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Methods for permittivity, permeability, and loss measurements of polymer composite magneto-dielectric laminates

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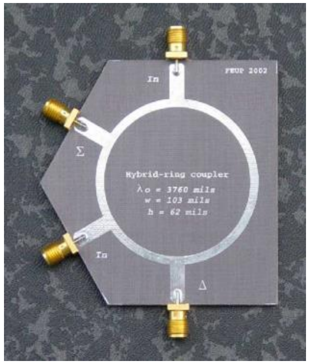
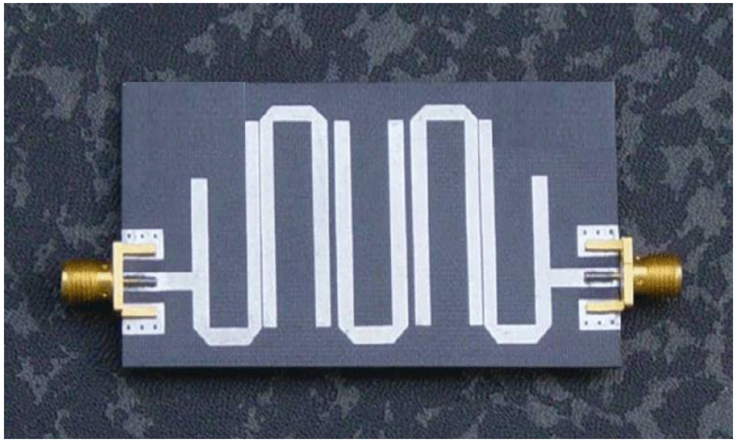
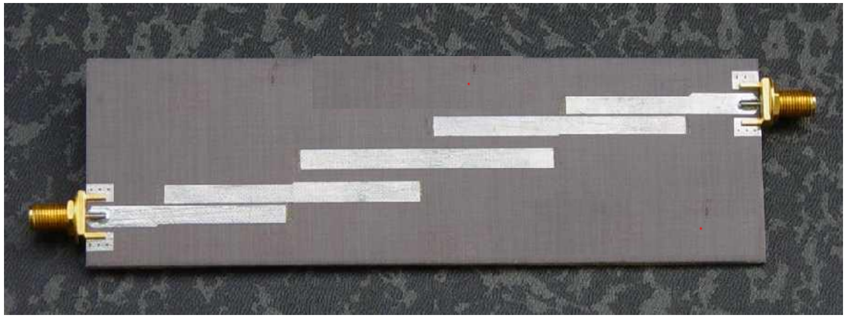
- Basics of copper-clad laminates for high frequency applications
- Magneto-dielectrics - MAGTREX™555 high impedance laminates
- Frequency dependence of dielectric and magneto-dielectric materials.
- Magneto-dielectric in patch antennas
- Permittivity and Permeability Testing
  - Loosely coupled resonators
  - Impedance Analyzer
  - Transmit/reflect measurements

- Measured & modeled performance

- In high frequency circuitry, precise control of signal wavelength affects circuit performance.
- Higher permittivity substrates allow miniaturization
- $\boldsymbol{\lambda = c/f\sqrt{\varepsilon_r \mu_{r_{(eff)}}}}$







Photos from https://paginas.fe.up.pt/~hmiranda/etele/microstrip/

- Miniaturization factor $\sqrt{\boldsymbol{\varepsilon_r \mu_r}}$
- Impedance of free space $\sqrt{\left(\frac{\mu_0}{\varepsilon_0}\right)}$
- Impedance of a material $\sqrt{\left(\frac{\mu_0}{\varepsilon_0}\right)\left(\frac{\mu_r}{\varepsilon_r}\right)}$
- Most materials have values of ε_r> 1 and μ_r = 1, exceptions being ferrous metals, alloys, and ferrites.
- Material impedance is lower than free space, leading to impedance mis-match and reflections.

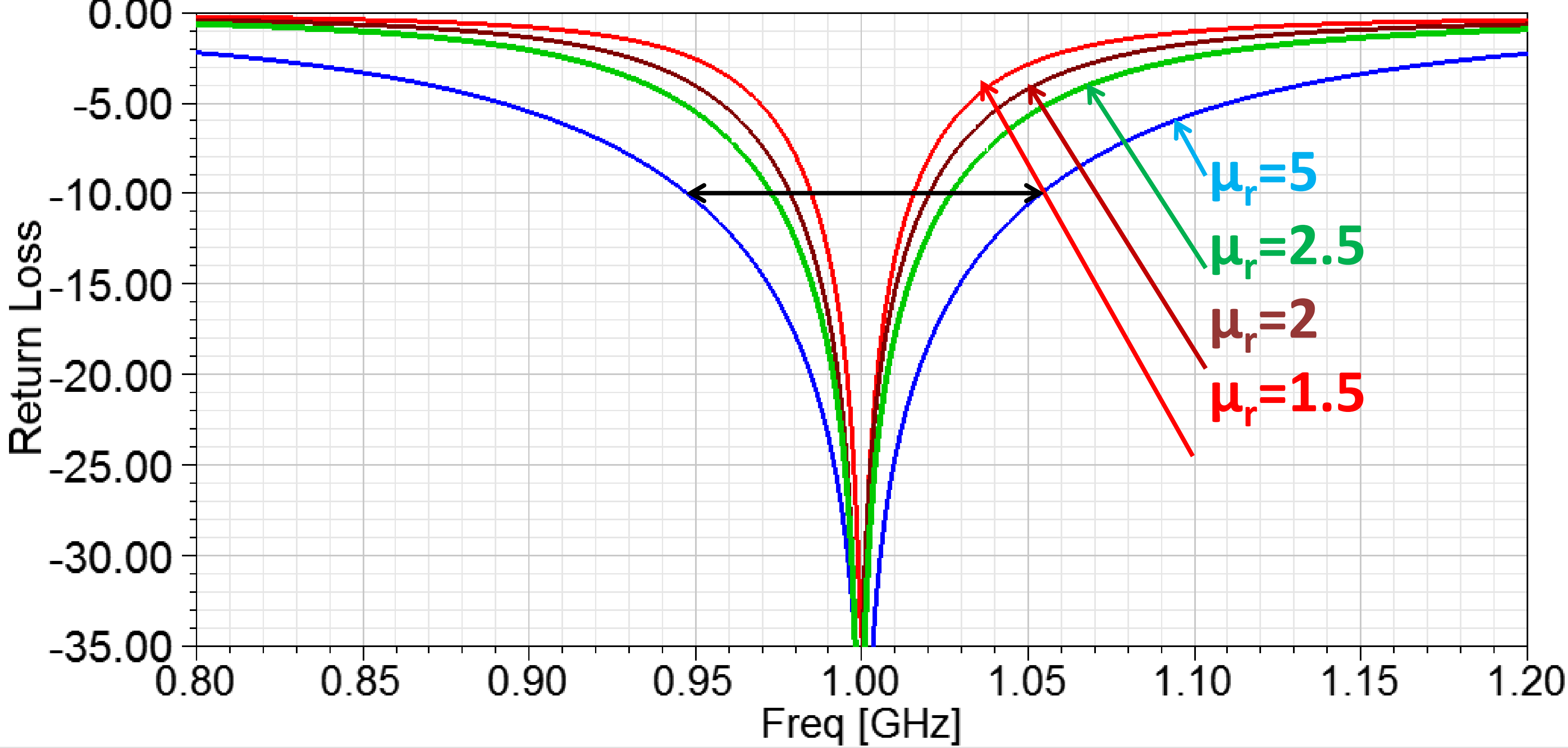
- If $\mu_r = \varepsilon_r$, then $\sqrt{\left(\frac{\mu_0}{\varepsilon_0}\right)\left(\frac{\mu_r}{\varepsilon_r}\right)} = \sqrt{\left(\frac{\mu_0}{\varepsilon_0}\right)}$

- The material is impedance-matched to free-space and if it has a high enough dielectric and magnetic loss, it is radar-absorbing.

