CHAPTER 12

MEASURED DATA OF MATERIALS AND COMPOSITES

This chapter concludes the book by summarizing the composite measurement techniques and correlating them with physics suggested by the composite models. Tabulated data for over 300 composites (and their components when available) dielectric and magnetic properties are presented. Data are at frequencies from a few megahertz to hundreds of gigahertz. Unless otherwise noted, frequency variables (e.g., resonance or relaxation) are in units of gigahertz. Selected composite data are presented for measurements made before, after, and during the exposure to environmental extremes. Ceramic and ceramic composites are often used in high-temperature environments; thus data are shown from ambient to temperatures in excess of 1600°C. Select materials were chosen to overlap data of von Hippel and other publications and thereby supply the reader with comparative measurements. Those data include measurements using multiple techniques, environmental exposures, and frequency ranges. Unique among those measurements are data for semiconducting films, ferrites, magnetic composites, and data for ceramics above 1600°C.

The chapter is composed of 14 sections where each section annotates data for one material class or environmental testing of one material class. In some cases, data tables are preceded by a background discussion on the materials. The introductory discussions may also be used to refer the reader to other reference data on the material class. For example, some of the honeycomb data can be found in company brochures and these serve as a comparative data set. The tabulations begin with the discussion and data on the dense ceramics. In the tables, exponentials are often shown as (bE). The form means $b*10^{-a}$. Thus, –2E-004–7.6E-003j is equal to –0.0002 –j0.0076.

12.1 SOLID CERAMIC VERSUS FREQUENCY

Table 12.1 shows the parametric fits of permittivity for various ceramics. All ceramic samples were machined from large parts and measured in circular waveguide or transmission line cavity. The fitted functional form is shown at the beginning of the table. Functions are those causal functions that were derived in Chaps. 2 and 3 for dielectric and magnetic media. When available, additional data are shown; these may include density, measured frequency span serving as basis for fits, tabulated information, and chemical and/or physical composition. In the tables exponentials are often shown as bE—which means $b*10^{-a}$. Thus –2E-004–7.6E-003j is equal to –0.0002–j0.0076. Typical fits (showing measured and fitted functions) are presented in Fig. 12.1 for BeO and Al_2O_3, Fig. 12.2. Figure 12.2 illustrates how fitting can smooth anomalous measured data that often occur with low-loss materials.

TABLE 1.1 Important Vector Relationships

Sample ID							
$\varepsilon(f) = B + 2Cf^{D} + G\{1 - J*(f-H)^2 - j2If\}^{-1}$							
	B	C	D	G	H	I	J
3D Quartz–alumina silica nitride 2.16 g/cc (8–40 GHz)							
	0.9921–1E-004j	1.0147–4E-004j	–8.79E-002+2E-003j	0.9732–2E-004j	3E-003+4E-004j	–2E-004–7.6E-003j	–2.06E-004+1.03E-005j
Alumina 99.5% dense (1–250 GHz)							
	2.399+1E-004j	2.399+1E-004j	1.22E-004–1.93E-005j	2.40+1E-004j	–6.93E-006–3.75E-006j	1.33E-005–2.31E-006j	–5.62E-008–3.26E-008j
Alumina 99.9% dense 3.86–3.90 g/cc (1–300 GHz)							
	2.3945+3.3E-003j	2.3985+3.2E-03j	2.43E-002–1E-003j	2.39+3.4E-003j	5E-004	1E-004+7E-004j	2.30E-006–2.94E-007j
Alumina 96–97% dense, 3.71 g/cc (5–250 GHz)							
	2.4313+1.5E-003j	2.4285+1.4E-003j	1.12E-002–1E-004j	2.2536–2.9E-003j	4E-004	1.3E-003j	6.48E-006–6.25E-008j
SRM709 (0.01–18 GHz), Lead oxide glass							
	4.0907–1.74E-002j	4.0907–1.74E-002j	2E-004–3.1E-003j	4.0902–1.68E-002j	1E-004–1.4E-003j	7.4E-003+4E-003j	5E-004–6E-004j
Mullite 97% dense (2–35 GHz), $3Al_2O_3 \bullet 2SiO_2$							
	1.6387+7E-004j	1.6387+7E-004j	1E-004–1E-004j	1.6387+7E-004j	–2.16E-005–1.42E-005j	1.14E-005–3.09E-005j	–4.63E-007+8.63E-007j
Magnesium oxide (MgO) (2–35 GHz)							
	2.3743+3E-004j	2.3743+3E-004j	2.4E-003	2.3743+3E-004j	4E-004–1E-004j	5E-004j	1.75E-005+5.91E-007j

Slip-cast silica, 2.05 g/cc (2–35 GHz)	0.8174+ 1E-004j	0.8174+ 1E-004j	1.2E-003+ 1E-004j	0.8174+ 1E-004j	−2E-004− 1E-004j	−1.21E-005+ 3.56E-004j	3.62E-006+ 1.33E-006j
Shuttle tile LI2200 (30–100 GHz)	0.3371+ 1.2E-003j	0.3371+ 1.2E-003j	−2.6E-003 −6E-004j	0.3374+ 1.2E-003j	5E-004− 2E-004j	1E-004+ 7E-004j	1.53E-005 −2.49E-007j
Shuttle tile FRIC12 (3–100 GHz)	0.2741+ 6E-004j	0.2741+ 6E-004j	4E-002− 8E-004j	0.2755+ 5E-004j	−3.1E-003+ 1E-004j	1E-004 −3E-004j	−1.39E-005 −3.60E-007j
Beryllium oxide (BeO) (0.2–250 GHz)	1.6503+ 1E-004j	1.6503+ 1E-004j	−2.3E-003	1.6502+ 1E-004j	1.042E-005 −1.02E-006j	2.546E-006 −3.57E-004j	−1.84E-006 −1.09E-008j
Boron nitride; 2.28 g/cc (1–40 GHz) (Nominal $\varepsilon_r = 4.08$, Accumet Engineering)	1.1255+ 2E-004j	1.1255+ 2E-004j	1E-004+ 6E-004j	1.1255+ 2E-004j	1E-004− 1E-004j	1E-004 −1.1E-003j	5.02E-006+ 5.04E-006j
Magnesium calcium titanate 30 (8–50 GHz) (Nominal $\varepsilon_r = 30$)	−0.2585+ 2.7E-003j	8.1811+ 0.5195j	0.4159 + 0.3298j	0.5493+ 8E-004j	−2.4E-003+ 1E-004j	−2.16E-002j	−5E-004
SRM 709 Lead-oxide glass (.01–18 GHz)	4.0905− 1.73E-002j	4.0905− 1.73E-002j	2E-004− 3.1E-003j	4.0905− 1.75E-002j	1E-004− 1.4E-003j	7.4E-003+ 4E-003j	5E-004− 6E-004j
SRM 710a Sodalime glass (.01–18 GHz)	1.7687− 4E-004j	1.7687− 4E-004j	−2.4E-003 −3E-004j	1.7687− 4E-004j	−4E-004+ 1.5E-003j	1.7E-003 −6E-004j	−1E-004− 1E-004j

PyroCeram (2–40 GHz)							
	1.4171+ 3E-004j	1.4171+ 3E-004j	−2E-004	1.4171+ 3E-004j	−1.94E-007 −1.37E-008j	1.7437E-005− 1.5427E-004j	−2.36E-006− 3.28E-008j
Sapphire wafer (.1" thick, 2" dia.) #1 of two perpendicular E field directions (80–100 GHz)							
	2.8008+ 3.29E-002j	2.7989+ 3.9-002j	−7.77E-002+ 2.5E-002j	2.8204+ 2.54E-002j	4E-003− 1.2E-003j	−6E-004- 4.6E-003j	−4.93E-005+ 5.30E-006j
Sapphire wafer (.1" thick, 2" dia.) #2 of two perpendicular E field directions (80–100 GHz)							
	2.4304+ 4.26E-002j	2.4285+ 4.14E-002j	2.47E-002+ 2.37E-002j	2.4585+ 4.76E-002j	4.1E-003+ 3.2E-003j	−4.9E-003+ 2.7E-003j	2.72E-005+ 4.04E-005j
Silicon nitride 3.2–3.3 g/cc (2–35 GHz)							
	1.3598+ 2.4E-003j	1.36+ 2.5E-003j	1.15E-002+ 1E-004j	1.3599+ 2.5E-003j	1E-003− 8E-004j	1.4E-003j	5.96E-005+ 4.61E-006j
Fused silica-glass (2–40 GHz) Dynasil 4000 (generic)							
	0.9688+ 1E-004j	0.9688+ 1E-004j	−1.2E-003+ 1E-004j	0.9688+ 1E-004j	2E-004+ 2E-004j	−1.2161E-005 −4.6692E-005j	−7.15E-006+ 6.33E-007j
Fused silica glass Dynasil 4000, 2.16-2.2 g/cc (0.1–100 GHz)							
	0.9469+ 1E-004j	0.9469+ 1E-004j	−8.1E-003	0.9468+ 1E-004j	−3E-004	−1.9E-003j	−3.35E-005 −7.4E-008j
Spinel magnesium aluminum oxide $MgAl_2O_4$ (2–35 GHz)							
	2.0614+ 4E-004j	2.0615+ 4E-004j	9.8E-003+ 1E-004j	2.0614+ 4E-004j	2E-003	2.2E-003j	8.64E-005+ 1.07E-006j

Magnesium titanate 16 (0.01–18 GHz) (nominal ε_r = 16)						
4.2136+ 9.9E-003j	4.2131+ 9.9E-003j	9.4E-003+ 5.5E-003j	4.2135+ 9.9E-003j	7.3E-003+ 7E-004j	8.5E-003+ 4.6E-003j	4E-004– 1.1E-003j
Barium titanate 38, 4.41–4.48 g/cc (8–50 GHz) (nominal ε_r = 38)						
7.5015+ 1.52E-002j	6.3603+ 7.3E-003j	0.1914	8.0033– 4.36E-002j	–6.1E-003+ 2E-004j	3E-004 – 1.74E-002j	–1.6E-003
Cordierite $Mg_2Al_4Si_5O_{18}$ 4, 2.3–2.5 g/cc (8–50 GHz)						
1.2293+ 1.19E-002j	1.5892+ 2.3E-003j	–0.2778 –3.36E-002j	1.6774+ 0.1004j	–6.7E-003 –3.5E-003j	5E-004 –2.2E-003j	4.43E-005- 2.35E-005j
Magnesium aluminum titanate 11, 3.3–3.5 g/cc (8–50 GHz) (nominal ε_r = 11)						
2.3079– 3.25E-002j	2.5009+ 0.2874j	0.1472-0.1533j	1.7366+ 0.8388j	1.14E-002– 3.19E-002j	1.2E-002– 1.55E-002j	–3E-004– 3E-004j
Stycast 2662 (10–60 GHz) 1.385 g/cc (nominal 1.44 g/cc, ε_r = 3.5–3.61 MHz)						
0.4099+ 7.1E-003j	0.8644 –5.51E-002j	0.1859– 8.5E-002j	0.8048+ 0.4175j	3.2E-003 –1.82E-002j	1.03E-002– 9.3E-003j	–1E-004– 2E-004j
Corning 7940 fused silica, 2.201 g/cc (nominal ε_r = 3.8 at MHz) (10–100 GHz)						
0.9389– 3E-004j	0.9413– 2E-004j	2.61E-002+ 8E-004j	0.9381– 5E-004j	1.7E-003	–1E-004+ 2.6E-003j	3.50E-005+ 1.31E-006j
Corning 7957 fused silica, 2.20 g/cc (nominal ε_r = 3.8 at 1 MHz) (27–60 GHz)						
0.9213 –3.07E-002j	0.936– 2.03E-002j	4.7E-002+ 5.24E-002j	0.9583– 7.7E-002j	1E-004+ 6.4E-003j	–6.4E-003+ 1.9E-003j	3.63E-005+ 6.44E-005j

