TIME DOMAIN METHOD FOR MATERIALS CHARACTERIZATION USING MICROSTRIP FIELD APPLICATORS

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Microstrip and stripline field applicators have found increasing use for broadband measurement of the electromagnetic properties of materials. Frequency-domain calibration methods for field applicators have been developed which require measurements of a short located at three different positions within the applicator, and two measurements of the empty applicator.

Recently there has been an increased interest in high temperature measurements of the electromagnetic properties of materials at microwave frequencies. Because of its simple design, the microstrip field applicator is well suited for making such measurements. However, due to the complex propagation-mode spectrum associated with the microstrip, use of the frequency domain method with the microstrip has been limited to characterizing low permittivity, low loss materials. In addition, the frequency domain calibration method becomes cumbersome and of questionable accuracy for high temperature measurements, requiring that the applicator be heated and cooled several times to allow placement of the various standards. Multiple heating/cooling cycles limit the lifetime of the applicator and increase measurement time and cost. It has therefore become desirable to perform calibrations using a minimum number of standards.

The number of standard measurements required for calibration can be reduced by taking advantage of the inherent properties of the time-domain response of the field applicator. By careful design of that applicator and use of time-domain windowing techniques, the applicator can be calibrated with the measurement of only one short and one measurement of the empty applicator. This greatly reduces calibration time and measurement uncertainties caused by misplacement of the shorts and sample materials. In addition, the use of time-windowing techniques may permit the characterization of a wider variety of materials using the microstrip applicator.

This paper will discuss a calibration method for microstrip field applicators using time domain principles and will provide a comparison of material properties measured using both the time domain method and the usual frequency domain method.

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I. INTRODUCTION

Materials characterization requirements

- broadband frequency coverage
- 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
- applicator should be flexible in order to accommodate various sample sizes
- applicator should be suited for high temperature experiments

Advantages of time domain materials characterization

- requires only four measurements (seven required for frequency domain technique)
  - fewer measurements desirable for high temperature studies

II. MICROSTRIP APPLICATOR

Advantages of microstrip applicator

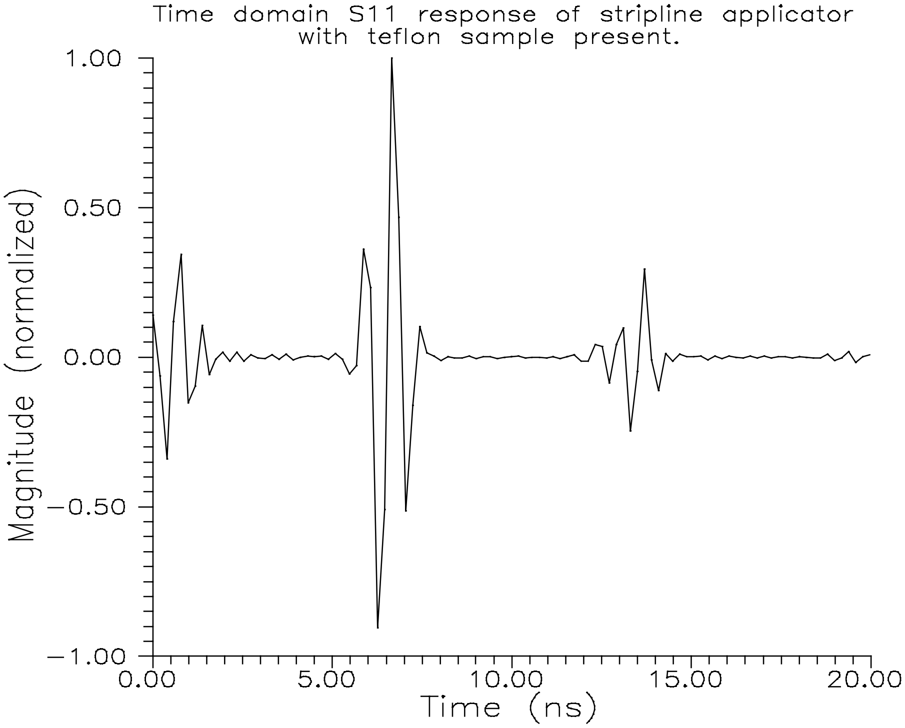
- microstrip applicator mechanically simple
    - allows for easy placement and adjustment of standards and sample materials
    - less difficult to machine standards and sample materials
    - applicator can accommodate a wide variety of sample sizes
- microstrip ideally suited for high temperature experiments
    - requires only a sample substrate reducing thermal expansion difficulties
    - simple design less likely to experience mechanical failures due to multiple heating/cooling cycles