- If the material can be made to have low magnetic and dielectric loss, it can be used to substantially improve the patch size-antenna height – bandwidth trade-off of patch antennas

- In 2000, Hansen and Burke modeled patch antenna performance when then-hypothetical low loss $\mu_r > 1$ and $\varepsilon_r > 1$ laminates.
- Result for VSWR = 2 bandwidth

$$BW = \frac{96\sqrt{\left(\frac{\mu_r}{\varepsilon_r}\right)}\, t/\lambda_o}{\sqrt{2}\,\left[4 + 17\sqrt{(\mu_r \varepsilon_r)}\right]}$$



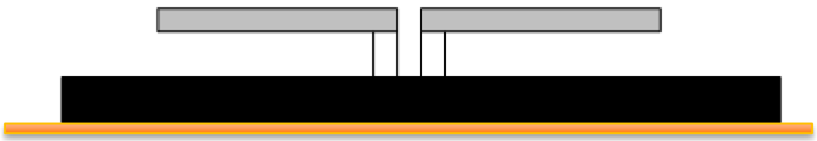
Initial Patch Size: 4.3 X 4 cm
Ground: 7.2 X 6.8cm
Substrate thickness: 4mm
Epsilon=6, Tan(eps)=0.005,
Mu, 1.5, 2, 2.5, 5 for constant tandμ

Patch Bandwidth Equation → for a given material miniaturization factor, bandwidth is μ_r times larger.

1. Hansen, R. C., and Mary Burke. "Antennas with magneto-dielectrics." Microwave and Optical Technology Letters 26.2 (2000): 75-78.

Material Use Cases

Cavity Loading Element



- Air gap between antenna elements and MAGTREX™ material
- Material provides Z – Axis miniaturization

Height reduction with excellent antenna performance.

Hybrid PCB Antenna

- PCB substrate between antenna conductor and MAGTREX material
- Material primarily used for Z axis miniaturization

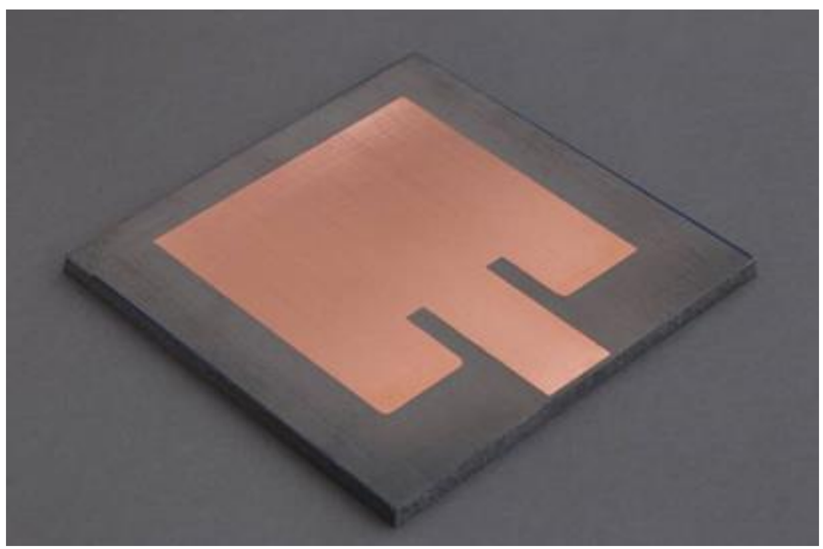
Additional size reduction, reduced height, and X/Y area.

MAGTREX | PCB | Copper

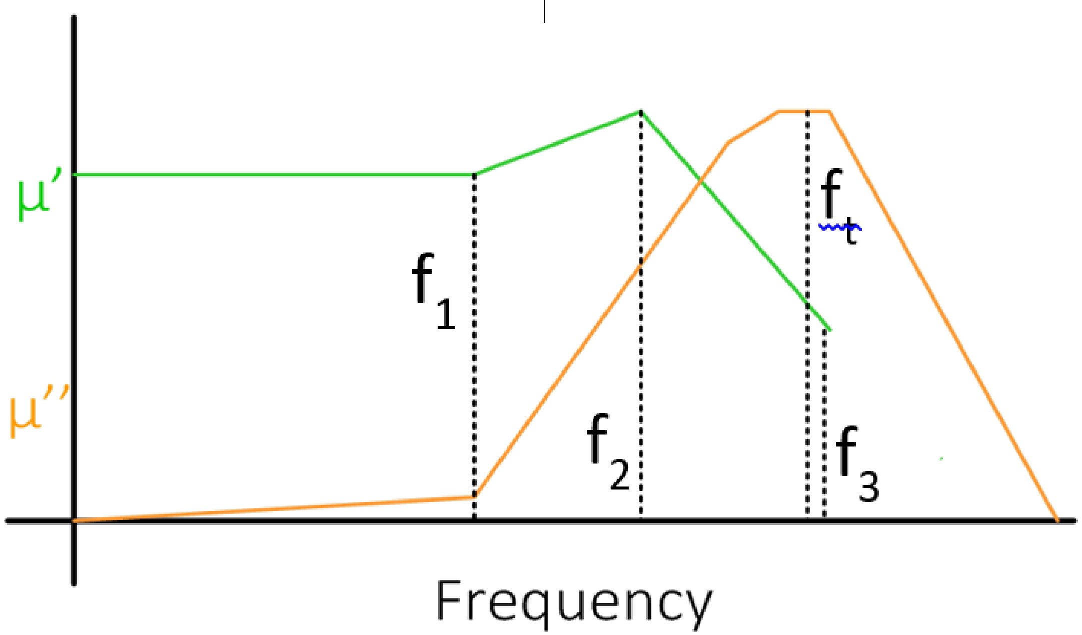
Material Use Cases

MAGTREX™ 555 Laminate

- Copper-clad laminate
- X,Y,Z Miniaturization



- Low loss dielectric materials exhibit simple behavior of permittivity and loss with frequency.
- ε_R decreases slightly with increasing frequency.
- DF increases slightly with increasing frequency
- Frequency effects on permeability and magnetic loss are more complicated



f_1 – μ' starts rising

f_2 – Peak of μ'

f_3 – μ' = 1.0

f_t – Cutoff frequency;

peak of μ"