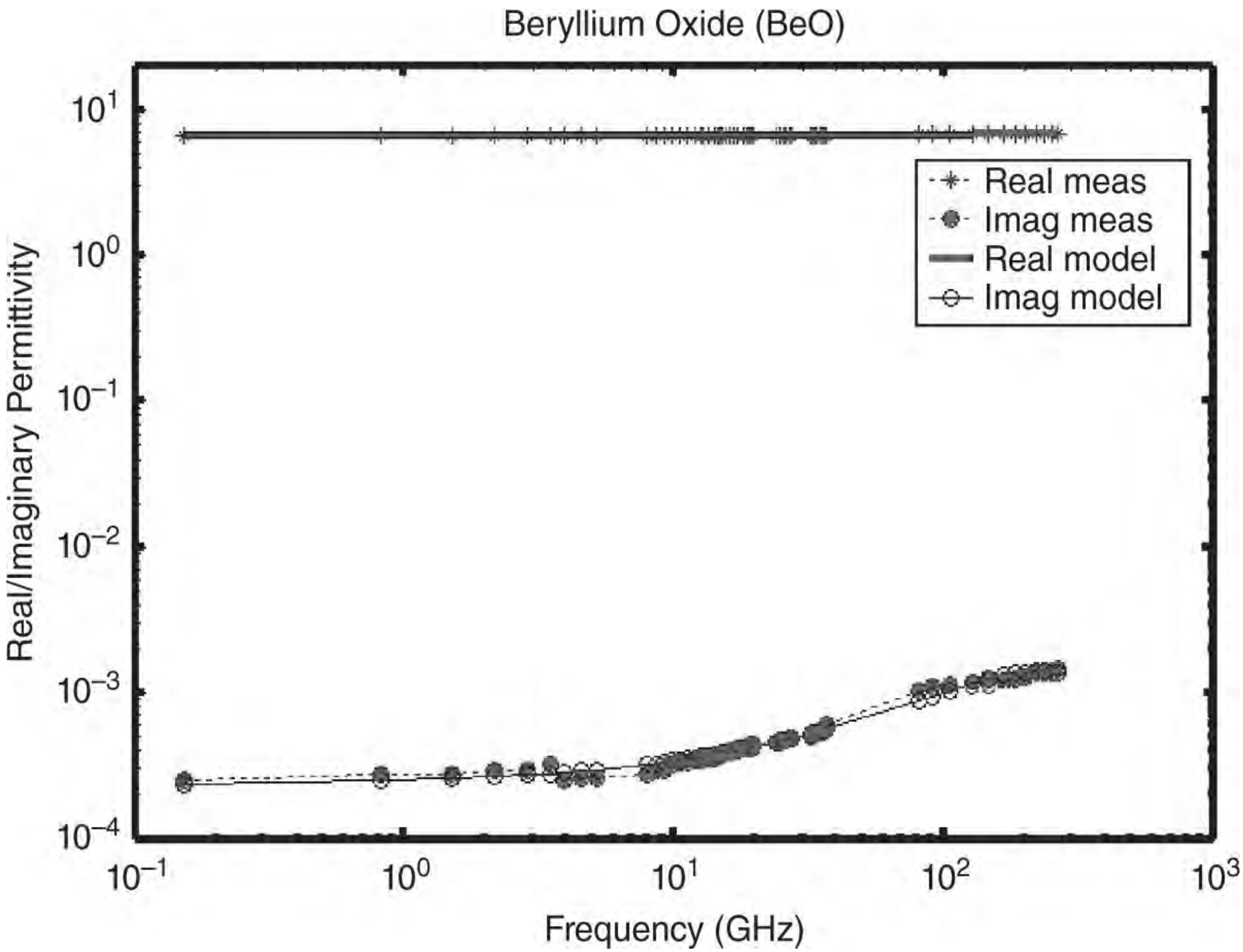


FIGURE 12.1 Measured and model fit of BeO permittivity.

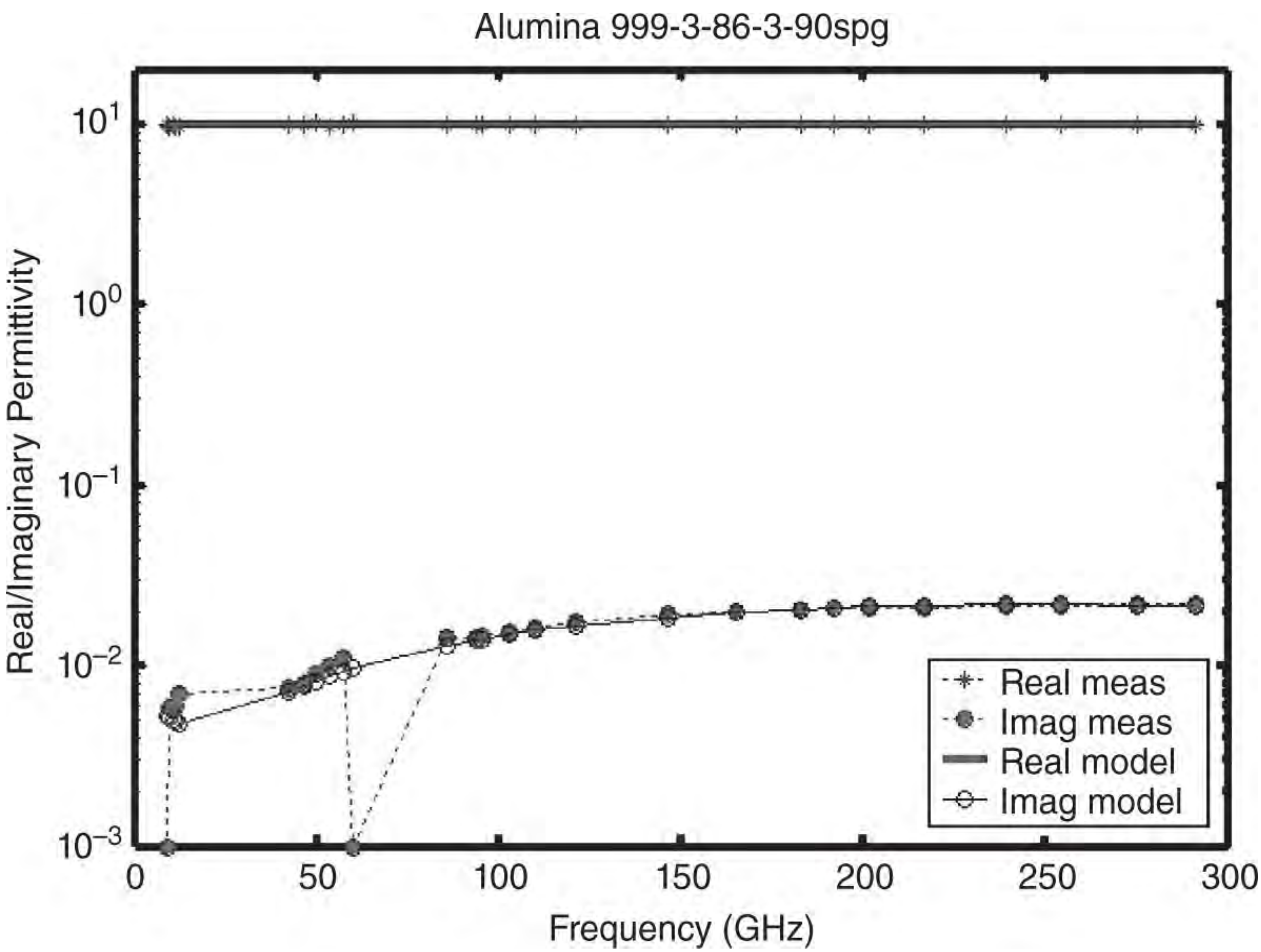


FIGURE 12.2 Measured and model fit of Alumina 999 permittivity.

Disclaimer: Data are results obtained by the author on samples prepared in the laboratory. Variations may be observed by other researchers when prepared in their laboratories. Data are not "guaranteed" by a manufacturer or the author. Variations in properties may be observed and users of the products should verify properties. All material properties are guides for engineering design. Materials prepared in the laboratory should be considered as experimental and also guides for engineering design.

12.2 SOLID CERAMIC VERSUS TEMPERATURE

Table 12.2 shows the parametric fits of permittivity and temperature for various ceramics as functions of temperature. All test samples were machined from larger parts. Measurements were made in circular waveguide and/or with transmission line cavities. The fitted functional form is shown at the beginning of the table. Functions are those causal functions that have been derived in Chaps. 2 and 3 for dielectric and magnetic media. When available, additional data are shown; these may include density, measured frequency span serving as basis for fits, tabulated information, and chemical and or physical composition. In the tables exponentials are often shown as bE—which means b*10^{-a}. Thus –2E-004–7.6E-003j is equal to –0.0002–j0.0076. Typical fits and measured data for two ceramics (one low loss and one of moderate loss) are shown in Figs. 12.3 and 12.4.