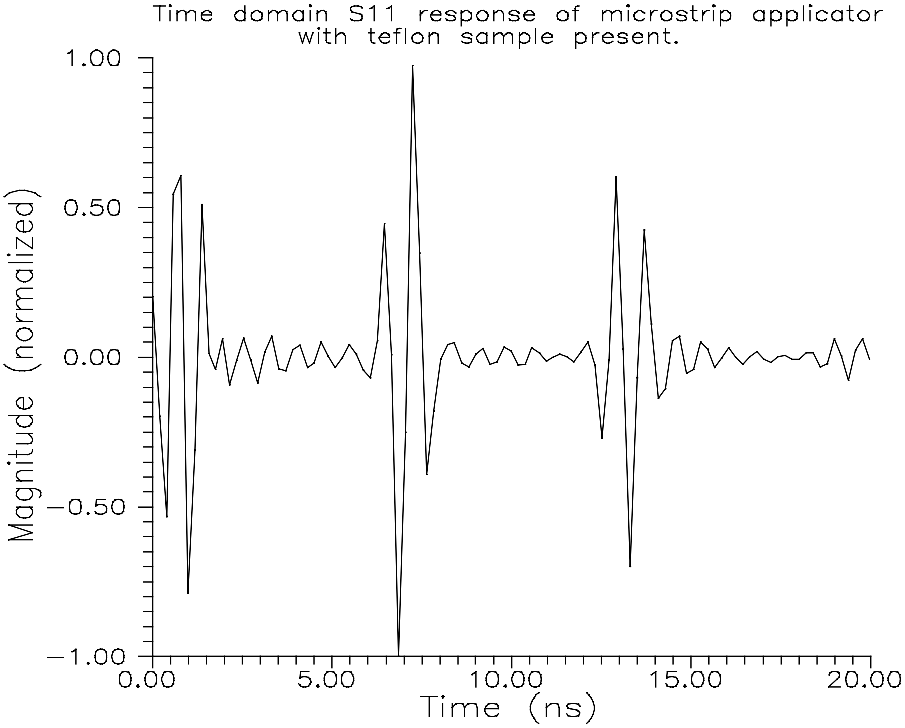
Difficulties associated with microstrip applicator

- complex propagation-mode spectrum makes analysis of applicator difficult
- good results presently limited to measurement of low permittivity, low loss materials.
- difficult to design good coax-to-microstrip transitions

Comparison of Applicator Responses

- reflections and noise from microstrip transition regions are more severe than for stripline





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
  - 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

  ·$S^{p}_{11\ short} = [S^{a}_{12}]\,[S^{a}_{21}]\,[-1]$ $\qquad C_{R} = [S^{a}_{12}]\,[S^{a}_{21}]$

  ·$S^{p}_{11} = [S^{a}_{12}]\,[S^{a}_{21}]\,S_{11\ sample}$

  ·$S^{p}_{21\ empty} = [S^{a}_{21}]\,[S^{b}_{21}]\,e^{-jk_{o}l_{s}}$ $\qquad C_{T} = [S^{a}_{21}]\,[S^{b}_{21}]$

  ·$S^{p}_{21} = [S^{a}_{21}]\,[S^{b}_{21}]\,S_{21\ sample}$

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

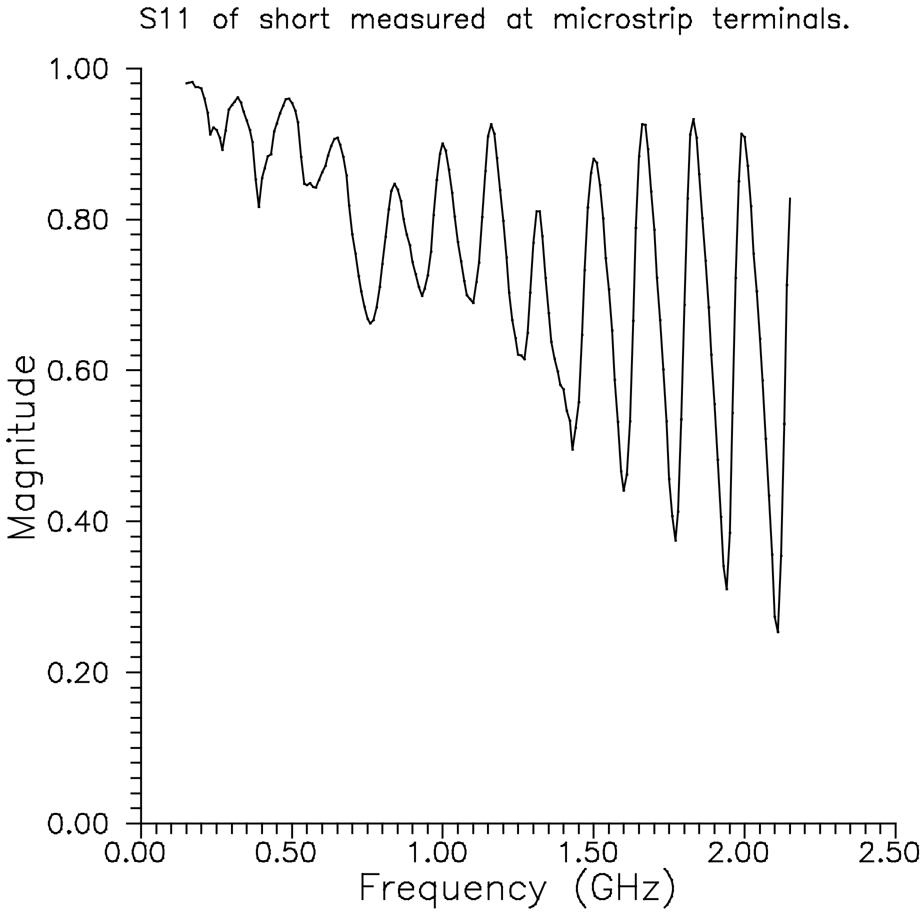
- effective complex constitutive parameters (ε_{eff},μ_{eff}) of sample material determined from processed sample S-parameters using Nicholson-Ross-Weir method