Figure 1
Typical μ' and μ" behavior versus frequency

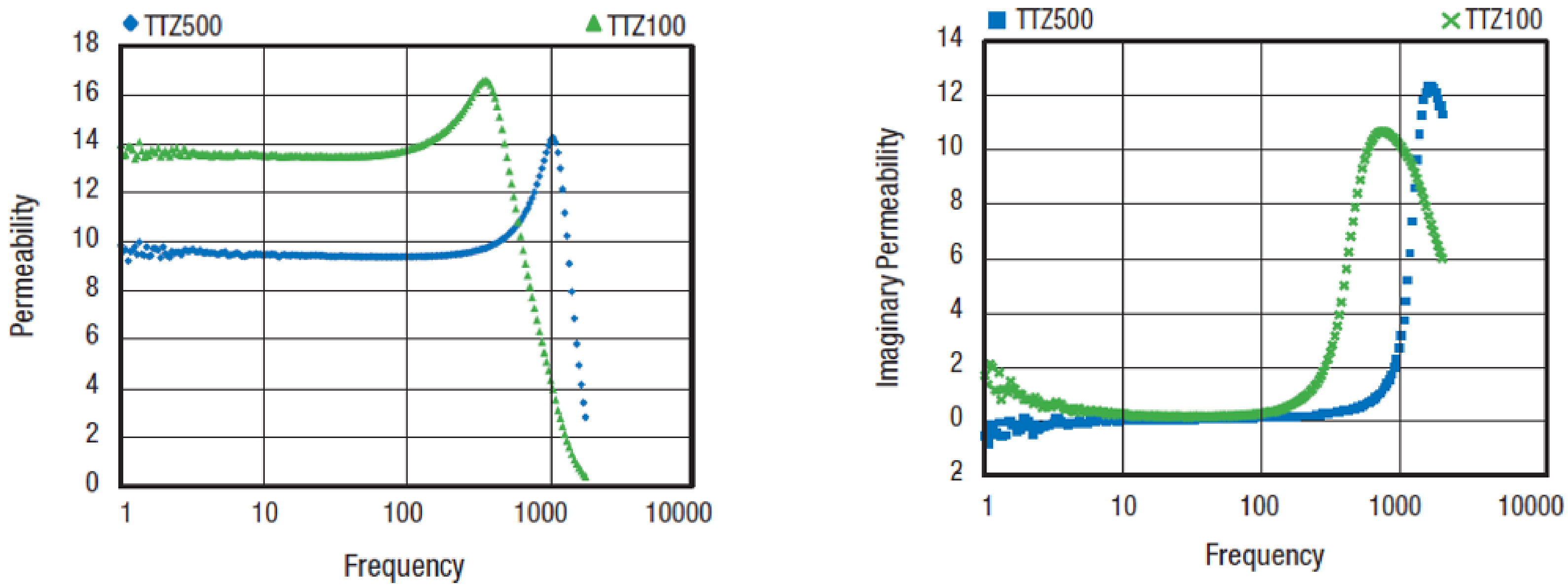


Figure 2

μ’ and μ” for Skyworks TTZ-100 and TTZ-500 Hexaferrites – taken from reference 12

Frequency in MHz

- Loosely coupled resonator tests eliminate need for system calibration, but one can only extract $\sqrt{\boldsymbol{\varepsilon}_{\boldsymbol{r}}\mu_{\boldsymbol{r}}}$ and not separate ε_R and μ_R values

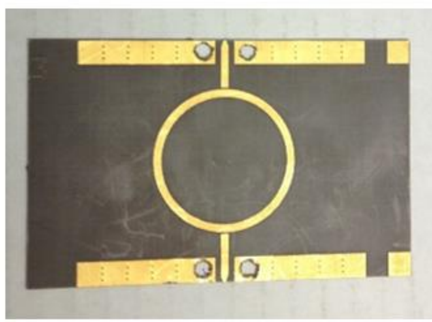


Figure 4a – microstrip ring resonator

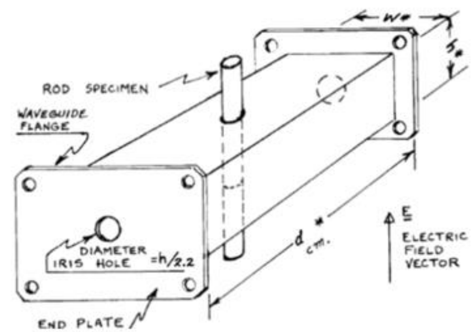
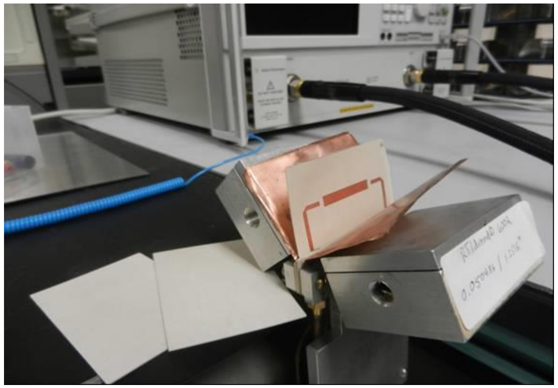
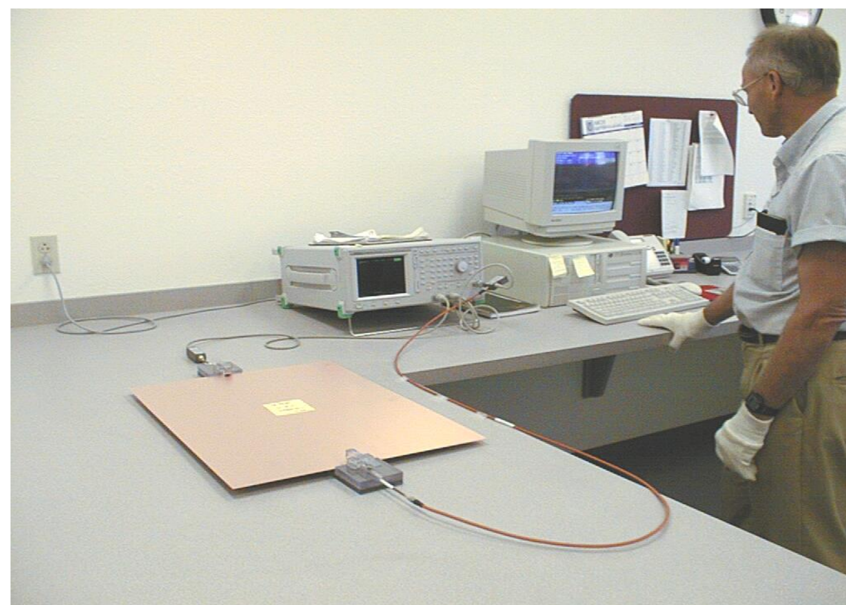


Figure 4b – waveguide cavity resonator



Clamped stripline resonator
IPC-TM-650 2.5.5.5.1



Full Sheet Resonator
IPC-TM-650 2.5.5.6

- $\sqrt{\boldsymbol{\varepsilon_r}\mu_r}$ is calculated from the sample size and change in resonant frequency in the case of a cavity resonator

- $\sqrt{\boldsymbol{\varepsilon_r}\mu_r}$ is calculated from resonant frequency and resonator dimensions for ring or patch circuits

Clamped stripline patch - $\mu_R\varepsilon_R = (n\ c / 2\ f_r\ (L + \Delta L))^2$

Ring - $(\mu_R\varepsilon_R)_{\mathrm{eff}} = (n\ c / f_r\ 2\pi R))^2$

Full-sheet - $\mu_R\varepsilon_R = \left(\frac{c}{2f_{R[M:N]}}\right)^2 \left(\left\{\frac{M}{L}\right\}^2 + \left\{\frac{N}{W}\right\}^2\right)$

- Resonator tests require an impedance discontinuity (gap or iris plate) to create the resonant structure.