TABLE 12.2 Solid Ceramics versus Temperature (K)

Sample ID				
$\varepsilon_r(T)=B+CT+DT^2;\varepsilon_i(T)=B+CT^De^{-E/kT}$				
E = Energy (ev)				
	B	C	D	E
Fused silica (Dynasil 4000) 9.5 GHz, 300–2200 K; 2.2 g/cc (nominal ε_r = 3.83, Accumet Engineering)				
$\varepsilon_r(T)$	3.82	−0.0004	$3.35\times10^{(-7)}$	
$\varepsilon_i(T)$	0.0015	0.2648	0.5069	1.0395
Fused silica #1 (Dynasil 4000), 35 GHz, 300–1800 K				
$\varepsilon_r(T)$	3.85	−0.00009	$1.21\times10^{(-7)}$	
$\varepsilon_i(T)$	0.0005	0.0026	0.16	0.062
Fused silica #2 (Dynasil 4000) 35 GHz, 300–1800 K				
$\varepsilon_r(T)$	3.81	0.00009	$2.91\times10^{(-8)}$	
$\varepsilon_i(T)$	0.0014	0.0014	−0.0034	0.024
Fused silica #3 (Dynasil 4000), 35 GHz, 300–1800 K				

Real permittivity	3.86	−0.0001	$1.3 \times 10^{(-7)}$	
$\varepsilon_r(T)$	0.0009	0.0024	0.011	0.048
$\varepsilon_i(T)$	0.0004	0.0004	0.0042	0.018
Alumina 97–99% dense, 9.5 GHz, 300–2000 K (3.7–3.97 g/cc)				
Real permittivity nominal, $\varepsilon_r = 9.6$, Accumet Engineering				
$\varepsilon_r(T)$	9.37	0.0006	$8.60 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.0209	3.689	4.72	6.37
Alumina 97% dense, 36.3 GHz, 300–900 K				
$\varepsilon_r(T)$	9.15	0.001	$1.7 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.0003	0.0097	0.026	0.[illegible]91
Alumina 99.7% dense, 36.1 GHz, 300–825 K (3.87 g/cc) (nominal $\varepsilon_r = 9.8$–10.0, Accumet Engineering)				
$\varepsilon_r(T)$	9.7	0.0007	$2.32 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.0014	0.0014	0.0[illegible]47	0.032

$Mg_2Al_4Si_5O_{18}$ (Cordierite), 9.7 GHz, 300–1000 K, 2.6 g/cc (nominal $\varepsilon_r = 4.7$, Accumet Engineering)

$\varepsilon_r(T)$	4.96	−0.0001	$2.21 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.0104	0.0846	0.0924	0.112

Beryllium oxide #1, BeO 99.5% dense, 36.5 GHz, 300–850 K; 2.85 g/cc (nominal $\varepsilon_r = 6.5$, Accumet Engineering)

$\varepsilon_r(T)$	6.48	0.0001	$4.80 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.0007	0.0007	0.0066	0.027

Beryllium oxide #2 BeO 99.5% dense, 36.5 GHz, 300–850 K

$\varepsilon_r(T)$	6.45	0.0007	$4.50 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.001	0.28	0.029	0.023

Beryllium oxide #3, BeO, 35 GHz, 300–1700 K

$\varepsilon_r(T)$	6.80	−0.0007	$1.1 \times 10^{(-6)}$	
$\varepsilon_i(T)$	0.0107	0.28	0.35	0.494

Boron nitride #2, BN, 2.28 g/cc, 9.5 GHz, 300–1000 K (nominal $\varepsilon_r = 4.08$, Accumet Engineering)

$\varepsilon_r(T)$	4.54	−0.0001	$1.8 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.0003	0.0022	0.014	0.079

Boron nitride (BN) 2.28 g/cc, 35.0 GHz, 300–1700 K

$\varepsilon_r(T)$	4.54	−0.0002	$3.03 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.0006	0.0076	0.021	0.093

Borosilicate glass, thin film, 9.5.0 GHz, 300–1600 K, 2.23 g/cc (nominal $\varepsilon_r = 4.6$, Accumet Engineering)

$\varepsilon_r(T)$	3.93	−0.00015	$4.4 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.042	0.041	−0.0032	−0.0083

LI 1500 Shuttle tile, 35.0 GHz, 300–1500 K

$\varepsilon_r(T)$	1.21	−0.00004	$2.95 \times 10^{(-8)}$	
$\varepsilon_i(T)$	0.0007	0.0007	0.01	0.056

Magnesium calcium titanate, ~about 4 g/cc,15.0 GHz, 300–1450 K

$\varepsilon_r(T)$	31.97	−0.0121	$5.16 \times 10^{(-6)}$	
$\varepsilon_i(T)$	0.0353	0.7149	1.046	0.95

$3Al_2O_3 \bullet 2SiO_2$, Mullite (about 50% dense), 1.5 g/cc + 1% SiC, 10.0 GHz, 300–1250 K

$\varepsilon_r(T)$	5.19	0.005	$-1.3 \times 10^{(-6)}$	
$\varepsilon_i(T)$	0.46	2.04	0.16	0.065

$3Al_2O_3 \bullet 2SiO_2$, Mullite (about 50% dense), 1.5 g/cc, 10.0 GHz, 300–1250 K

$\varepsilon_r(T)$	2.97	0.0004	$6.7 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.077	0.808	0.472	0.29

$3Al_2O_3 \bullet 2SiO_2$, Mullite (about 97% dense), 9.7 GHz, 300–1000 K, 2.8–3.2 g/cc (nominal $e_r = 6.0$, Accumet Engineering)

$\varepsilon_r(T)$	6.58	0.00007	$9.1 \times 10^{(-8)}$	
$\varepsilon_i(T)$	0.0001	0.000036	0.0002	0.0003

Slip cast silica, 2.05 g/cc, 9.7 GHz, 270–1100 K

$\varepsilon_r(T)$	3.39	−0.000007	$2.3 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.0003	0.163	0.04	0.15

Slip cast silica, 2.05 g/cc, 35.3 GHz, 270–850 K

$\varepsilon_r(T)$	3.43	−0.0001	$8.4 \times 10^{(-8)}$	
$\varepsilon_i(T)$	0.002	0.002	−0.0015	0.0034

Fused quartz (124), 35 GHz, 300–820 K, 2.21 g/cc (nominal $\varepsilon_r = 3.8$, Accumet Engineering)

$\varepsilon_r(T)$	3.75	0.0003	$-1.97 \times 10^{(-7)}$	
$\varepsilon_i(T)$ no measurable change	0.001	0	0	0

Tin oxide (SnO_2), 35. GHz, 300–1300 K

$\varepsilon_r(T)$	9.82	−0.006	$7.94 \times 10^{(-6)}$	
$\varepsilon_i(T)$	3.5	0.84	0.901	0.49

Sapphire wafer, 35. GHz, 300–1700 K, 3.97 g/cc (nominal $\varepsilon_r = 9.3–11.4$, Accumet Engineering)

$\varepsilon_r(T)$	9.86	−0.0004	$8.1 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.005	0.032	0.07	0.186

Sapphire wafer, 95. GHz, 300–1900 K				
$\varepsilon_r(T)$	9.45	0.0005	$4.24 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.009	0.018	0.023	0.09
Sapphire rod 99% dense, 9.7 GHz, 300–1500 K				
$\varepsilon_r(T)$	10.2–10.3	0.0001–0.00005	$9.1–9.50 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.0024–0.003	0.0990.085	0.12–0.100	0167–0.143
Silicon Nitride. 3.2–3.3 g/cc, 9.5 GHz, 300–1000 K (nominal $\varepsilon_r = 7.0$, Accumet Engineering)				
$\varepsilon_r(T)$	7.99	0.0001	$2.1 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.02	0.022	0.007	0.18
$MgAl_2O_3$, Spinel, 9.6 GHz, 300–1250 K				
$\varepsilon_r(T)$	7.95	0.0008	$5.4 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.0006	0.027	0.052	0.16
PyroCeram 9.6 GHz, 300–1150 K				
$\varepsilon_r(T)$	5.58	0.00014	$1.7 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.0005	0.024	0.04	0.113

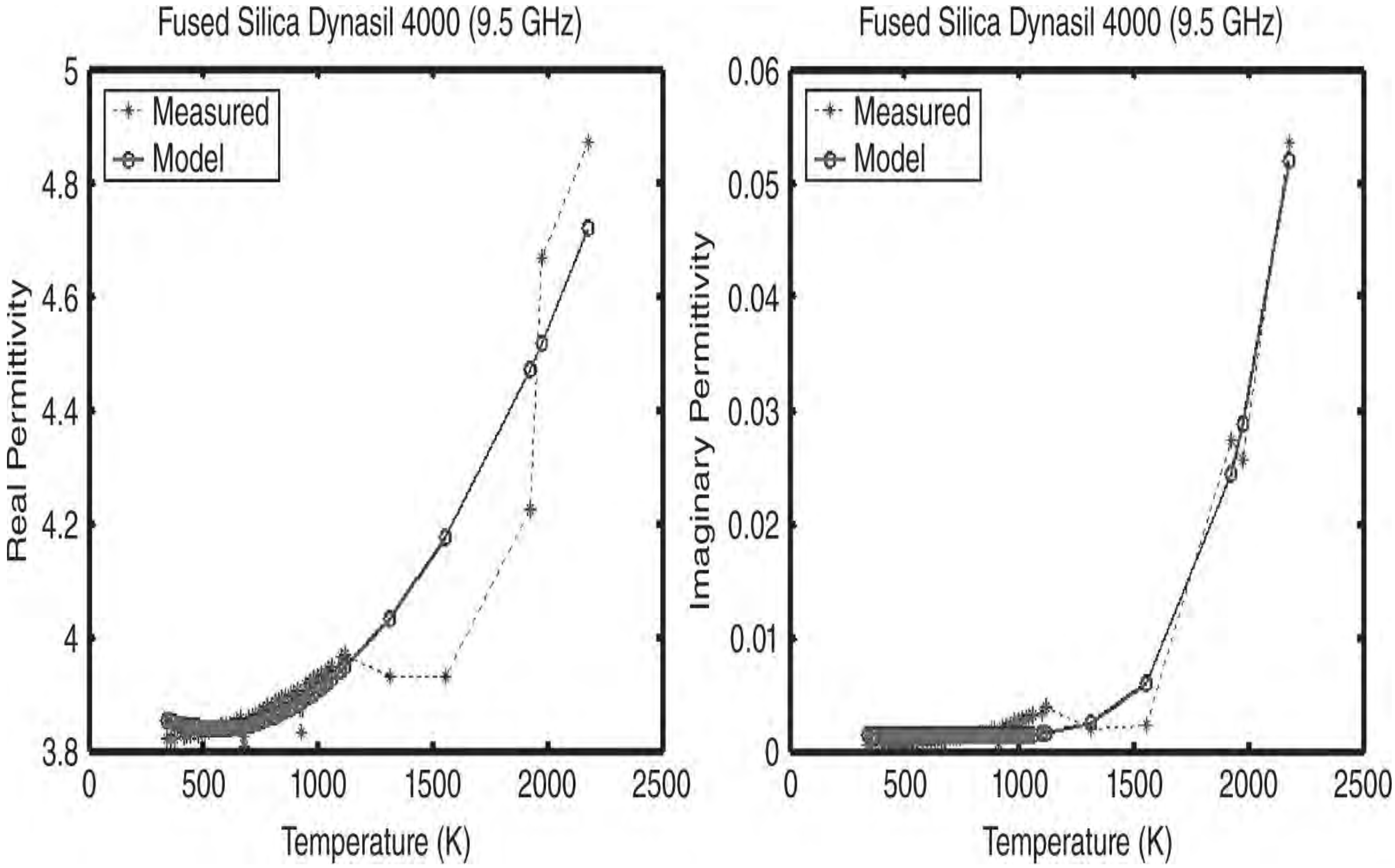


FIGURE 12.3 Measured and fitted permittivity vs. temperature for Dynasil.