- relative complex constitutive parameters (ε_{r},μ_{r}) of sample material determined from effective values using Pucel-Masse equations

Signal Processing Scheme

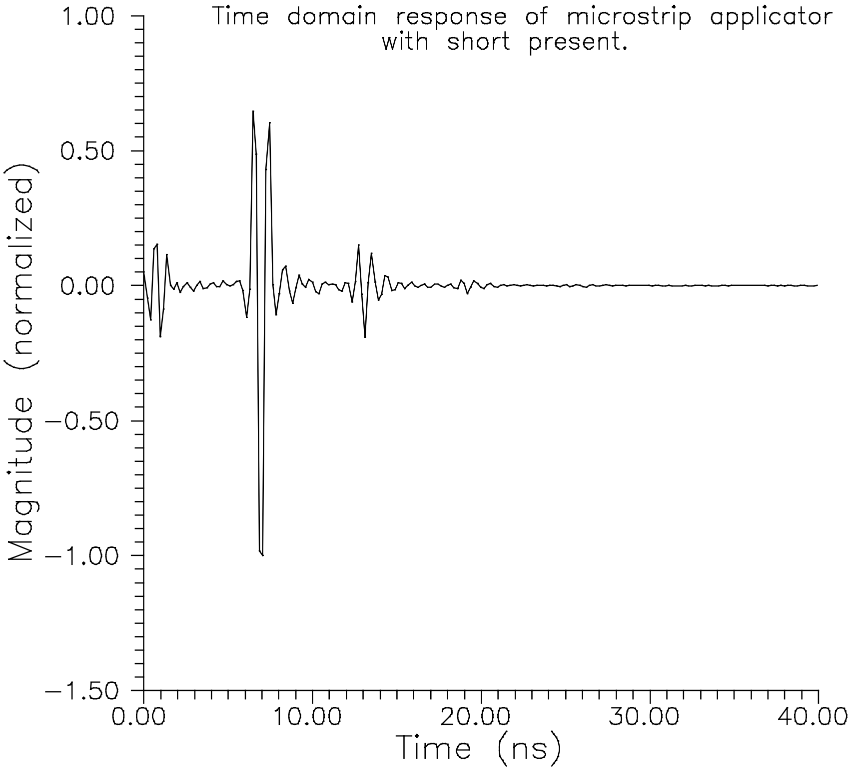
i. determination of sample S_{11} parameter (S_{11}^{s}):

- terminal short circuit S_{11} measurement:

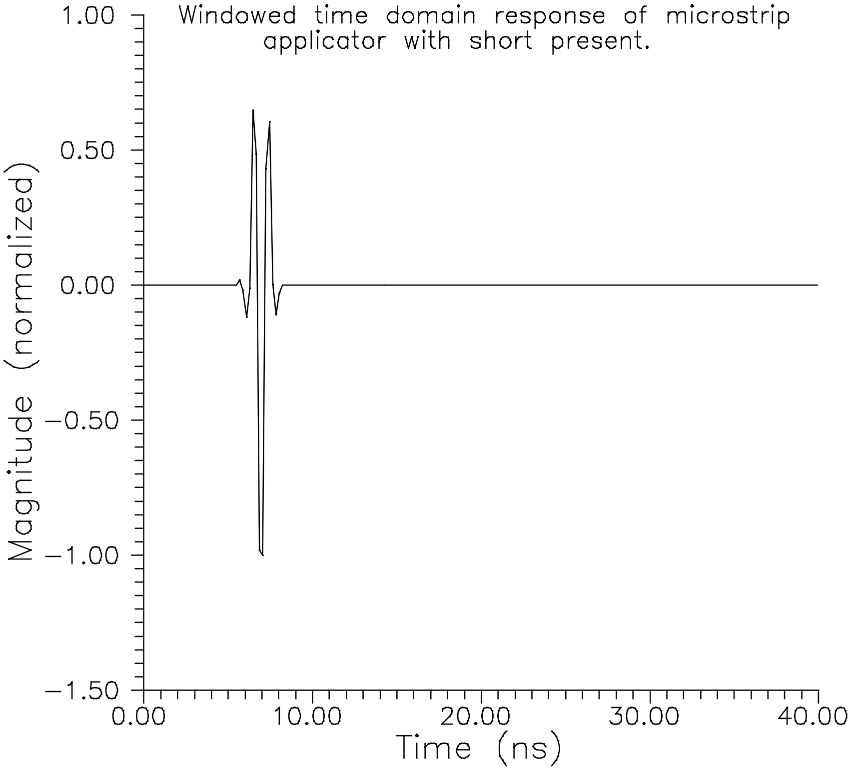


- apply weighting function to short circuit S_{11} measurement

- calculate IFFT of weighted short circuit S_{11}



- window out transition region effects



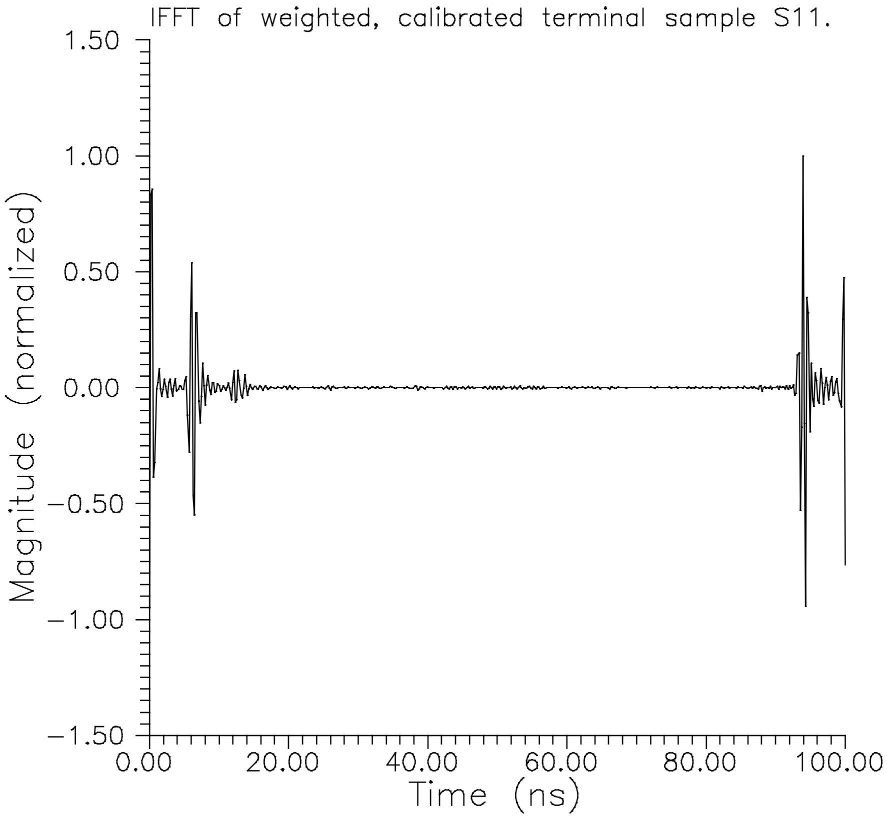
- calculate FFT of windowed time-domain data
- remove weighting function

remaining signal is $\boldsymbol{R}_1 = [S_{12}^a]\,[S_{21}^a]\,S_{11\,short} = -[S_{12}^a]\,[S_{21}^a]$

- scale amplitude of R_1 by factor of -1

remaining data is reflection calibration $C_{\boldsymbol{R}} = [S_{12}^a]\,[S_{21}^a]$

- 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}):

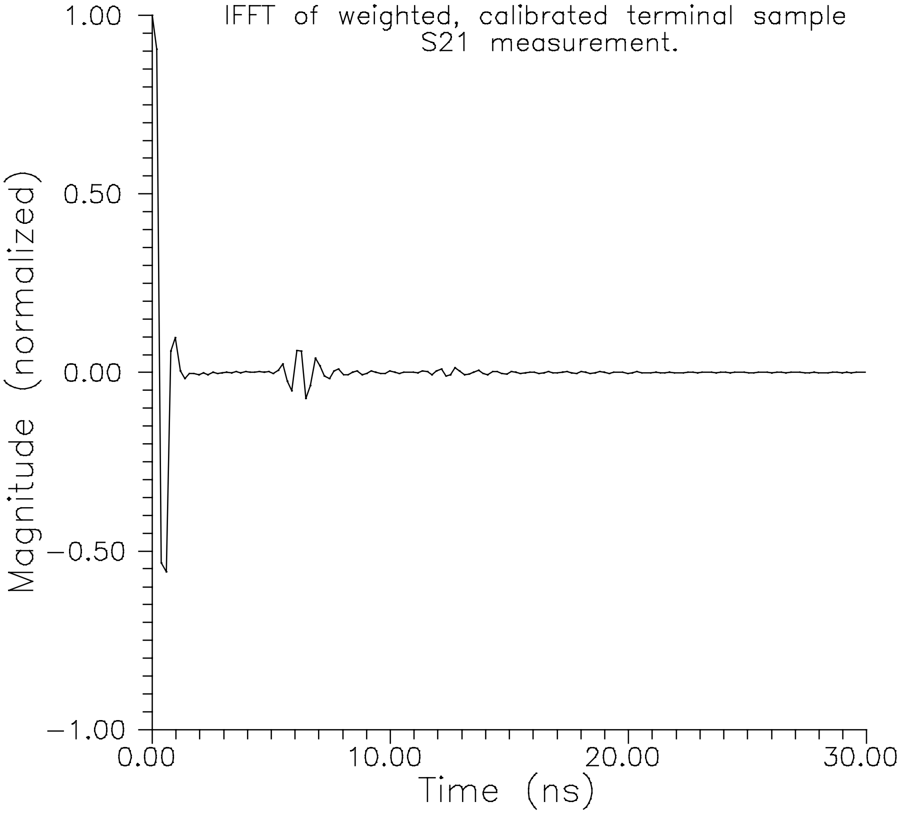
- terminal empty applicator S_{21} measurement

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

- 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 transmissions
- 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

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

- effective constitutive parameters ε_{eff} and μ_{eff} represent a continuous, homogeneous medium filling dielectric and air regions of the microstrip

- determine effective constitutive parameters (ε_{eff}, μ_{eff}) from processed sample region S-parameters

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

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

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

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

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

β = propagation phase constant of sample region

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

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

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

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

- equating measured $\beta_m(\omega)$ and $\Gamma_m(\omega)$ to corresponding theoretical values leads to a pair of equations which can be solved for effective complex ϵ_{eff} and μ_{eff}.