- The impedance discontinuity dominates the reflection, not the impedance of the sample.

- A transmission and reflection method is needed to obtain both $\sqrt{\boldsymbol{\varepsilon_r}\mu_{\boldsymbol{r}}}$ and $\sqrt{\left(\frac{\mu_r}{\varepsilon_r}\right)}$ to calculate ε_R and μ_R separately

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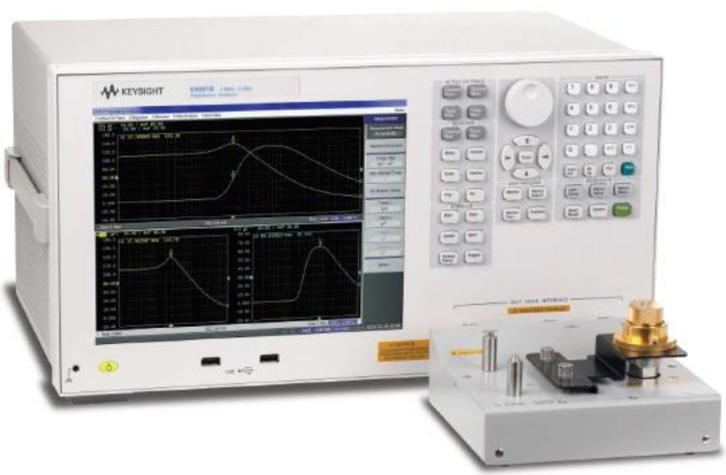
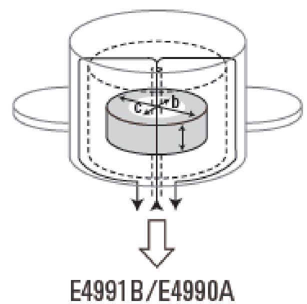
- The most commonly used method for measuring permeability of magnetic materials at higher frequencies is the Keysight 16454A Magnetic Test Fixture paired with an impedance analyzer that nominally operates to 1 GHz.



Applicable instruments: E4991B (Option E4991B-002)*, E4990A, and 42942A



$$\dot{\mu} = \frac{(\dot{Z}m - \dot{Z}sm)}{j\omega\mu_0}\,\frac{2\pi}{h\ ln\,\frac{c}{b}} + 1$$

$\dot{\mu}$	Relative permeability
$\dot{Z}m$	Measured impedance with toroidal core
$\dot{Z}sm$	Measured impedance without toroidal core
μ_0	Permeability of free space
h	Height of MUT (material under test)
c	Outer diameter of MUT
b	Inner diameter of MUT

Unfortunately, Keysight's data show that the instrument exhibits high error (>20%) in the range of μ_R <10 at frequencies above 100 MHz

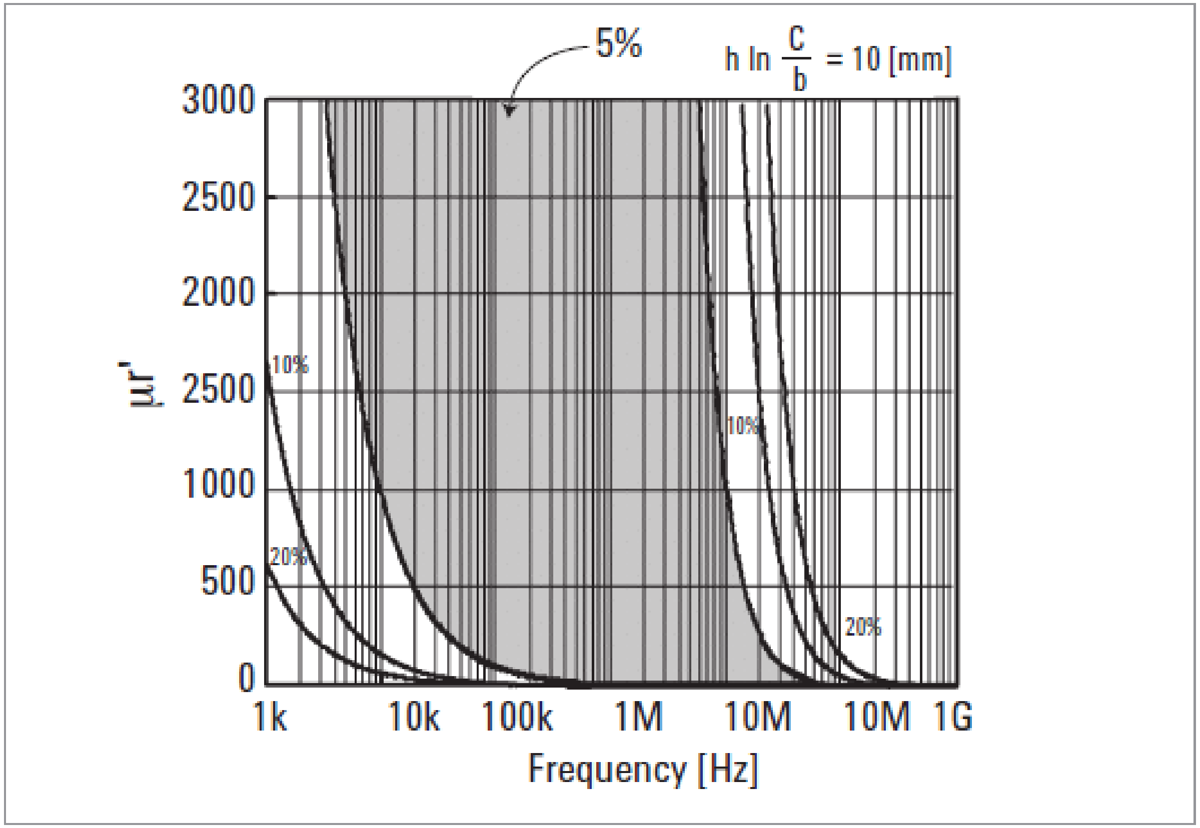
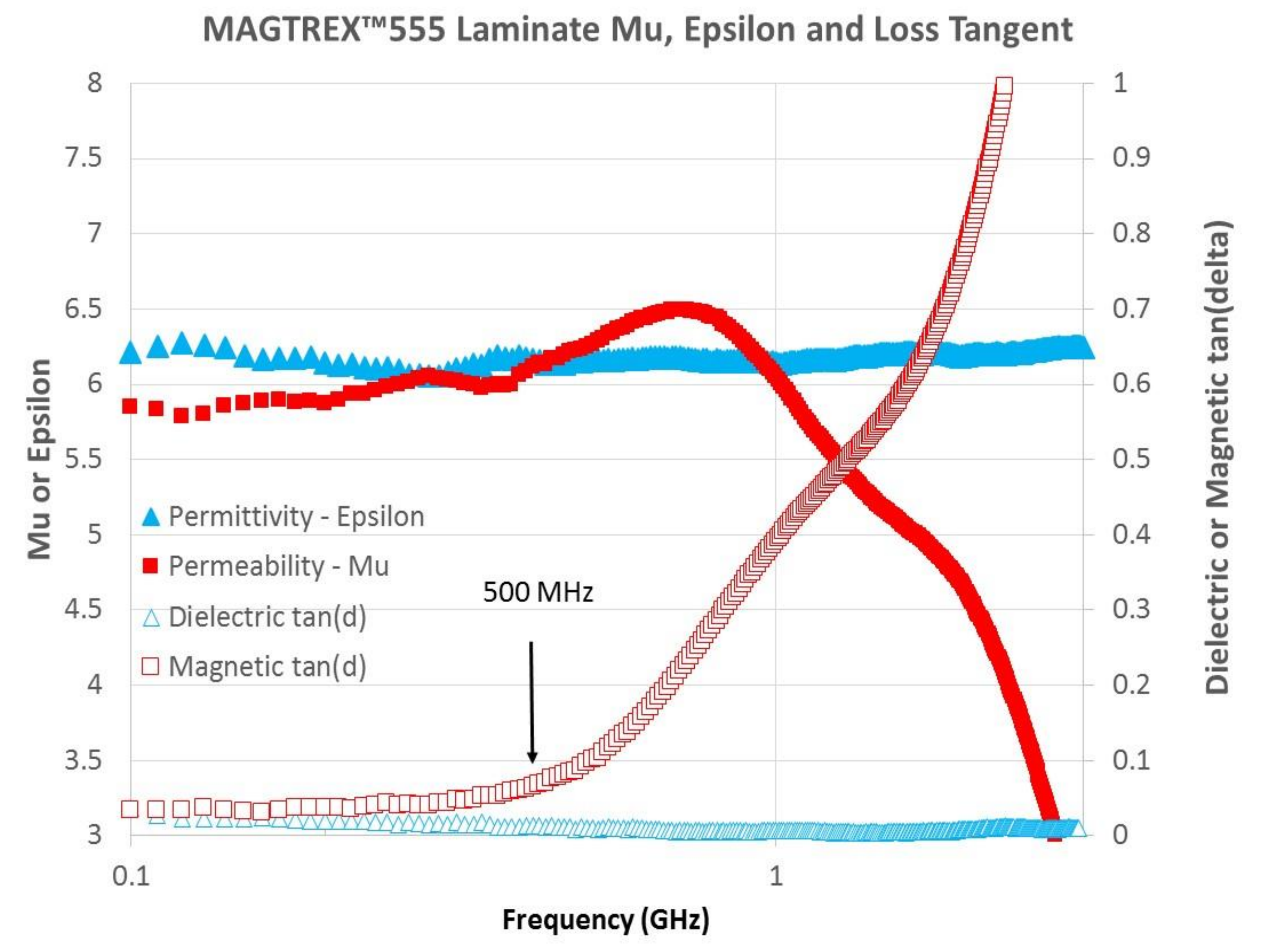