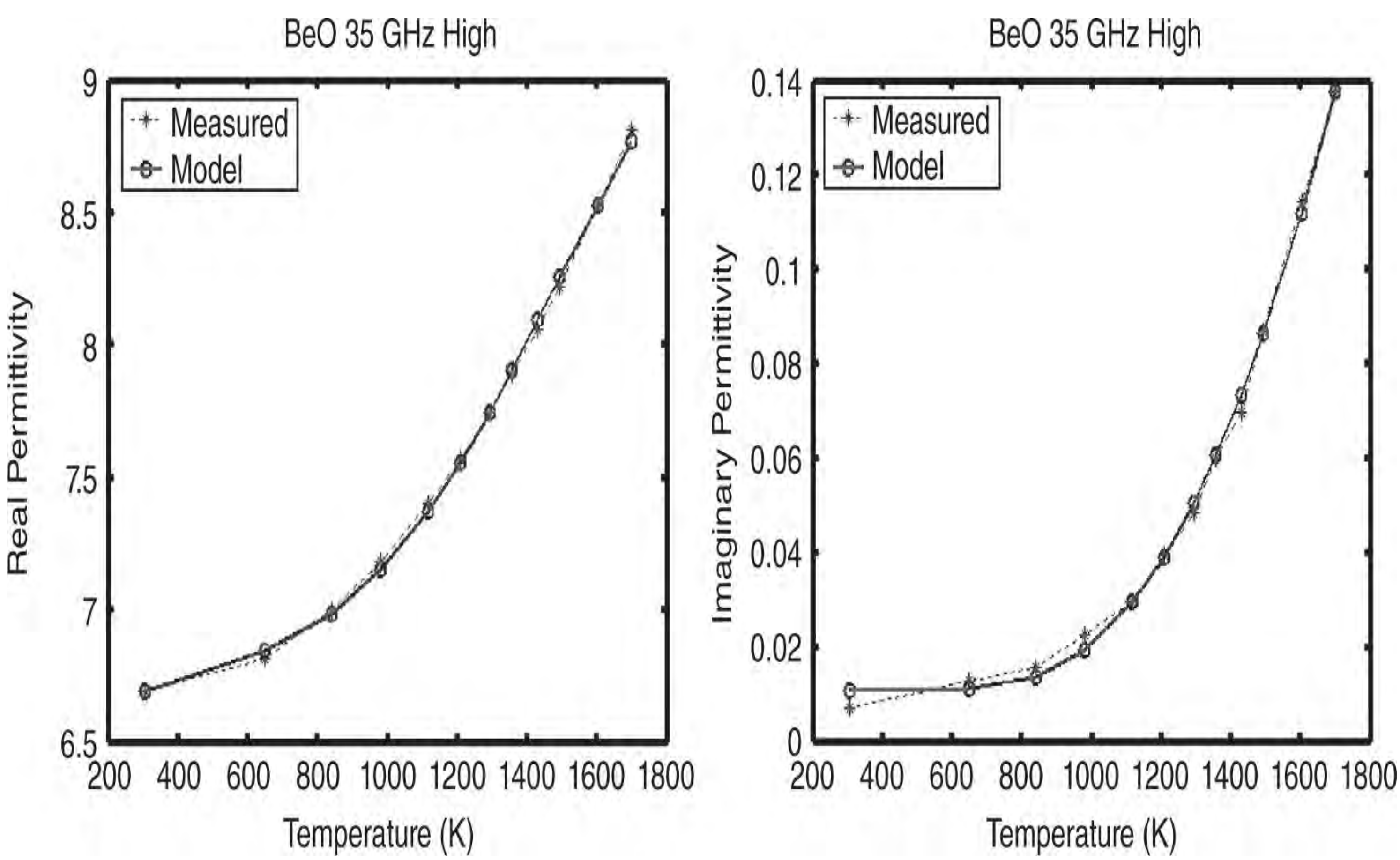


FIGURE 12.4 Measured and fitted permittivity vs. temperature for BeO.

Disclaimer: Data are results obtained by the author on samples prepared in the laboratory. Variations may be observed by other researchers when prepared in their laboratories. Data are not "guaranteed" by a manufacturer or the author. Variations in properties may be observed and users of the products should verify properties. All material properties are guides for engineering design. Materials prepared in the laboratory should be considered as experimental and also guides for engineering design.

12.3 CERAMIC FIBER VERSUS TEMPERATURE

Ceramic fiber temperature fits to permittivity utilize X and Ku band TE_{10N} measurements (Table 12.3). Samples were extracted from longer fiber strands. Therefore, they are subject to volumetric or density variations. The total fiber volume, used in calculation of the permittivity, was based on fiber-tow weight/unit length and manufacturers quoted densities. In selected cases, data are included to show post-temperature exposure and repeat measurement at room temperature. The chemical composition is shown when it was made available to the author. Figure 12.5 shows typical fit and measured data for a low- and high-loss fibers.

TABLE 12.3 Ceramic Fiber Fits to Temperature

Sample ID				
$\varepsilon_r(T)=B+CT+DT^2;\varepsilon_i(T)=B+CT^De^{-E/kT}$				
E = Energy (ev)				
	B	C	D	E
Ceramic rods 97–99%, Al_2O_3, 3.85–3.95 g/cc, 10 GHz, 300–1450 K				
$\varepsilon_r(T)$	10.19	0.0001	$9.1\times10^{(-7)}$	
$\varepsilon_i(T)$	0.003	0.1	0.114	0.16
SiC fiber (1% O, 69% Si, 30% C), A–B, 14.4 GHz, 300–1041 K				
$\varepsilon_r(T)$	5.30	0.0044	−0.0000026	
$\varepsilon_i(T)$	0.088	2.64	2.24	1.24
SiC fiber (12% O, 57% Si, 31% C), A–B, 16.4 GHz, 300–1041 K				
$\varepsilon_r(T)$	5.43	0.004	−0.0000021	
$\varepsilon_i(T)$	0.081	2.11	2.43	1.31

SiC fiber (12% O, 57% Si, 31% C), A–B, Post 1041 K exposure

Real permittivity	14.4 GHz	16.4 GHz
$\varepsilon_r(T = 300)$	6.35	6.47
$\varepsilon_i(T = 300)$	0.07	0.04

SiC fiber (12% O, 57% Si, 31% C), 2.55 g/cc, 10 GHz, 300–1400 K, real nominal $\varepsilon_r = 9.6$

$\varepsilon_r(T)$	8.70	−0.01	$8.5 \times 10^{(-6)}$	
$\varepsilon_i(T)$	0.33	1.86	1.09	0.8

SiN fiber (2% O, 57% Si, 32–39% N, <1% C), 2.3 g/cc, 10 GHz, 300–1250 K

$\varepsilon_r(T)$	1.93	0.0045	$-3.2 \times 10^{(-6)}$	
$\varepsilon_i(T)$	−0.025	0.013	0.135	0

SiN fiber (2% O, 57% Si, 32–39% N, <1% C), 2.45 g/cc, 10 GHz, 300–1250 K

$\varepsilon_r(T)$	4.13	−0.0024	$9.3 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.005	0.04	0.06	0.13

SiN fiber (2% O, 57% Si, 32–39% N, <1% C), 2.3–2.48 g/cc, 10 GHz, 300–1250 K

$\varepsilon_r(T)$	3.03	−0.0024	$1.23 \times 10^{(-6)}$	
$\varepsilon_i(T)$	0.0014	0.009	0.0013	0.02

Si_3N_4, 2.5 g/cc, 14.4 GHz, pre-heat treatment: 300–1040 K

$\varepsilon_r(T)$	9.89	−0.006	0.00000015	
$\varepsilon_i(T)$	−0.5	0.37	0.028	−0.027

Si_3N_4, 2.5 g/cc, 16.4 GHz, pre-heat treatment: 300–1040 K

$\varepsilon_r(T)$	11.37	−0.011	0.0000044	
$\varepsilon_i(T)$	−0.19	0.28	0.021	−0.026

Si_3N_4, 2.5 g/cc, pre-heat treatment, post 1040 K exposure

	14.4 GHz	16.4 GHz
$\varepsilon_r(T)$	4.46	4.55
$\varepsilon_i(T)$	0.001	0.001

Para-aramid fiber [-CO-C_6H_4-CO-NH-C_6H_4-NH-]$_n$, 14.4 GHz, 300–700 K

$\varepsilon_r(T)$	3.84	0.0048	−0.0000068	
$\varepsilon_i(T)$	−0.26	0.217	0.0144	−0.023

Para-aramid fiber [-CO-C_6H_4-CO-NH-C_6H_4-NH-]$_n$, 16.4 GHz, 300–700 K

$\varepsilon_r(T)$	4.05	0.0033	−0.000005	
$\varepsilon_i(T)$	−0.33	0.264	0.0115	−0.023

Para-aramid fiber [-CO-C_6H_4-CO-NH-C_6H_4-NH-]$_n$, T = 300 K, post 700 K exposure

	14.4 GHz	16.4 GHz
$\varepsilon_r(T)$	4.07	4.13
$\varepsilon_i(T)$	0.05	0.04

PBI (polybenzimidazole), 16.4 GHz, 300–650 K

$\varepsilon_r(T)$	3.77	0.0003	−0.0000016	
$\varepsilon_i(T)$	−0.011	0.091	0.014	−0.023

PBI (polybenzimidazole), 14.4 GHz, 300–650 K

$\varepsilon_r(T)$	3.56	0.005	−0.0000069	
$\varepsilon_i(T)$	−0.13	0.12	0.0076	−0.02

PBI (polybenzimidazole), post 650 K exposure

	14.4 GHz	16.4 GHz
$\varepsilon_r(T)$	3.18	3.38
$\varepsilon_i(T)$	0.09	0.05

PBT (polybutylene terephthalate), 16.4 GHz, 300–810 K

$\varepsilon_r(T)$	6.98	−0.003	0.0000031	
$\varepsilon_i(T)$	0.022	0.05	0.025	0.028

PBT (polybutylene terephthalate), 14.4 GHz, 300–810 K

$\varepsilon_r(T)$	7.52	−0.005	0.0000052	
$\varepsilon_i(T)$	0.017	0.056	0.031	0.028