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

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

- effective constitutive parameters relate to characteristic impedance and propagation constant by

$$\beta = k = \frac{\omega}{c}\sqrt{\epsilon_{eff}\mu_{eff}}\ , \qquad Z_c = \eta f_g = \eta_0\sqrt{\frac{\mu_{eff}}{\epsilon_{eff}}}f_g \qquad \mathbf{(10)}$$

f_g = purely geometrical factor

$$\Gamma = \frac{\sqrt{\frac{\mu_{eff}}{\epsilon_{eff}}} - 1}{\sqrt{\frac{\mu_{eff}}{\epsilon_{eff}}} + 1} \quad \text{... provides} \quad \frac{\mu_{eff}}{\epsilon_{eff}} = \left(\frac{1+\Gamma}{1-\Gamma}\right)^2 = X \qquad \mathbf{(11)}$$

$$\ln(T) = -j\beta l_s \quad \text{... provides} \quad \epsilon_{eff}\mu_{eff} = -\left[\frac{c}{\omega l_s}\ln(T)\right]^2 = Y \qquad \mathbf{(12)}$$

consequently

$$\epsilon_{eff} = \sqrt{\frac{Y}{X}}\ , \qquad \mu_{eff} = \sqrt{XY} \qquad \mathbf{(13)}$$

ii. Pucel-Masse Method

- relationship between effective permittivity and relative permittivity 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

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

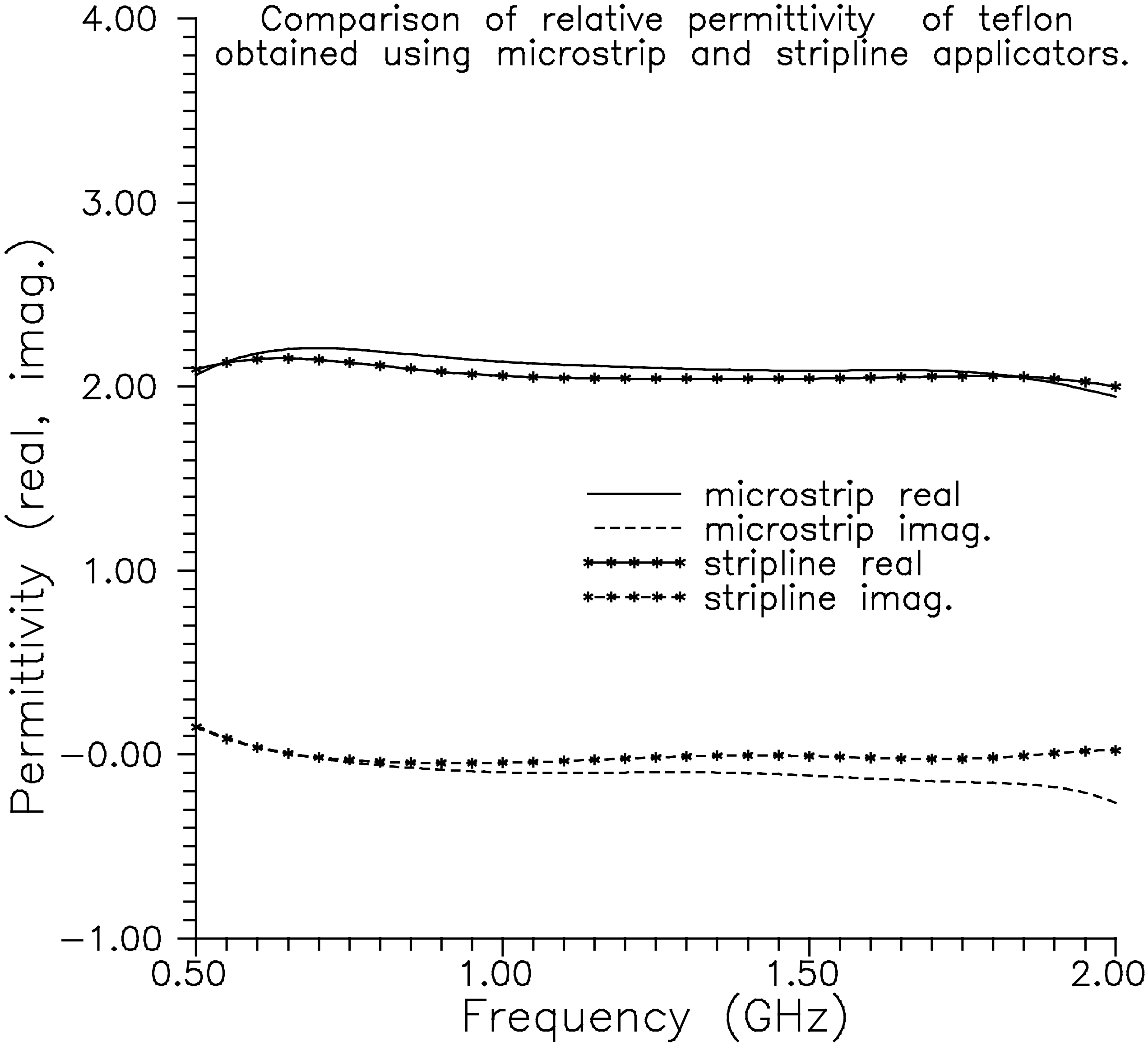
- relative permittivity and relative permeability are determined from root searches of