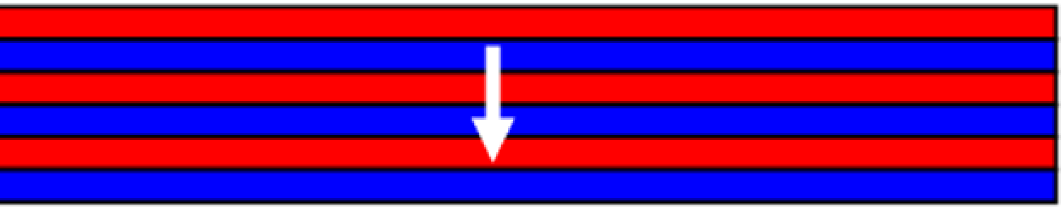
Figure 28. Permeability measurement accuracy (supplemental data)

- Baker-Jarvis et al[15] from NIST-Boulder describe non-resonant transmission line test methods using waveguides and coaxial airlines.
- We are interested in the 100 MHz to 1 GHz frequency range.
- Those would be inconveniently large waveguides and several different bands would be necessary to cover the range.
- Coaxial airlines commonly are made in diameters of 7, 14, and 25 mm. NIST recommends as large as possible to minimize errors associated with sample dimensions

Damaskos, Inc. 25 mm Coaxial Airline

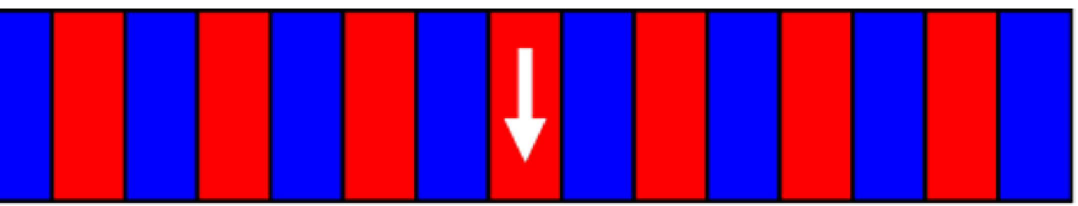
- Calibrate to cable ends
- Keysight “AFR” (automatic fixture removal – 2XThrough)
- Insert precision machined annular ring sample
- Measure full s-parameters from 100 MHz to 3 GHz.
- Apply Nicholson-Ross-Weir equations to extract permittivity, permeability and magnetic and dielectric losses


MAGTREX™555 Laminate Mu, Epsilon and Loss Tangent
Mu or Epsilon
Dielectric or Magnetic tan(delta)
Frequency (GHz)
Permittivity - Epsilon
Permeability - Mu
Dielectric tan(d)
Magnetic tan(d)
500 MHz
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
1



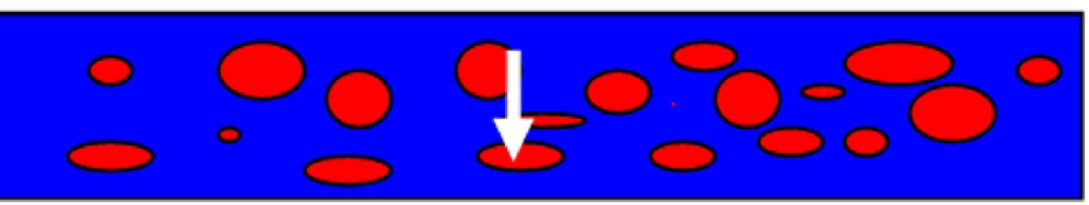
$$\varepsilon_{Rcomposite} = 1/\sum_{i=1}^{N} v_i \varepsilon_{Ri}^{\ -1}$$