PBT (polybutylene terephthalate), post 810 K exposure

	14.4 GHz	16.4 GHz
$\varepsilon_r(T)$	5.96	6.01
$\varepsilon_i(T)$	0.001	0.001

Flame-resistant meta-aramid fiber, 16.4 GHz, 300–650 K

$\varepsilon_r(T)$	3.60	0.002	−0.0000024	
$\varepsilon_i(T)$	0.1	0.323	0.31	0.172

Flame-resistant meta-aramid fiber, 14.4 GHz, 300–650 K[c]

$\varepsilon_r(T)$	4.18	−0.0013	0.0000019	
$\varepsilon_i(T)$, no measurable change	0.12	0.8	0.905	0.41

Flame-resistant meta-aramid fiber, 14.4 GHz, post 650 K exposure

	14.4 GHz	16.4 GHz
$\varepsilon_r(T)$	3.83	3.81
$\varepsilon_i(T)$	0.08	0.05

Ceramic 97–99%, Al_2O_3, 3.6–3.88 g/cc, 10 GHz, 300–900 K				
$\varepsilon_r(T)$	10.6	−0.007	$5.5 \times 10^{(-6)}$	
$\varepsilon_i(T)$	0.09	2.49	3	0.4
Ceramic 70%, Al_2O_3, 28% SiO_2, 2% B_2O_3, 3.05 g/cc, 9.7 GHz, 300–1400 K				
$\varepsilon_r(T)$	6.00	0.00004	$3.7 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.04	0.39	0.39	0.13
Ceramic 70% Al_2O_3, 28% SiO_2, 2% B_2O_3, 3.05 g/cc, 9.7 GHz, 300–1400 K				
$\varepsilon_r(T)$	6.40	−0.0015	$1.54 \times 10^{(-6)}$	
$\varepsilon_i(T)$	−0.04	0.48	0.24	0.25
Ceramic 62% Al_2O_3, 24% SiO_2, 14% B_2O_3, 2.7 g/cc, 9.7 GHz, 300–1400 K				
$\varepsilon_r(T)$	5.4	−0.0003	$5.9 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.024	0.39	0.36	0.31
Carbon-nickel-conducting fiber, 9.7 GHz, 300–950 K				
$\varepsilon_r(T)$	−7.8	0.11	$-9.7 \times 10^{(-5)}$	
$\varepsilon_i(T)$	0.12	7.37	0.92	0.11

59% Si, 10% C, 28% N, 3% O, –03 (400 filament tow), 2.23–2.27 g/cc, 9.7 GHz, 300–1250 K				
$\varepsilon_r(T)$	7.43	–0.004	$1.7 \times 10^{(-6)}$	
$\varepsilon_i(T)$	0.08	2.53	1.9	1.4
59% Si, 10% C, 28% N, 3% O, –03 (200 filament tow), 2.59–2.64 g/cc, 9.7 GHz, 300–1250 K				
$\varepsilon_r(T)$	10.3	–0.0113	$5.76 \times 10^{(-6)}$	
$\varepsilon_i(T)$	0.29	0.79	0.21	1.3
59% Si, 10% C, 28% N, 3% O, 02 + 04 (400 filaments), 2.23–2.27 g/cc, 9.7 GHz, 300–1550 K				
$\varepsilon_r(T)$	6.0	–0.0004	$5.0 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.02	0.16	0.15	0.2
Glass (astroquartz) with sizing, 9.7 GHz, 300–1400 K				
$\varepsilon_r(T)$	3.62	0.0007	$-4.0 \times 10^{(-7)}$	
$\varepsilon_i(T)$	0.0003	0.05	0.09	0
Glass (astroquartz) without sizing, 9.7 GHz, 300–1400 K				
$\varepsilon_r(T)$	3.74	–0.00003	$2.9 \times 10^{(-8)}$	
$\varepsilon_i(T)$	0.0075	0	0	0.015
Si-Ti-C-O fiber (55%–2%–32%–10%), 2.48 g/cc, 9.7 GHz, 300–1100 K				
$\varepsilon_r(T)$	7.11	0.0001	$3.5 \times 10^{(-6)}$	
$\varepsilon_i(T)$	–15.3	48.4	–0.09	0.06
85% Alumina, 15% Silica, 3.2 g/cc, 9.7 GHz, 300–1450 K				
$\varepsilon_r(T)$	7.17	–0.0013	$2.0 \times 10^{(-6)}$	
$\varepsilon_i(T)$	–0.46	1.6	0.15	0.07
99% Alumina, 3.9 g/cc, 9.7 GHz, 300–1400 K				
$\varepsilon_r(T)$	11.9	–0.0074	$5.6 \times 10^{(-6)}$	
$\varepsilon_i(T)$	–0.9	1.851	0.234	0

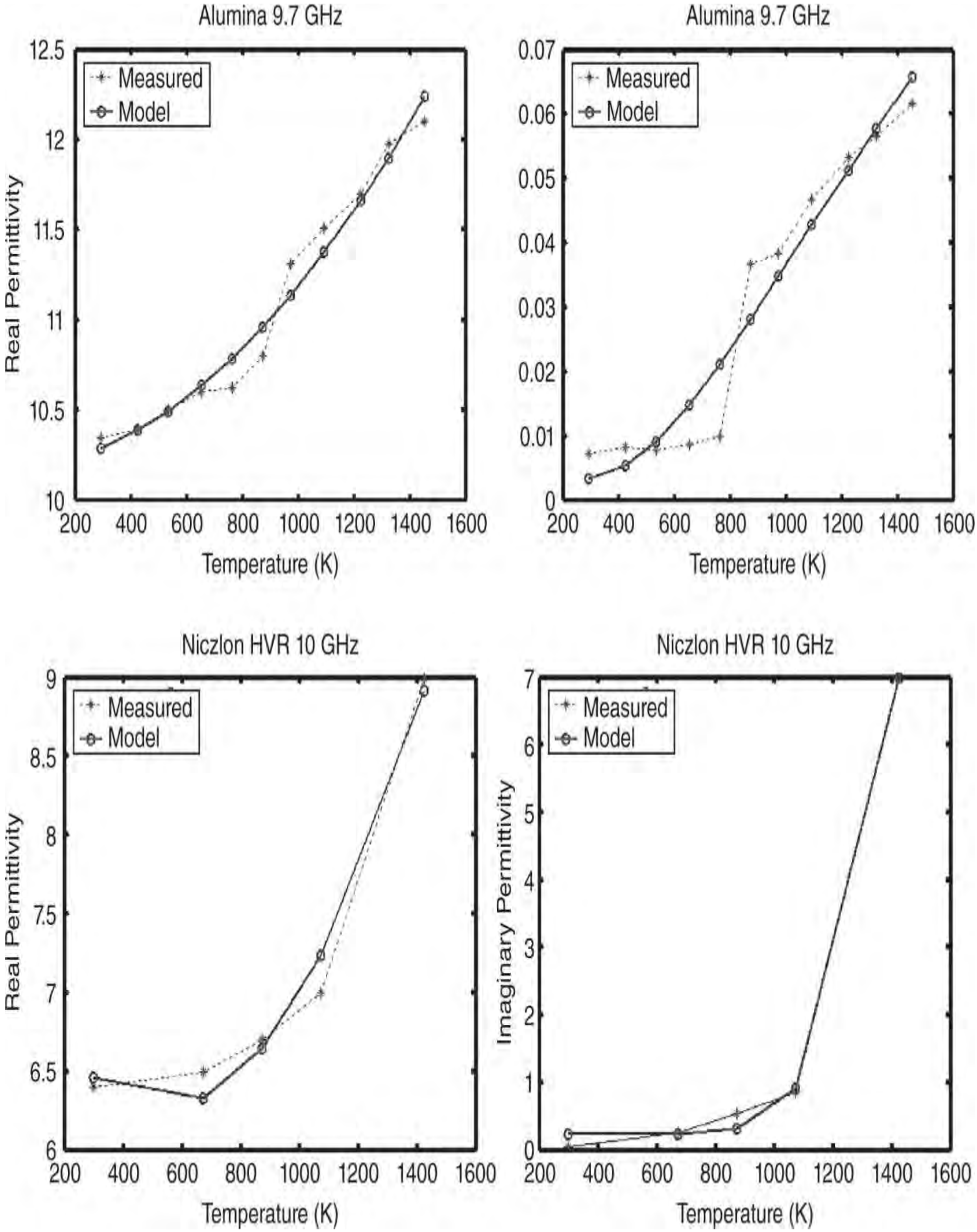


FIGURE 12.5 Measurement and model fits for a low loss (alumina1) and high loss (Nicalon HVR) fiber.

Disclaimer: Data are results obtained by the author on samples prepared in the laboratory. Variations may be observed by other researchers when prepared in their laboratories. Data are not "guaranteed" by a manufacturer or the author. Variations in properties may be observed and users of the products should verify properties. All material properties are guides for engineering design. Materials prepared in the laboratory should be considered as experimental and also guides for engineering design.

12.4 TWO-PHASE FERRITE-POLYMER COMPOSITES AND THREE-PHASE FERRITE-Fe-POLYMER COMPOSITES

Table 12.4 shows the parametric fits of susceptibility and permittivity for various two-phased ferrite polymer composites and three-phase ferrite-Fe-polymer composites. All samples were made in the laboratory and formed into coaxial sample shapes for testing. The functional forms are shown at the beginning of the table. *Note, use the absolute parameter values (i.e., $|B|$, $|C|$, $|D|$) when calculating permeability*. Functions are those causal functions that have been derived in Chaps. 2 and 3 for dielectric and magnetic media. All data are based on laboratory-prepared samples and their measurement. *Caution should be observed when the derived parameters are over a narrow bandwidth that does not fully encompass the fundamental resonance. In those cases, extrapolation of the parameters outside the original measured band can lead to an error*. Chemical and/or physical composition is shown when available. In the table exponentials are often shown as bE—which means $b*10^{-a}$. Thus –2E-004–7.6E-003j is equal to –0.0002 –j0.0076. Figure 12.6 shows a typical three-phase measurement and numerical fit and Fig. 12.7 illustrates a fit to a two-phase composite.

