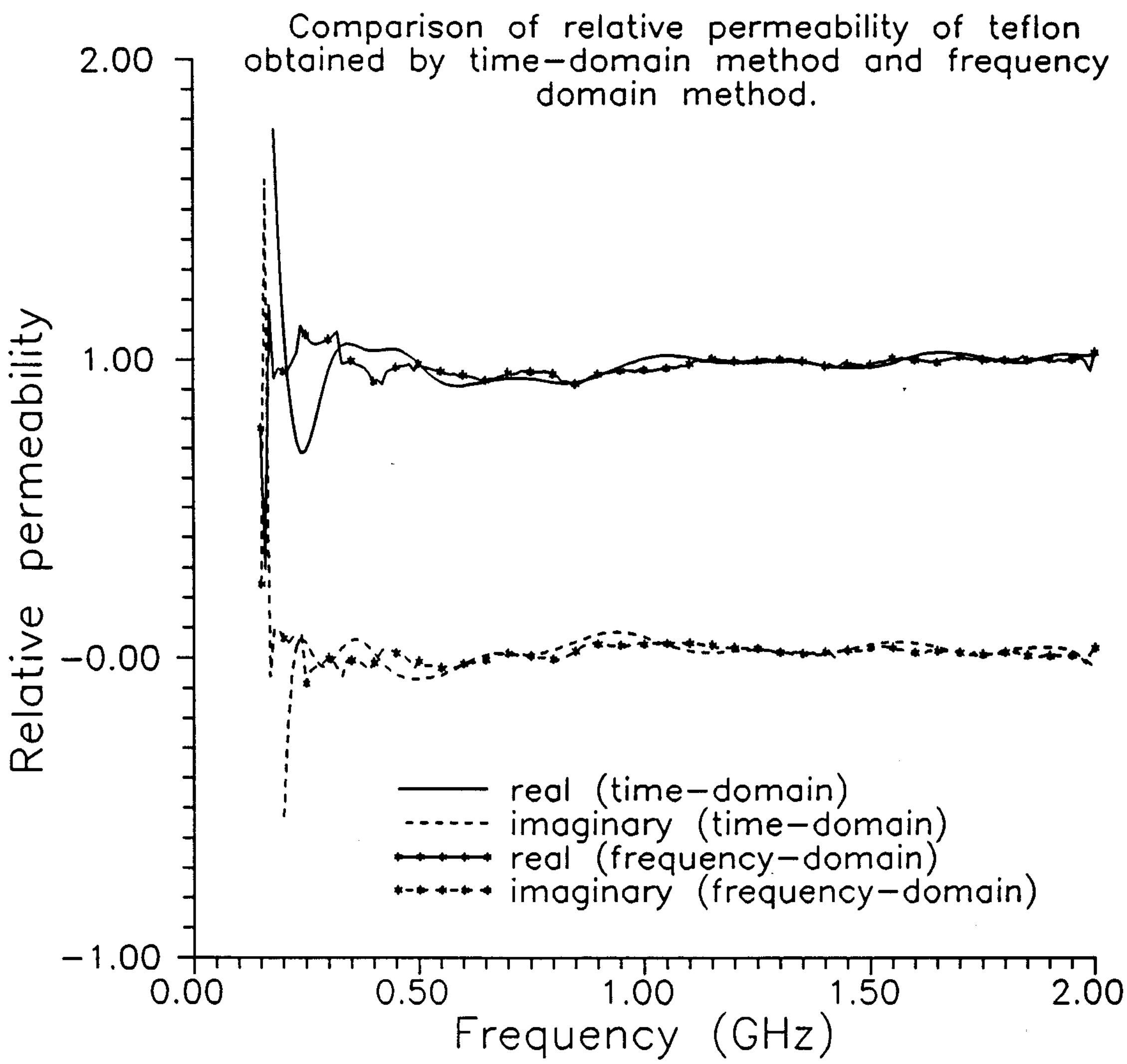




teflon data

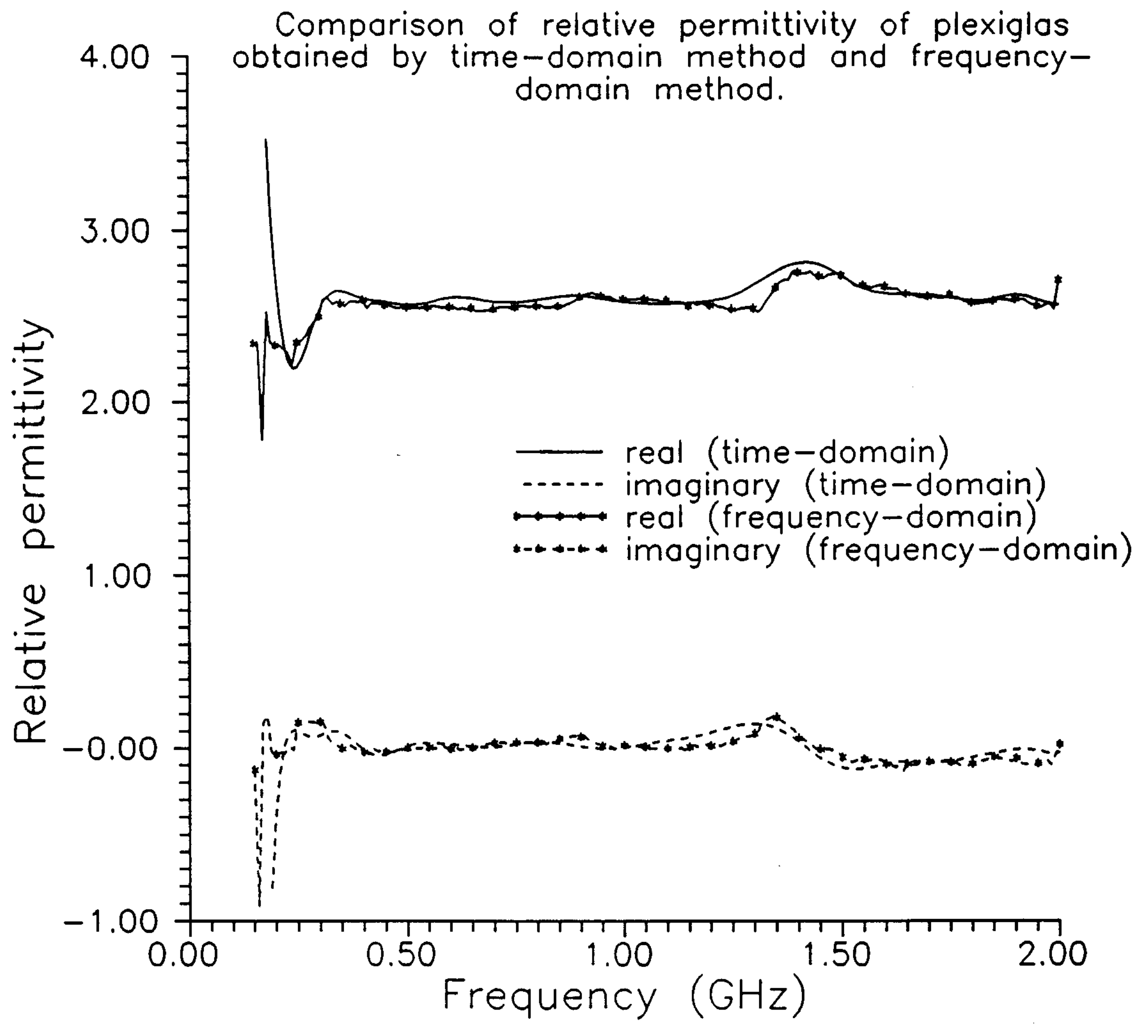

Comparison of relative permittivity of teflon obtained by time-domain method and frequency domain method.
4.00
3.00
2.00
1.00
-0.00
-1.00
Relative permittivity
real (time-domain)
imaginary (time-domain)
real (frequency-domain)
imaginary (frequency-domain)
0.00
0.50
1.00
1.50
2.00
Frequency (GHz)