Series Arrangement



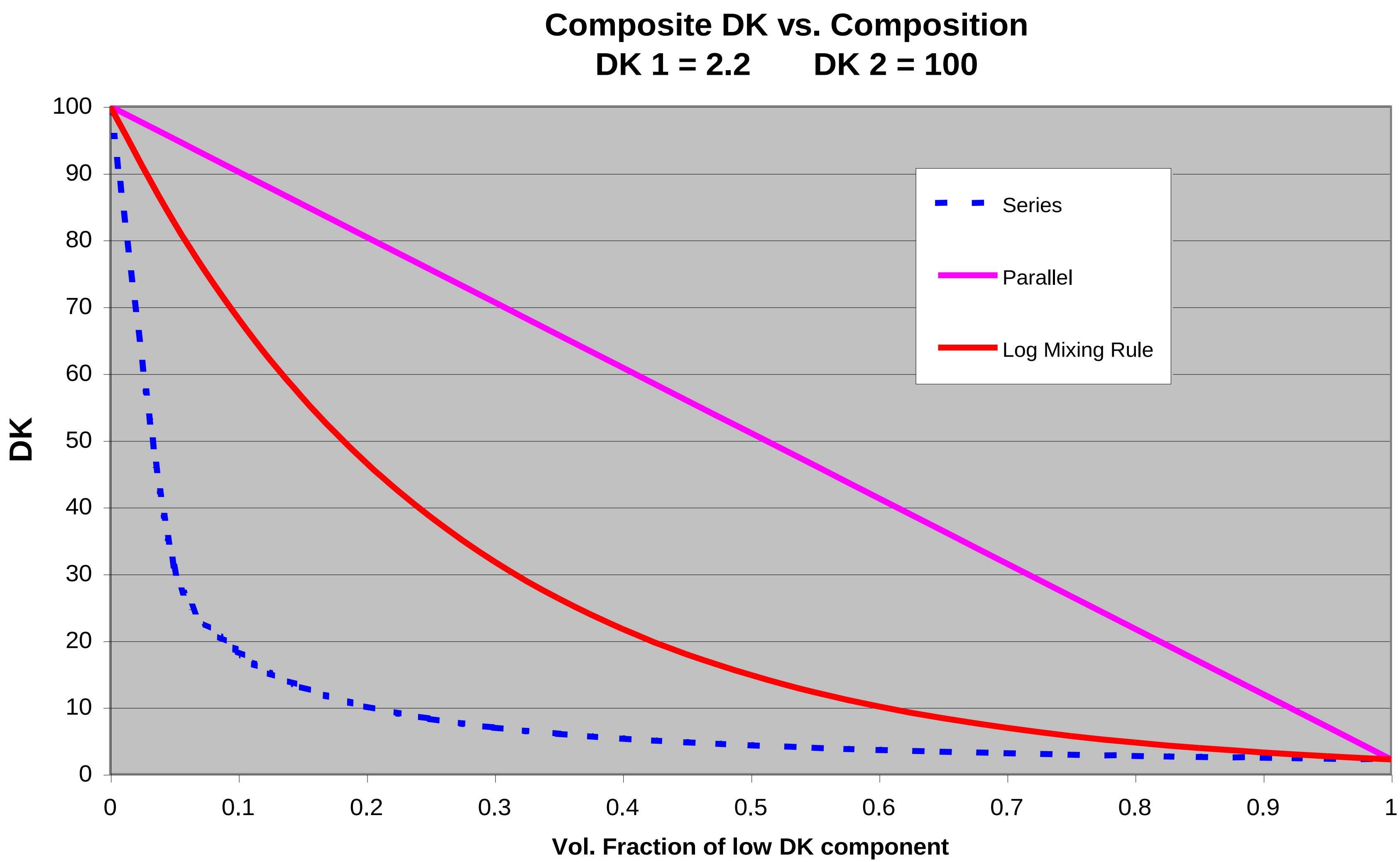
$$\varepsilon_{Rcomposite} = \sum_{i=1}^{N} v_i \varepsilon_{Ri}$$

Parallel Arrangement



$$\log(\varepsilon_{Rcomposite}) = \sum_{i=1}^{N} v_i \log(\varepsilon_{Ri})$$

Dispersed Arrangement

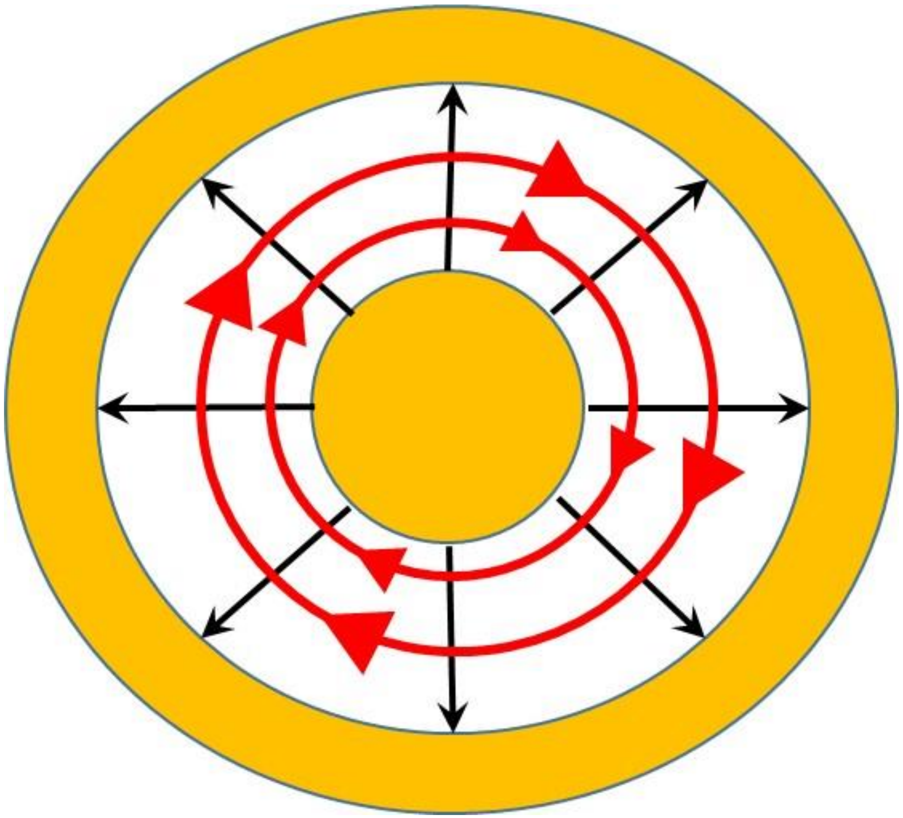

Composite DK vs. Composition
DK 1 = 2.2 DK 2 = 100
DK
100
90
80
70
60
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Vol. Fraction of low DK component
Series
Parallel
Log Mixing Rule

Copper foil

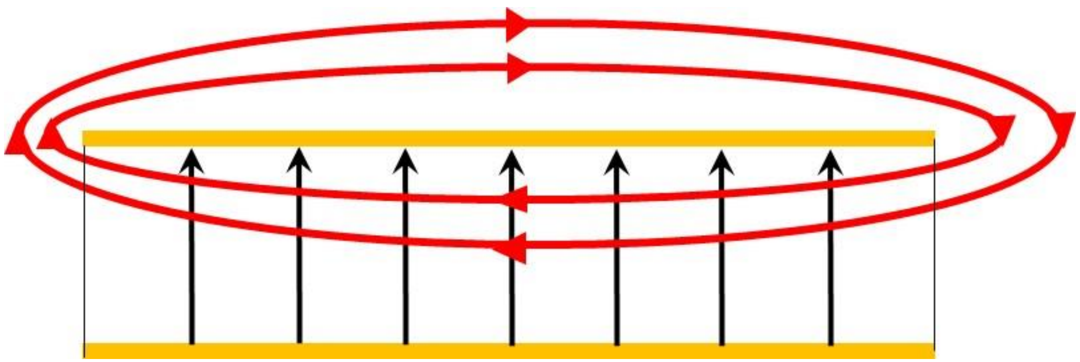
Composite with high degree of in-plane particle alignment