TABLE 12.4 Micrometer and Nanometer Ferrite and Ferrite-Fe Particulates and Composites

Sample ID and Information							
$\mu(f)-1=\chi_m(f)=B(1-j*f/D)\{1-(f/C)^2-j*(f/D)\}^{-1}$							
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$ are, respectively, the EMT-calculated DC magnetic particle susceptibility; calculated composite resonant frequency, $\|C\|$; EMT-calculated magnetic particle resonant frequency; calculated composite relaxation frequency, $\|D\|$; EMT-calculated magnetic particle relaxation frequency. Note, please apply the absolute parameter values (i.e., $\|B\|$, $\|C\|$, $\|D\|$) when calculating permeability.							
$\varepsilon_1(f)=B+Cf^D+E\{1-(f/F)^2-2j*(f/G)\}^{-1}$ $\varepsilon_2(f)=B+real(C)f^D+imag(C)f^E+F\{1-(f/G)^2-2j*(f/H)\}^{-1}$							
	B	C	D	E	F	G	H
Composites of polymer and $Ni_{.32}Zn_{.48}Cu_{.12}Fe_2O_{4.6}$							
About 80 μm 9%/volume in epoxy, 1.38 g/cc, 0.05–18 GHz,							
$\chi_m(f)$	0.33+ 0.1j	1.61+ 0.95j	−0.74− 0.4j				
$\|B\|$, $\|C\|$ and $\|D\|$	0.34	1.8694	0.8412				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	62.3	1.8694	0.42	0.8412	0.04		
$\varepsilon_2(f)$	2.47+ 0.26j	8E-002− 0.14j	0.61+ 0.68j	−0.17+ 0.48j	0.66− 7E-002j	10.66− 12.9j	−18.6+ 10.47j
About 80 μm16%/volume in epoxy, 1.6 g/cc, 0.001–10 GHz							
$\chi_m(f)$	1.16+ 3E-002j	0.65+ 9E-002j	−0.2+ 3E-002j				
$\|B\|$, $\|C\|$ and $\|D\|$	1.16	0.6562	0.2022				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$		0.6562		0.2022			
$\varepsilon_2(f)$	2.66 +0.16j	7E-002− 9E-002j	0.61+ 0.39j	0.26+ 0.42j	0.81+ 0.12j	4.3+ 10.9j	51.6+ 43.9j

About 80 μm 16.7%/volume in epoxy, 1.68 g/cc, 0.05–10 GHz

$\chi_m(f)$	0.85+0.89j	0.38+1.45j	0.37−0.45j	−0.76+1.03j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	1.23	1.499	0.583			
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$		1.499		0.583		
$\varepsilon_1(f)$	1.57+5E-002j	9E-002+0.14j	−1.7−0.25j	1.71+0.12j	5E-002−14.7j	1.52+43.6j

About 80 μm 29.9%/volume in epoxy, 2.22 g/cc, 0.05–10 GHz,

$\chi_m(f)$	2.01+0.91j	0.28−0.82j	0.51−0.79j	−6E-002−0.79j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	2.21	0.866	0.940			
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	31.8	0.87	0.19	0.55	0.07	
$\varepsilon_1(f)$	2.57+0.55j	1.46+0.56j	−3E-003−4E-003j	−0.44−1.1j	20.16+7.5j	−11.9−73.9j

About 80 μm 29.9%/volume in epoxy, 2.22 g/cc, 0.001–18 GHz

$\chi_m(f)$	2.04+7E-002j	0.53−0.16j	−0.17+0.17j	−0.98−0.53j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	2.04	0.554	0.240			
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	27.2	0.56	0.21	0.24	0.03	
$\varepsilon_1(f)$	1.18+4E-002j	1.14+3E-002j	−9E-002+5E-002j	1.26+4E-002j	13.8−13.7j	6.03+90.4j

About 80 μm 41.1%/volume in epoxy, 2.68 g/cc, 0.05–10 GHz							
$\chi_m(f)$	3.95+ 1.27j	0.37− 0.48j	8E-002+ 0.27j	−0.61− 0.89j			
$\|B\|$, $\|C\|$ and $\|D\|$	4.15	0.61	0.28				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	29.3	0.61	0.11	0.28	0.042		
$\varepsilon_1(f)$	1.75+ 7E-002j	1.58+ 0.18j	−0.23+ 3E-002j	1.85+ 0.16j	14.68− 10.64j	−34.2+ 15.8j	
$\varepsilon_2(f)$	3.23+ 0.44j	7E-002+ 0.11j	0.65+ 0.42j	−0.95+ 0.1j	1.96+ 0.17j	7.53− 3.33j	−10.26− 4.8j
About 80 μm 49.4%/volume in epoxy, about 3.0 g/cc, 0.001–10 GHz							
$\chi_m(f)$	6.18+ 0.15j	0.33-2E −002j	−0.11+ 5E-002j	−1.3− 0.51j			
$\|B\|$, $\|C\|$ and $\|D\|$	6.18	0.33	0.12				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	29.8	0.33	0.133	0.12	0.02		
$\varepsilon_2(f)$	3.16+ 0.26j	0.2+ 8E-002j	0.75+ 0.52j	−0.2+ 0.2j	1.86+ 2E-002j	9.42− 6.54j	−13.73− 1.87j

About 80 μm 53.6% in epoxy, about 3.2 g/cc, 0.05–10 GHz

$\chi_m(f)$	3.91+ 2.64j	0.23– 0.68j	0.33+ 9E-002j	5E-002– 1.06j			
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	4.72	0.7178	0.3421				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	18.1	0.72	0.17	0.34	0.09		
$\varepsilon_1(f)$	1.63– 2E-002j	1.47+ 7E-002j	−5E-002– 0.17j	1.89- 2E-002j	1.64+ 13.67j	14.2+ 22.1j	
$\varepsilon_2(f)$	3.28+ 2E-002j	0.31– 9E-002j	0.39+ 0.3j	−0.94+ 0.63j	1.72– 2E-003j	7.89+ 9.44j	6.18– 49.19j

About 80 μm 58.4%/volume in epoxy, about 3.29 g/cc, 0.05–10 GHz

$\chi_m(f)$	8.1+ 3.6j	0.12– 0.32j	9E-002+ 8E-002j	−0.54– 1.31j			
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	8.86	0.34	0.12				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	31	0.34	0.05	0.12	0.02		
$\varepsilon_1(f)$	1.2– 1.4j	1.9– 0.98j	−0.12– 0.16j	2.05+ 2.73j	7.32– 15.6j	−33.7+ 20.6j	
$\varepsilon_2(f)$	3.49+ 0.18j	0.6– 0.16j	0.34– 3.7E-002j	−0.74+ 0.72j	2.29+ 2E-002j	2.87+ 2.01j	0.9– 2.7j

About 80 μm 61.4%/volume in epoxy, about 3.52 g/cc, 0.05–10 GHz

$\chi_m(f)$	9.55+4.8j	0.16–0.37j	0.13+0.12j	−0.38–1.04j			
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	10.69	0.403	0.18				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	34.6	0.403	0.08	0.18	0.03		
$\varepsilon_1(f)$	1.89–1.31j	2.63–0.85j	−0.12–0.18j	2.72+2.88j	14.49–13.49j	−48.4+18.1j	
$\varepsilon_2(f)$	3.96+0.33j	1.05–0.11j	9E-002–0.2j	−1.02+0.82j	2.9+0.4j	8.7–2.2j	−3.12–11.9j

About 80 μm 61.8%/volume in epoxy, about 3.53 g/cc, 0.05–10 GHz

$\chi_m(f)$	6.55+3.65j	0.24–0.49j	0.18+0.19j	−0.37–0.98j			
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	7.50	0.55	0.26				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	23.1	0.55	0.13	0.26	0.07		
$\varepsilon_1(f)$	1.88–1.35j	2.1–0.62j	−8E-002–0.22j	2.54+2.62j	15.88–23.4j	−54.1+17.5j	
$\varepsilon_2(f)$	3.85+0.25j	0.95-0.15j	0.33–0.28j	−1.04+0.65j	2.79+0.14j	7.3–0.23j	1.48–5.1j

About 80 μm 76.1% by volume in epoxy, about 4.12 g/cc, 0.001–10 GHz

$\chi_m(f)$	14.2–2E-002j	0.18–1E-002j	–5E-002+1.6E-002j	–1.7–0.37j			
$\|B\|$, $\|C\|$ and $\|D\|$	14.20	0.18	0.053				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	31.7	0.18	0.03	0.053	0.014		
$\varepsilon_1(f)$	3.31+0.11j	2.32+0.15j	5E-003–6E-003j	1.87–0.22j	12.1–0.76j	–2.2–19.8j	
$\varepsilon_2(f)$	3.93+2E-002j	0.97–0.13j	3E-002+0.15j	–0.26+0.32j	2.8+0.16j	13.1–2.91j	–11.8–19j

Iron–Ferrite Composites 0.5

500-nm Fe 7% + 80-μm $Ni_{.32}Zn_{.48}Cu_{.12}Fe_2O_{4.6}$ at 7%/volumes in epoxy, 1.8 g/cc, 0.001–18 GHz

$\chi_m(f)$	1.04+0.15j	3.26–0.62j	–1.63+0.39j	–0.9+0.41j			
$\|B\|$, $\|C\|$ and $\|D\|$	1.05	3.32	1.68				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$		3.32		1.68			
$\varepsilon_1(f)$	0.99–1.45j	2.26–1.16j	–9.7E-003–2E-002j	2.1+2.73j	48.8+112j	47.2+119j	
$\varepsilon_2(f)$	2.94+0.29j	0.96–0.71j	0.49+8E-002j	0.32–0.12j	2.45+8E-002j	12.6+4j	–8.1–10.9j

500-nm Fe 10.2% + 80-μm $Ni_{.32}Zn_{.48}Cu_{.12}Fe_2O_{4.6}$ at 10.1%/volumes in epoxy, 2.1 g/cc, 0.001–10 GHz

$\chi_m(f)$	0.98+ 0.13j	3.45+ 2.25j	−1.32− 0.75j	−1.36− 9E-002j			
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.99	4.12	1.52				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	27	4.12	0.19	1.52	0.19		
$\varepsilon_1(f)$ 1	0.97− 1.54j	2.29+ 1.25j	0.11-6E− 002j	2.1+ 2.69j	8.39+ 13.31j	18.7+ 15.7j	
$\varepsilon_2(f)$	2.9+ 0.39j	1.01− 0.69j	0.51+ 0.32j	0.32− 2E-002j	2.24+ 0.24j	7.49− 2.7j	−8.4− 2.6j

500-nm Fe 13.4% + 80-μm $Ni_{.32}Zn_{.48}Cu_{.12}Fe_2O_{4.6}$ at 13.6%/volumes in epoxy, 2.43 g/cc, 0.05–10 GHz

$\chi_m(f)$	2.85+ 1.05j	0.56+ 1.78j	0.4+ 5E-002j	0.99+ 2.11j			
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	3.04	1.87	0.403				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	143	1.87	0.31	0.403	0.011		
$\varepsilon_1(f)$	1.4+ 1.37j	2.76− 1.06j	2E-002j	2.45+ 2.9j	266.8− 266.9j	−24.8− 26.1j	
$\varepsilon_2(f)$	3.53+ 0.2j	0.92− 0.75j	0.29+ 0.14j	0.44+ 4E-002j	2.92+ 0.2j	11.6− 12j	−34.8+ 6.3j