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

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

IV. COMPARISON OF MICROSTRIP AND STRIPLINE RESULTS

teflon data



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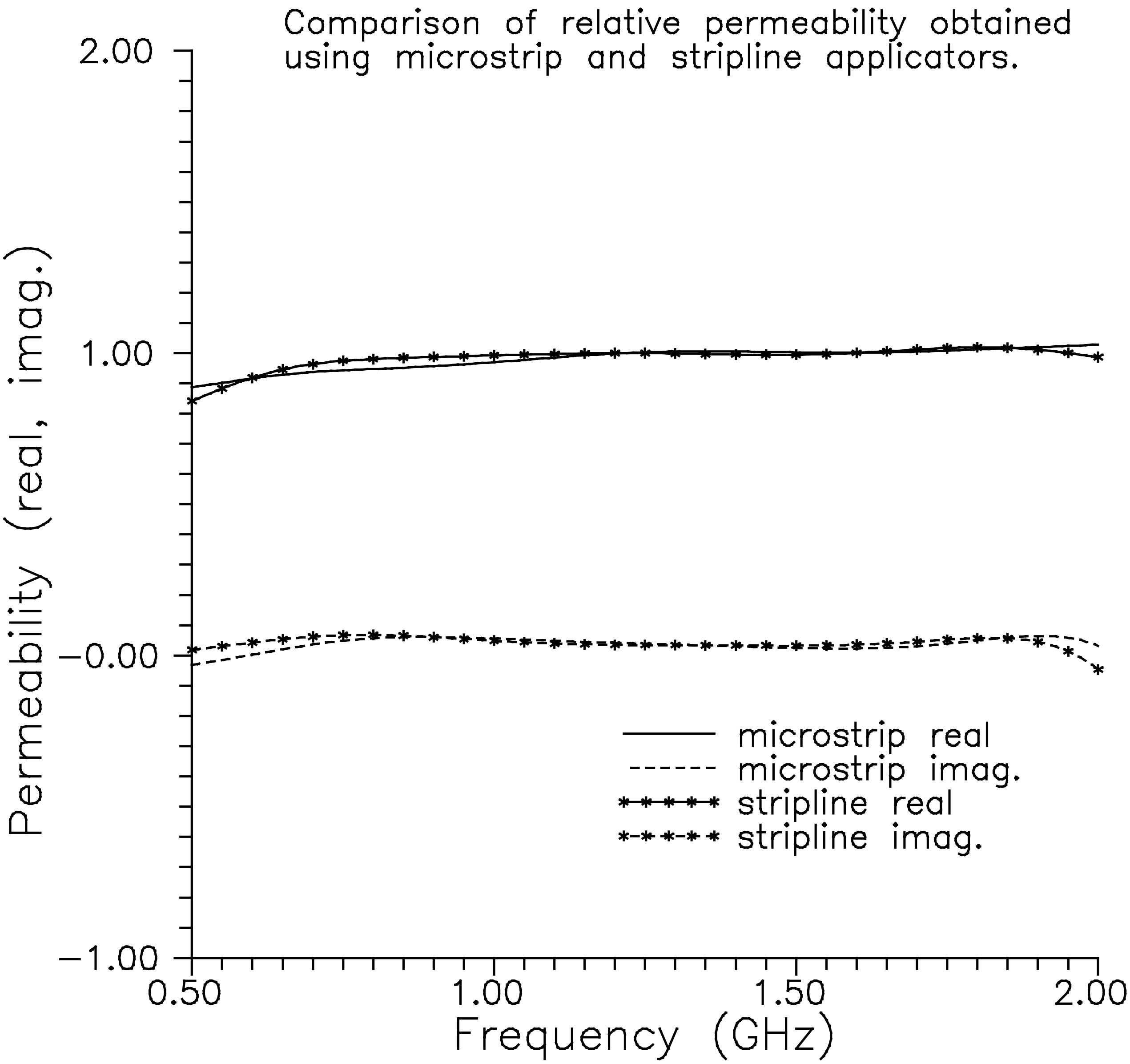
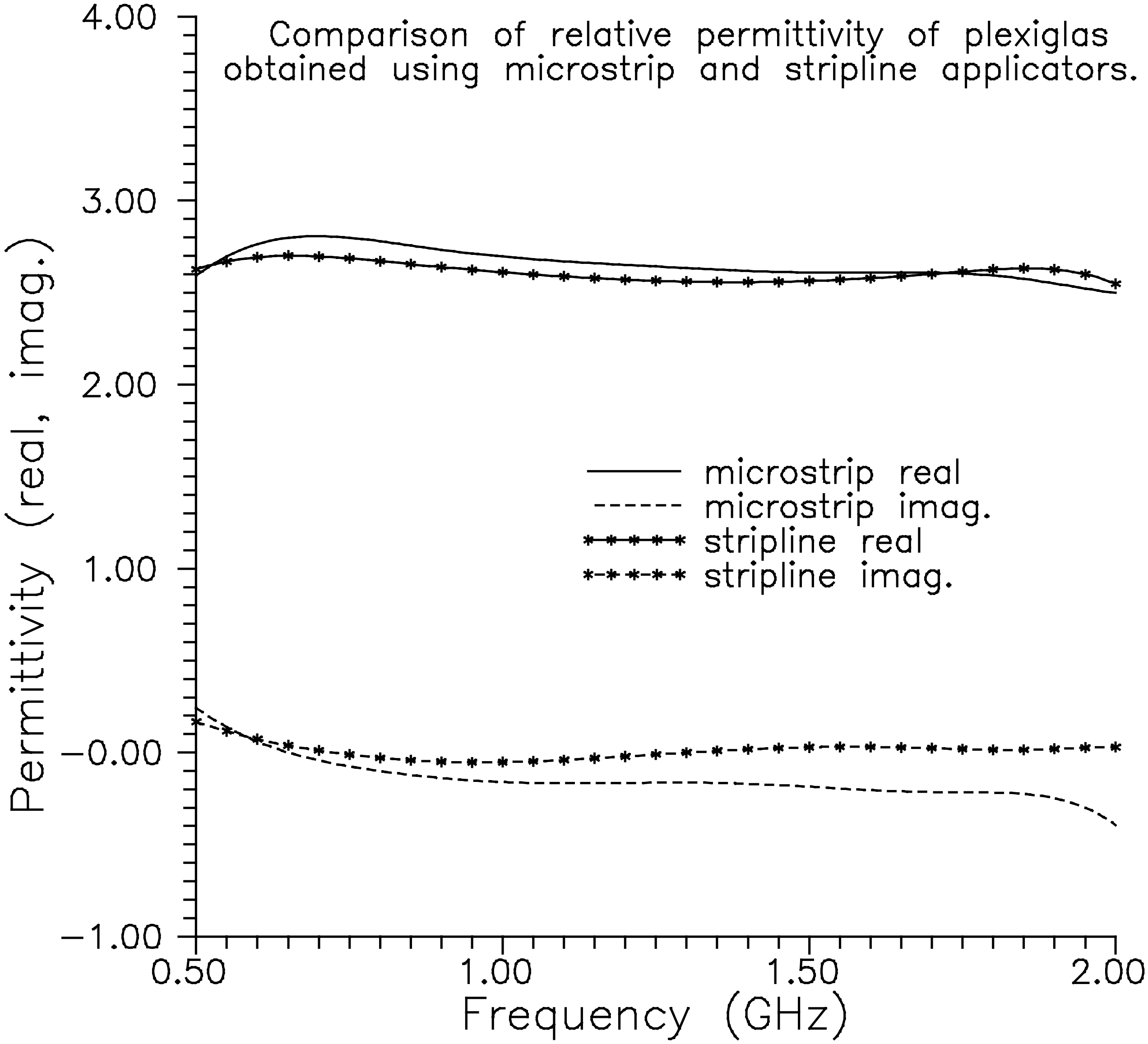