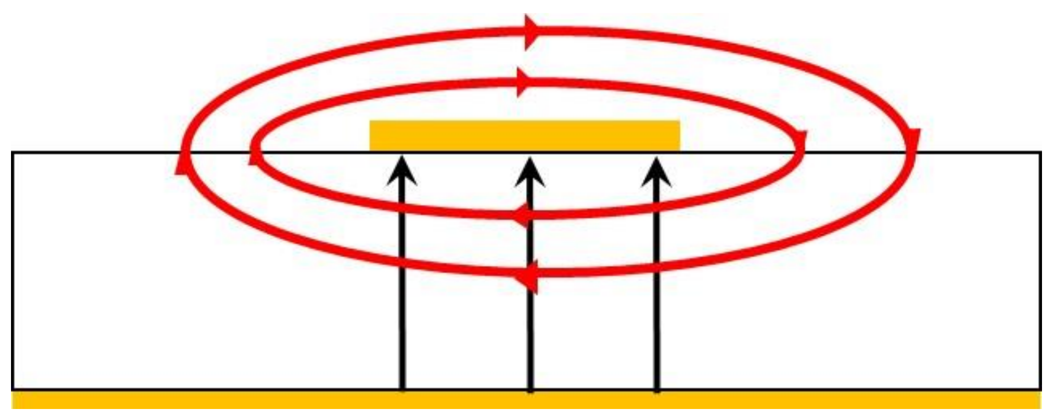
Copper foil

- Coaxial line: Both E-field and H-field are oriented in-plane



- Microstrip and Full-sheet resonance:
  E-field is out of plane – lower composite ε_R
  H-field is in-plane – same composite μ_R