500-nm Fe 17.5% + 80-μm $Ni_{.32}Zn_{.48}Cu_{.12}Fe_2O_{4.6}$ at 17.5%/volumes in epoxy, 2.82 g/cc, 0.05–10 GHz

$\chi_m(f)$	4.82+0.64j	0.83−0.47j	−0.29+0.22j	−1.3−0.2j			
$\|B\|$, $\|C\|$ and $\|D\|$	4.86	0.954	0.3640				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$		0.954		0.364			
$\varepsilon_1(f)$	2.08−0.82j	3.16−0.69j	0.28+9E-002j	5.78+2.28j	4.2+0.3j	1.26−2.32j	
$\varepsilon_2(f)$	4.3+0.26j	1.13−0.86j	−0.18−0.1j	0.57+0.11j	3.47+0.25j	2−16.1j	−0.32+22.9j

Iron–Ferrite Composites 0.5

500-nm Fe 19.9% + 80-μm $Ni_{.32}Zn_{.48}Cu_{.12}Fe_2O_{4.6}$ at 20.0% by volumes in epoxy, 3.1 g/cc, 0.001–10 GHz

$\chi_m(f)$	8.14+0.13j	0.54−0.1j	−0.21+2E-002j	−1.29+0.12j			
$\|B\|$, $\|C\|$ and $\|D\|$	8.14	0.55	0.21				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	100	0.55	0.12	0.21	1.3		
$\varepsilon_1(f)$	2.41−1.8j	3.27−1.2j	8E-002+0.61j	6.13+6.3j	1.39+1.64j	0.74−0.86j	
$\varepsilon_2(f)$	3.67−4E-002j	0.75−0.53j	−0.3−0.4j	−0.21+0.11j	3.05−6E-002j	23.64+12.3j	16.3+5.2j

500-nm Fe 23.3% + 80-μm $Ni_{.32}Zn_{.48}Cu_{.12}Fe_2O_{4.6}$ at 23.3%/volumes in epoxy, 3.4 g/cc, 0.05–10 GHz

$\chi_m(f)$	8.41+0.16j	0.52-7E−002j	−0.19-2E−004j	−1.34+0.21j			
$\|B\|$, $\|C\|$ and $\|D\|$	8.41	0.525	0.19				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	60.1	0.525	0.167	0.19	1.36		
$\varepsilon_1(f)$	5.41+1.1j	4-0.79j	−2E-003−2.6E-002j	−0.61+0.7j	0.18+0.57j	0.12+7E-002j	
$\varepsilon_2(f)$	4.48+0.16j	1.69−0.46j	−0.2−7E-002j	−0.62+0.11j	3.65+8E-002j	29.6−23.5j	−115+53.4j

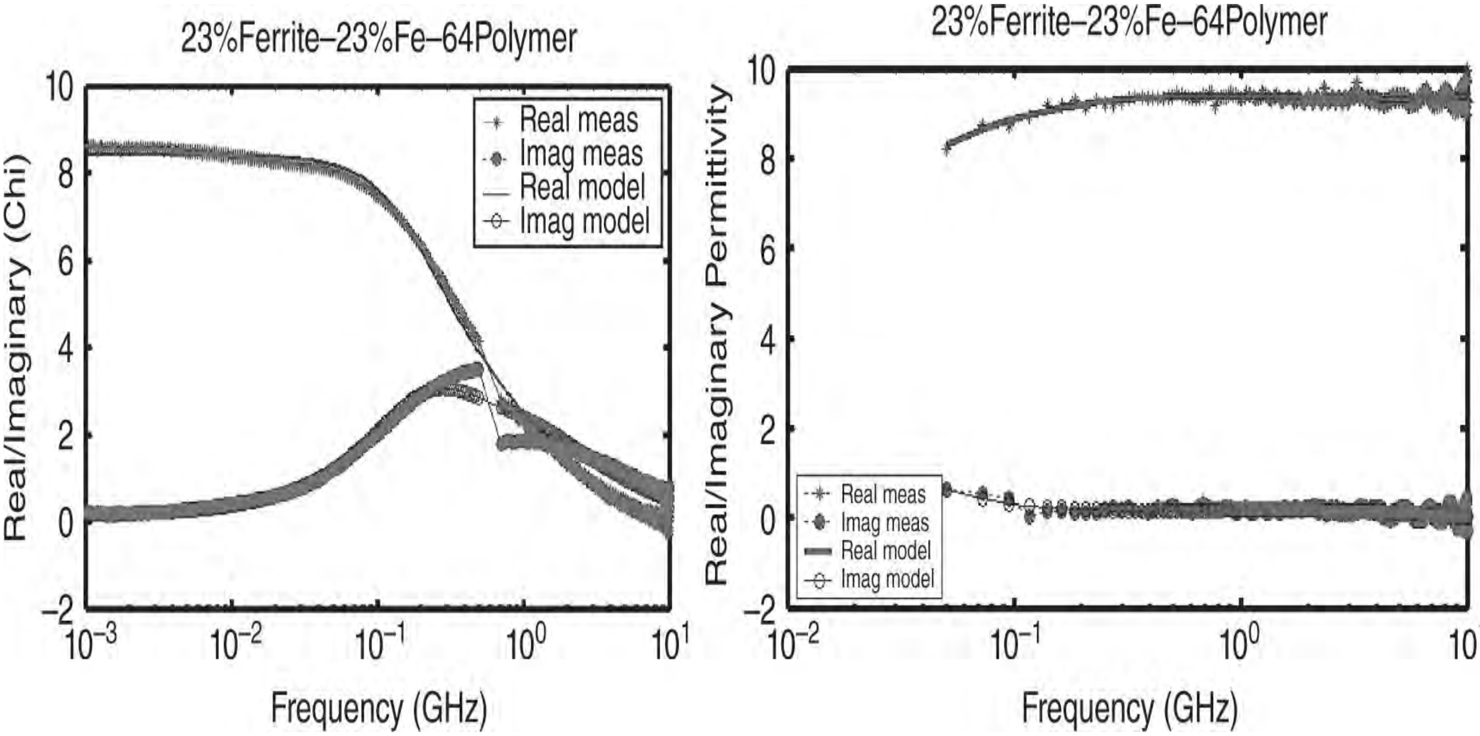


FIGURE 12.6 Data show measurements and fit to a three phase magnetic composite. Model and measurement have near overlaps.

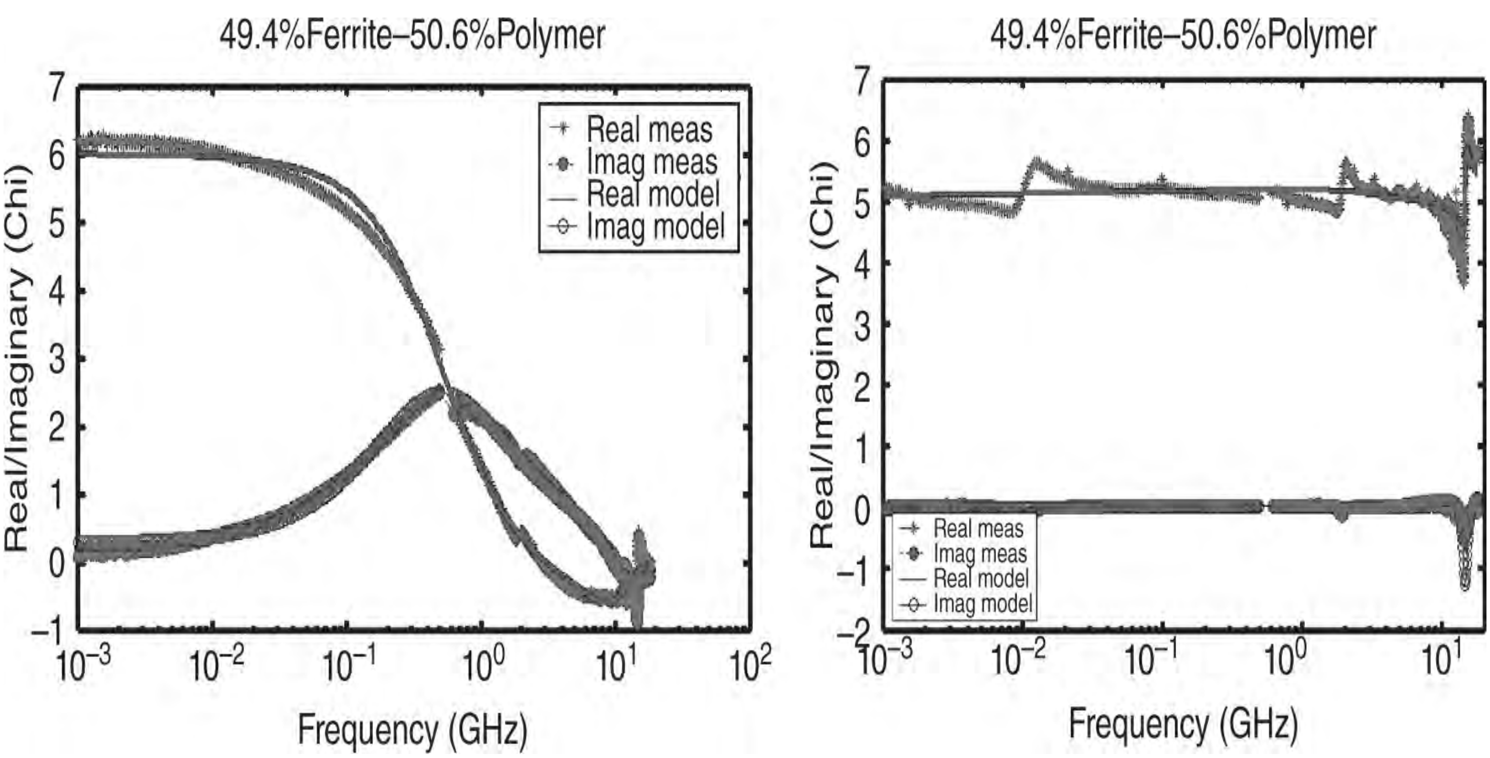


FIGURE 12.7 Data show measurements and fit to a two phase magnetic composite. Model and measurement have near overlaps.

Disclaimer: Data are results obtained by the author on samples prepared in the laboratory. Variations may be observed by other researchers when prepared in their laboratories. Data are not “guaranteed” by a manufacturer or the author. Variations in properties may be observed and users of the products should verify properties. All

material properties are guides for engineering design. Materials prepared in the laboratory should be considered as experimental and also guides for engineering design.