teflon data

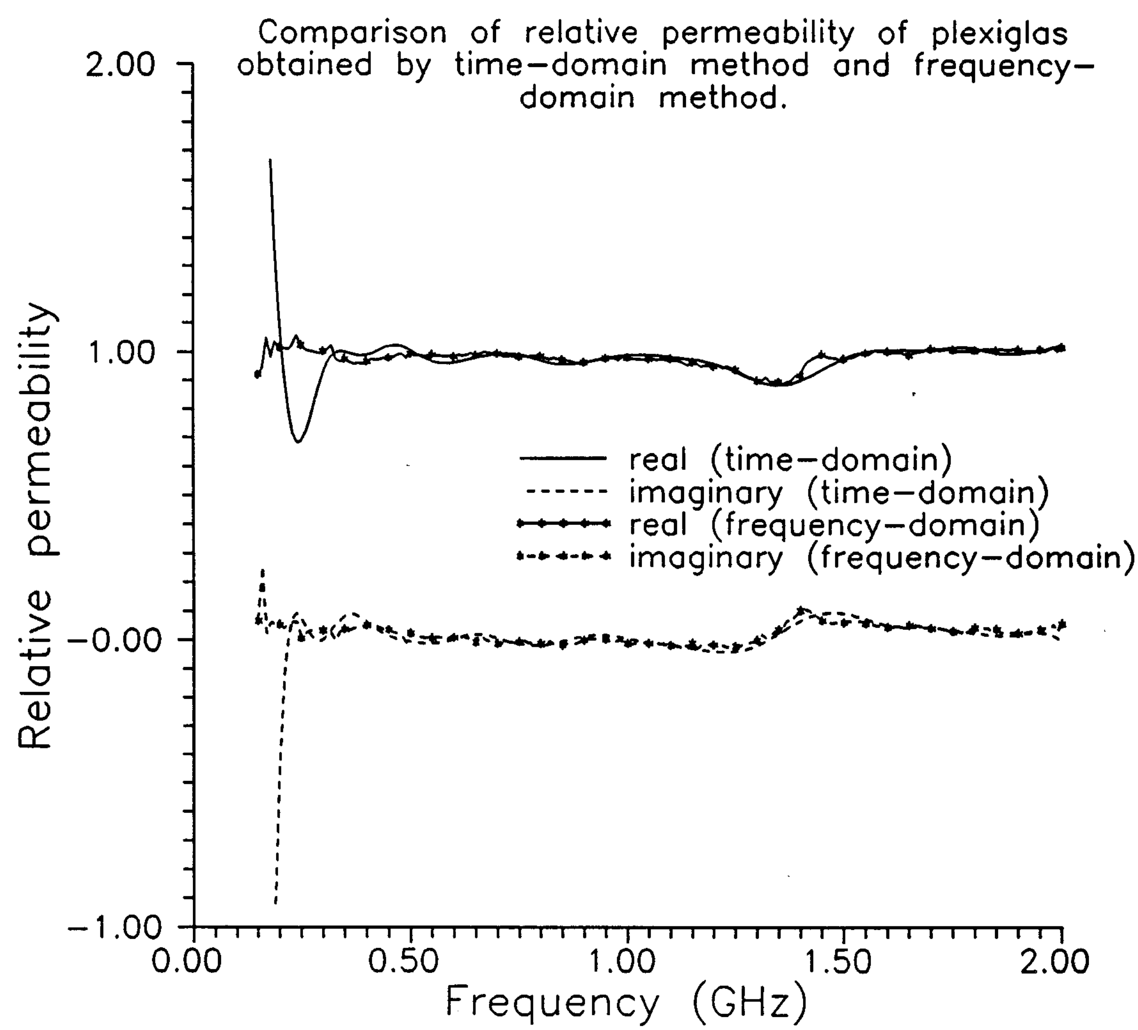


Comparison of relative permeability of teflon obtained by time-domain method and frequency domain method.
2.00
1.00
-0.00
-1.00
Relative permeability
real (time-domain)
imaginary (time-domain)
real (frequency-domain)
imaginary (frequency-domain)
0.00
0.50
1.00
1.50
2.00
Frequency (GHz)

plexiglas data



plexiglas data



VI. CONCLUSION

- The time domain calibration process provides results comparable to the frequency domain de-embedding technique over a wide bandwidth and requires fewer measurements

- The time domain method has distinct advantages for high temperature investigations

VII. FUTURE WORK

- The time domain method will be extended to use with a microsrtip applicator

- The applicator will be re-designed to extend bandwidth