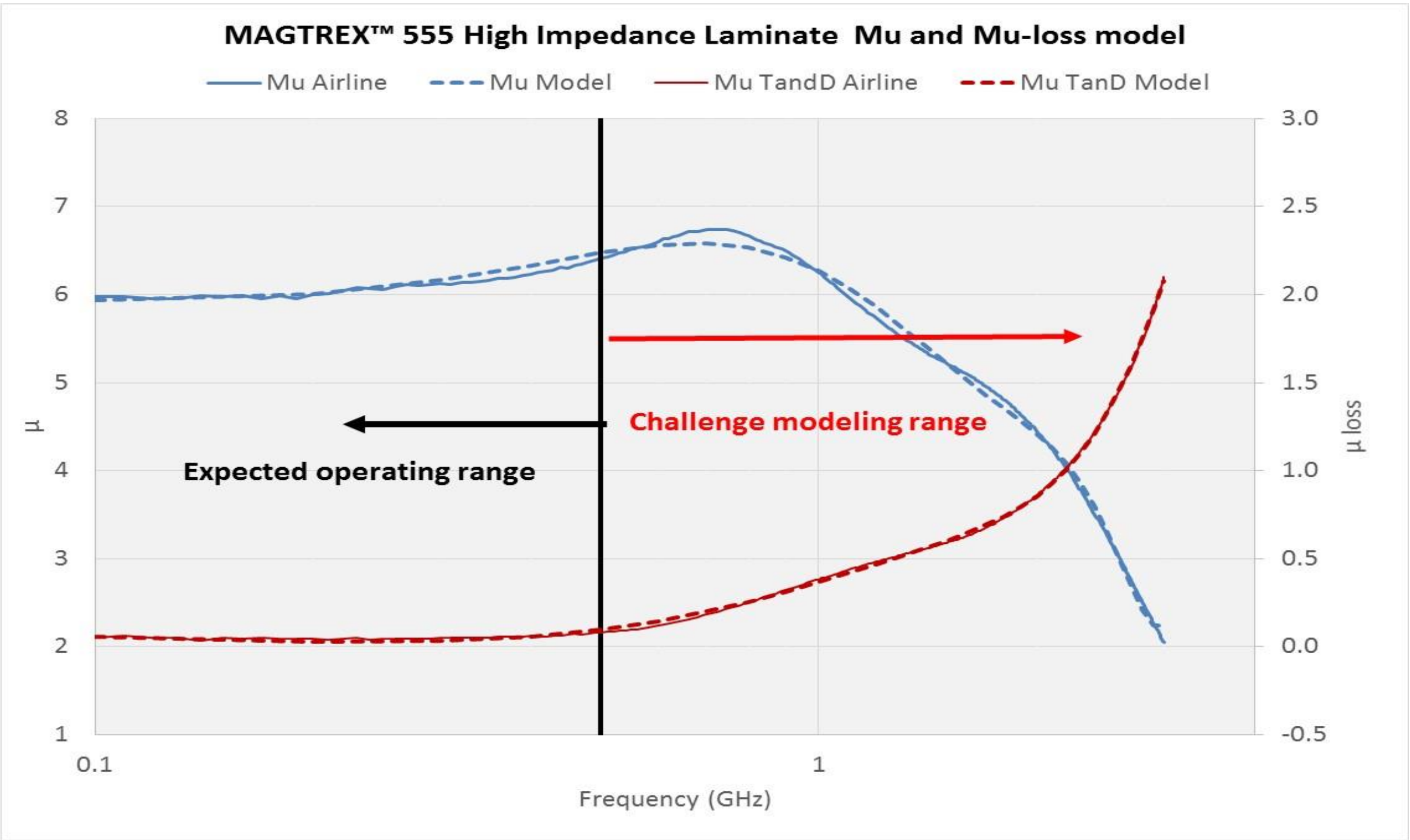


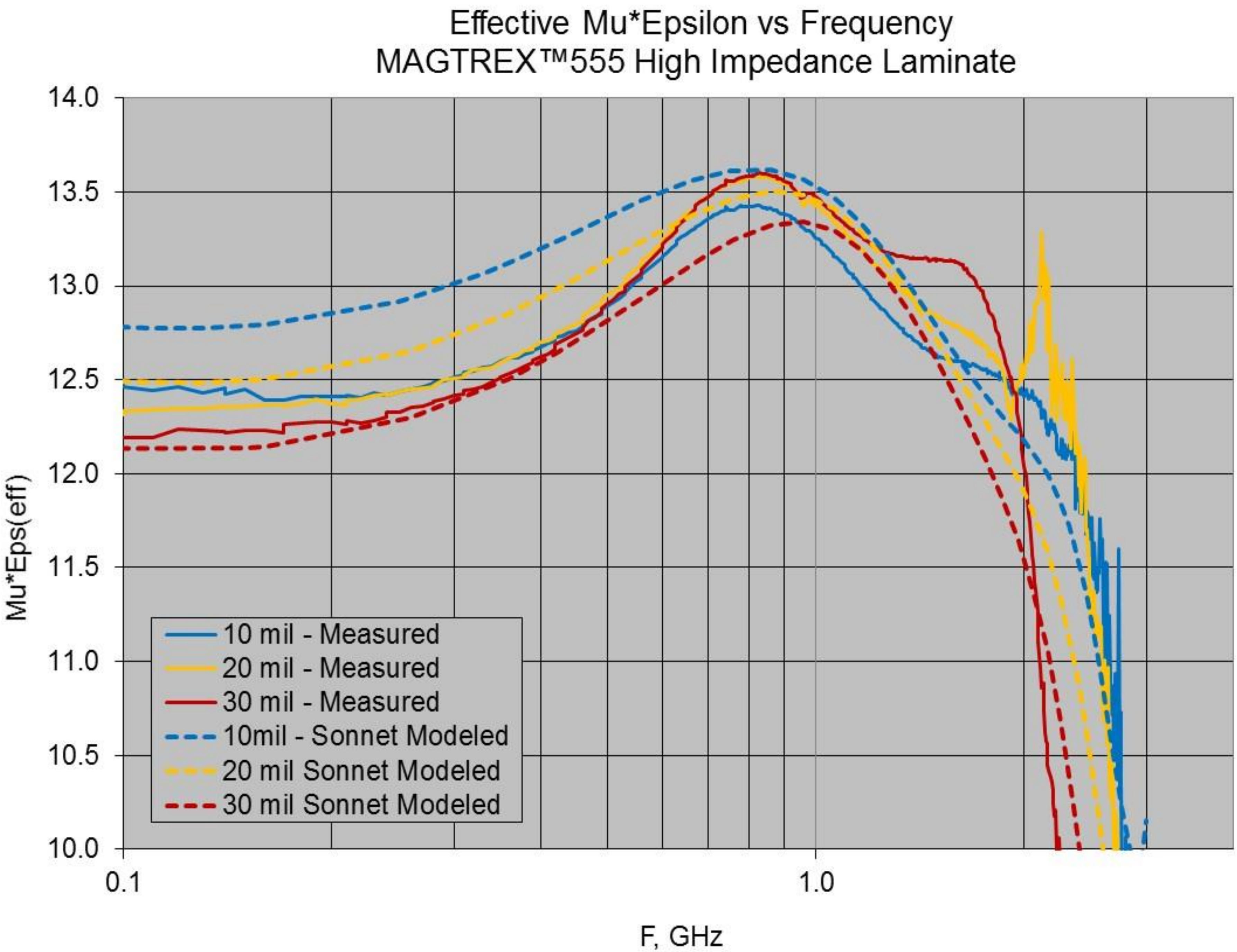


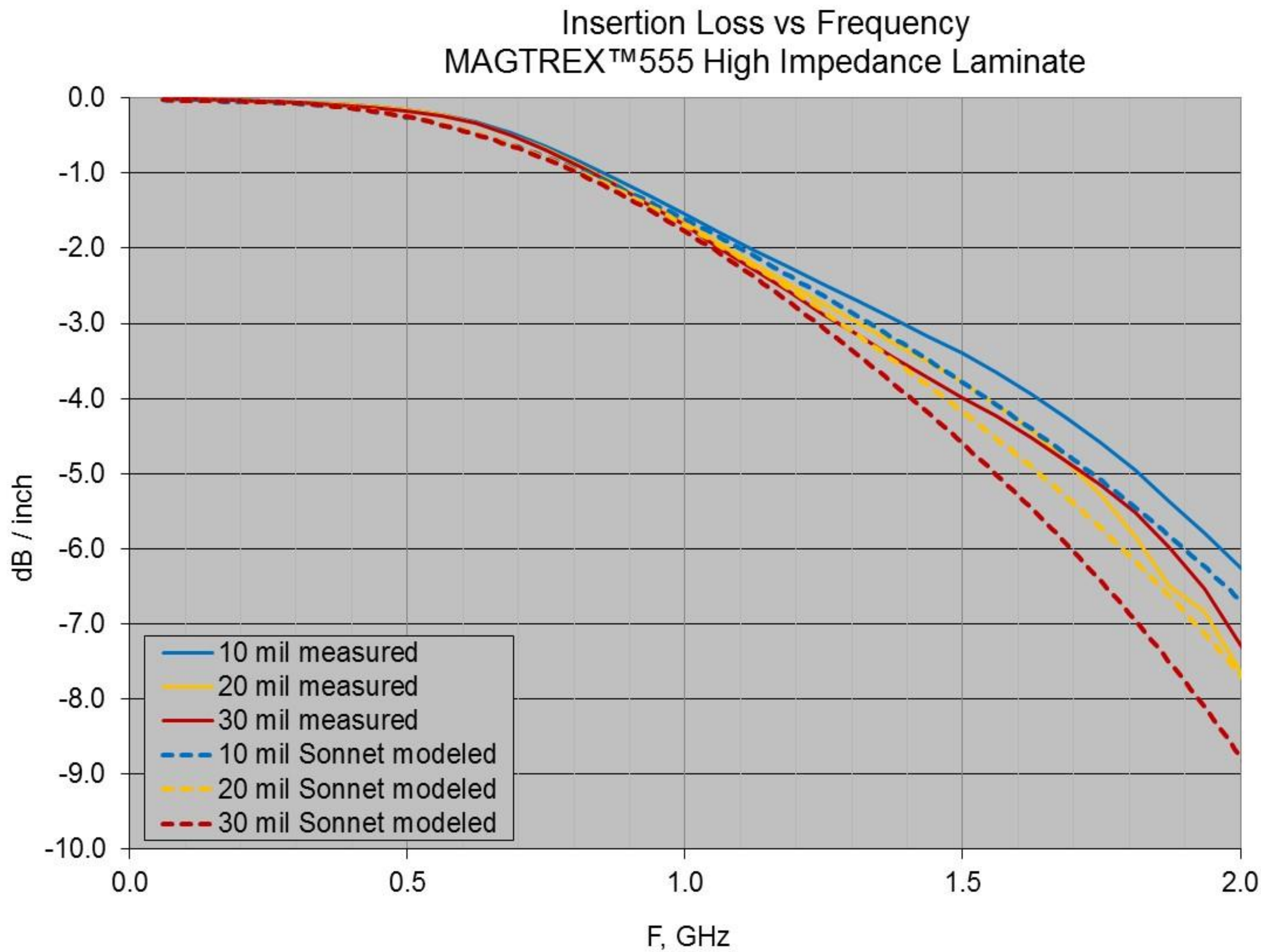
- $\varepsilon_R\mu_R$ value for coaxial airline is 36 (6x6)

- $\varepsilon_R\mu_R$ values for FSR of a 12”x18”x0.020” panel are approximately 30, implying that the out-of-plane (z-axis) ε_R is 5.0

- Sonnet Software modeling of microstrip transmission lines
- Fixed value of $\varepsilon_{R} = 5.0$ and $\tan\delta = 0.005$




Effective Mu*Epsilon vs Frequency
MAGTREX™555 High Impedance Laminate
14.0
13.5
13.0
12.5
12.0
11.5
11.0
10.5
10.0
Mu*Eps(eff)
0.1
1.0
F, GHz
10 mil - Measured
20 mil - Measured
30 mil - Measured
10mil - Sonnet Modeled
20 mil Sonnet Modeled
30 mil Sonnet Modeled


Insertion Loss vs Frequency
MAGTREX™555 High Impedance Laminate
dB / inch
F, GHz
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
-9.0
-10.0
0.0
0.5
1.0
1.5
2.0
10 mil measured
20 mil measured
30 mil measured
10 mil Sonnet modeled
20 mil Sonnet modeled
30 mil Sonnet modeled

- Magneto-dielectric laminates improve the trade-offs between patch size, thickness, and bandwidth of patch antennas.
- Permeability and magnetic loss a strongly dependent on frequency, so accurate broad band measurements are required.
- Anisotropy affects permittivity and permeability.
- Accurate modeling data can be obtained from a combination of airline and full-sheet resonance data.