Comparison of relative permeability obtained
using microstrip and stripline applicators.
2.00
1.00
−0.00
−1.00
Permeability (real, imag.)
0.50
1.00
1.50
2.00
Frequency (GHz)
microstrip real
microstrip imag.
stripline real
stripline imag.

plexiglas data



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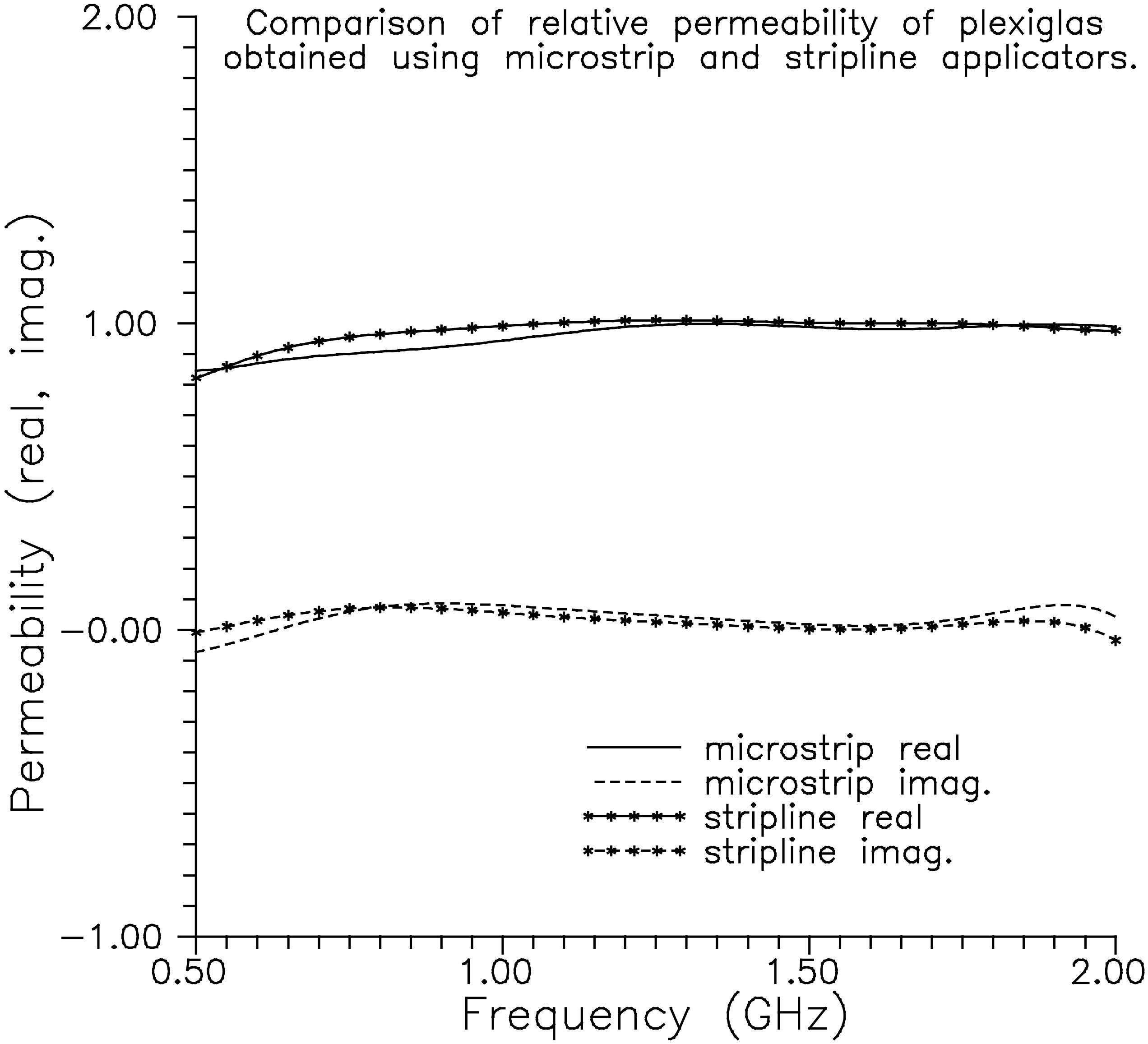
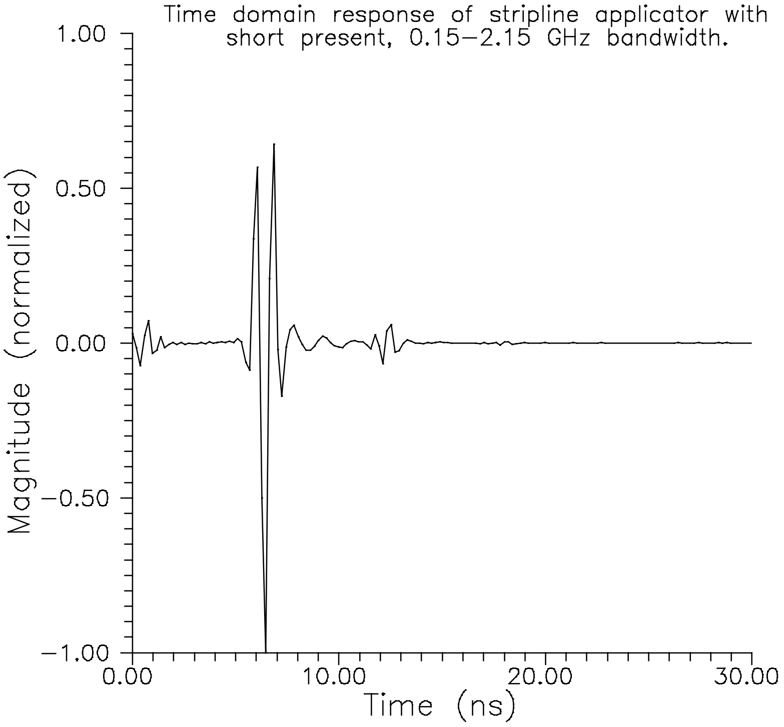
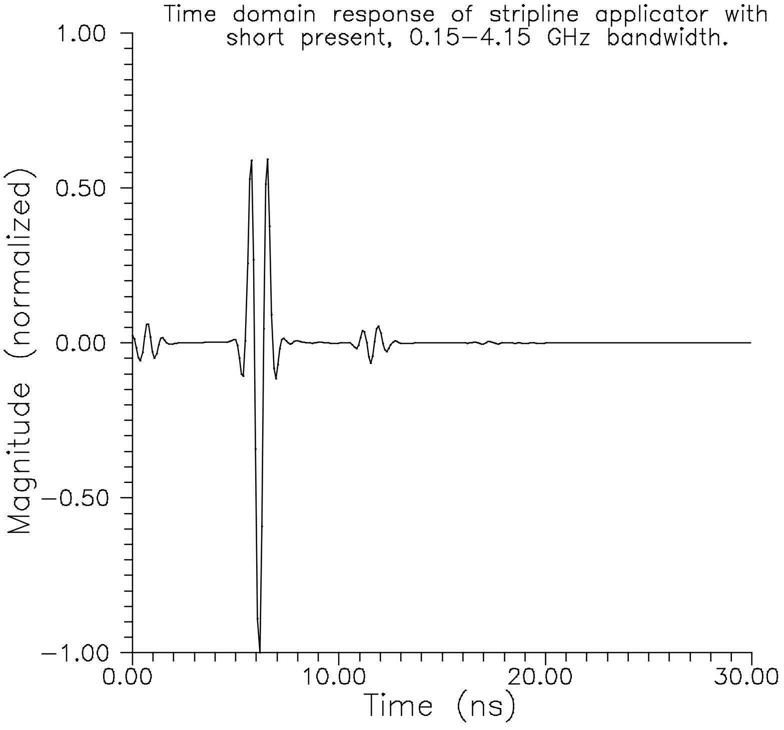


V. FUTURE WORK

- attempts will be made to extend the bandwidth of the microstrip applicator
  · extended bandwidth increases time domain resolution





VI. CONCLUSION

- a calibration process involving time windowing techniques has been developed for use with a microstrip field applicator

- results obtained using microstrip applicator are comparable to those obtained using a stripline applicator for low loss, low permittivity materials