12.5 COMPOSITES DEMONSTRATING PERCOLATION

Table 12.5 shows the parametric fits to permittivity for mixtures of semiconducting particulates (i.e., the microspheres of Chap. 11) and polymers. The PEA microspheres had approximately 70 percent of their surfaces covered with a high conductivity metal. The PEB had about 60 percent covered in a high-conductivity metal. All composites were 3D with thickness much larger than a particulate diameter. Composites were made and formed in the laboratory into test samples larger than 30 cm on a side and measured using free space focused beam. The functional form to which data are fitted are shown at the beginning of the table. Functions are those causal functions that have been derived in Chaps. 2 and 3 for dielectric and magnetic media. In the tables exponentials are often shown as bE—which means $b*10^{-a}$. Thus –2E-004–7.6E-003j is equal to –0.0002–j0.0076. Example fits and measurement are shown in Fig. 12.8. Materials were laboratory samples. See Chap. 11.4 for description of the particulates.

TABLE 12.5 Percolating Composites

Sample ID									
$\varepsilon(f) = B + Cf^{D} + Ef^{F} + G\{1 - J*(f-H)^{2} - j2If\}^{-1}$									
	B	C	D	E	F	G	H	I	J
38%—PEPB (4–100 GHz)									
	2.91+ 0.1j	3.02+ 7E-002j	−6E-02+ 3E-002j	3.02+ 7E-002j	−6E-002+ 3E-002j	0.25+ 6E-002j	1E-002− 2E-002j	14.2+ 56.4j	−2E-004
41%—PEB (4–100 GHz)									
	4.34+ 0.9j	5+ 7E-002j	−7E-02+ 4E-002j	6.7+ 0.7j	−0.62− 0.13j	0.19− 0.34j	−2.5E-002 +5.4E-002j	11.5+ 34.2j	−1E-003− 2E-004j
41%—PEB #2 (4–100 GHz)									
	5.34− 3E-002j	13.3− 7.23j	−1.4+ 1.3j	7.04− 14.4j	−1.65− 0.17j	5.12+ 0.21j	−4E-004− 1E-002j	69.7− 10.7j	−2E-004j
47%—PEB #1 (.2–100 GHz)									
	10.29+ 6.1j	11.29+ 15.1j	−0.46− 0.46j	8.3+ 14.87j	−1.37+ 0.15j	1.06+ 2.12j	0.41− 2E-002j	−0.19+ 4.8j	−2E-002− 8E-003j
47%—PEB #2 (0.2–100 GHz)									
	8.26+ 1.79j	9.31+ 18.1j	−0.41− 7E-002j	6.96+ 15.93j	−1.31+ 0.13j	3.95+ 4.02j	0.31− 2E-002j	−2.05+ 5.1j	−2E-002− 3E-003j

50%—PEA (0.2–100 GHz)									
	11.32+4.2j	0.86+42j	−1.3+0.3j	6.94+33.1j	−0.77−0.21j	12.1+7.4j	5.5E-002−0.13j	−18.21−6j	−5E-004+4E-003j
38%—PEAs (4–100 GHz)									
	5.46+1.9j	5.26+0.24i	−2E-002+0.14j	5.43+0.16j	−0.15−0.21j	2.34+13.25j	6.91+3.8j	−2.2−0.92j	9E-003+3E-002j
41%—PEA#1 (0.2–100 GHz)									
	8.36+3.4j	4.92−1.2j	−1.59−0.39j	12.8+12.2j	−0.33−5E-003j	5.89+11.62j	0.19−2E-002j	−5.3+1.3j	−4E-004+3E-003j
41%—PEA#2 (0.2–100 GHz)									
	9.34+3.94j	11.76+9.06j	−0.35−2E-002j	4.43+0.35j	−1.7−0.22j	7.84+11.5j	0.14−2E-002j	−8.4+1.96j	−1E-004+2E-003j
44%—PEA (0.2–100 GHz)									
	14.13+7.84j	6.41+30.12j	−1.46+0.22j	10.47+32.07j	−0.92−0.35j	8.39+25.1j	−0.5+3.3j	−27.1+7.1j	−4.3E-003+2E-003j

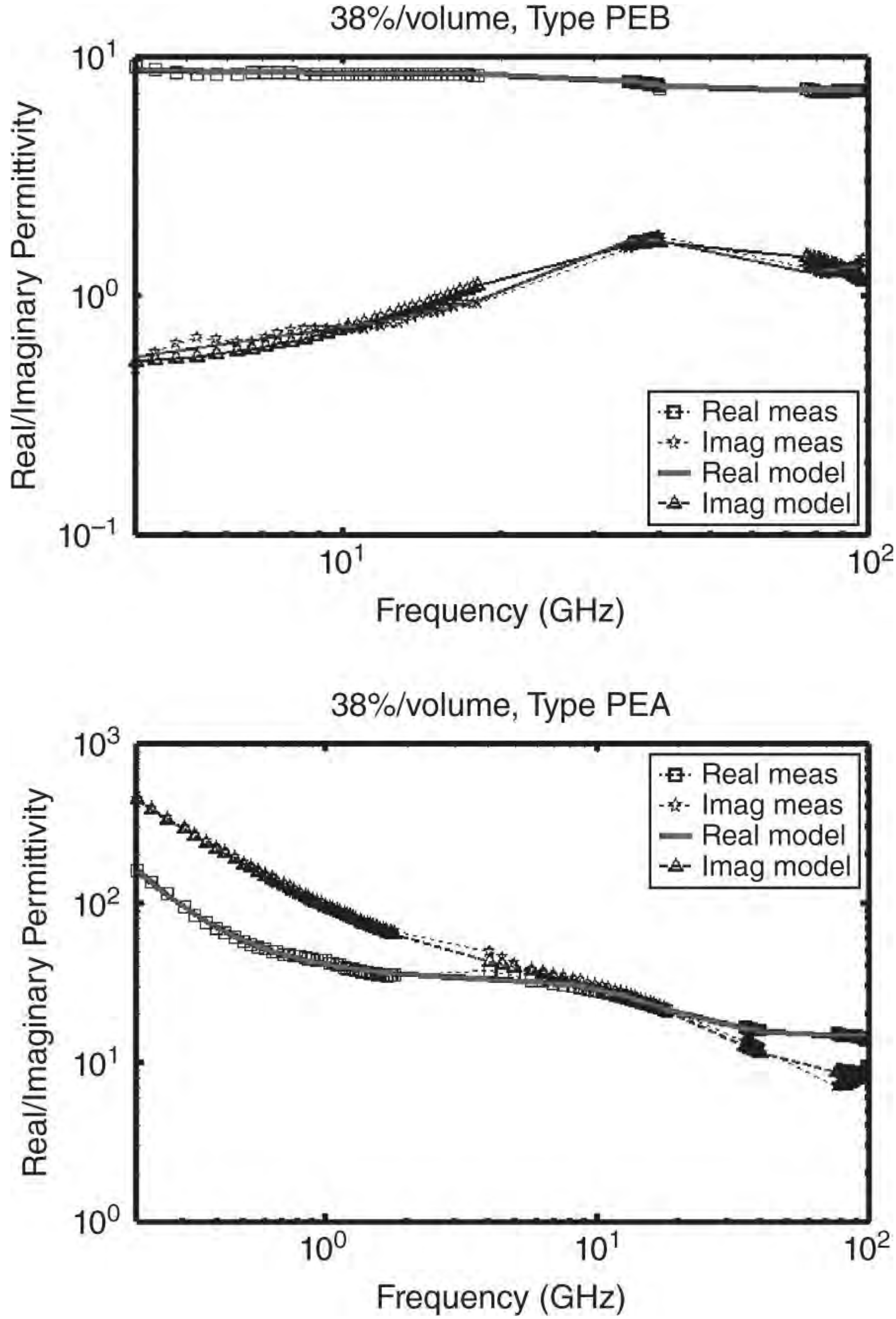


FIGURE 12.8 The left graph shows measurement and fit below percolation for the Type PEB particle. The rightmost graph, though at the same volume fraction, is above percolation for the Type PEA particle.

Disclaimer: Data are results obtained by the author on samples prepared in the laboratory. Variations may be observed by other researchers when prepared in their

laboratories. Data are not "guaranteed" by a manufacturer or the author. Variations in properties may be observed and users of the products should verify properties. All material properties are guides for engineering design. Materials prepared in the laboratory should be considered as experimental and also guides for engineering design.

12.6 SOLID SEMICONDUCTORS VERSUS FREQUENCY

Table 12.6 shows the parametric fits of permittivity for various semiconductors. Test samples were cut from large wafers for testing. Free space measurements of the full wafer were used for mmW measurements. The functional forms are shown at the beginning of the table. Functions are those causal functions that have been derived in Chaps. 2 and 3 for dielectric and magnetic media. Other data are shown when available. These include density, measured frequency span serving as basis for fits, tabulated information, and chemical and/or physical composition. In the tables exponentials are often shown as bE—which means $b*10^{-a}$. Thus, –2E-004–7.6E-003j is equal to –0.0002–j0.0076. Figure 12.9 shows a typical broadband fit. Please note that the Silicon and Germanium data were acquired over limited bandwidth.

TABLE 12.6 Semiconductors

Sample ID							
$\varepsilon(f) = B + Real(C) f^D + Imag(C) f^E + F(1-(f/G)^2 - j2f/H)^{-1}$							
	B	C	D	E	F	G	H
Zinc sulfide; 4.09 g/cc (3–240 GHz) (nominal ε_r = 8.5 at 2 MHz; Korth Kristalle GMBH)							
	2.44−6E-003j	2.58+6E-003j	0.15+6E-003j	0.15+6E-003j	1.9+3E-003j	3.5+53.24j	18.9+88.9j
Zinc selenide, 5.27 g/cc (5–240 GHz) (nominal ε_r = 8.98; Korth Kristalle GMBH)							
	2.37−0.13j	2.65−4E-002j	0.15+7E-002j	0.14+6E-002j	2.53+6E-002j	136−138j	−176+42.4j
Gallium arsenide (3–240 GHz) (nominal ε_r = 8.35–11.36; US pat. 6683510)							
	3.63−0.13j	3.64−7E-002j	8E-002+3E-002j	0.19−0.3j	3.73−4E-002j	76.9−367j	−547+598j
Silicon (2.33 g/cc) (9–12.4 GHz) (nominal ε_r = 10.2; Accumet Engineering)							
	3.89+8E-003j	3.89+8E-003j	−2E-003+2E-003j	−2E-003+2E-003j	3.89+8E-003j	440−1702j	−7627+10622j
Germanium (5.33 g/cc) (3–10 GHz) (nominal ε_r = 16; Virginia Semiconductor)							
	11.97+2.83j	13.23+3.4j	−2E-002+0.25j	0.53+1.44j	14.53+1.8j	1.1+6j	0.92+8.12j

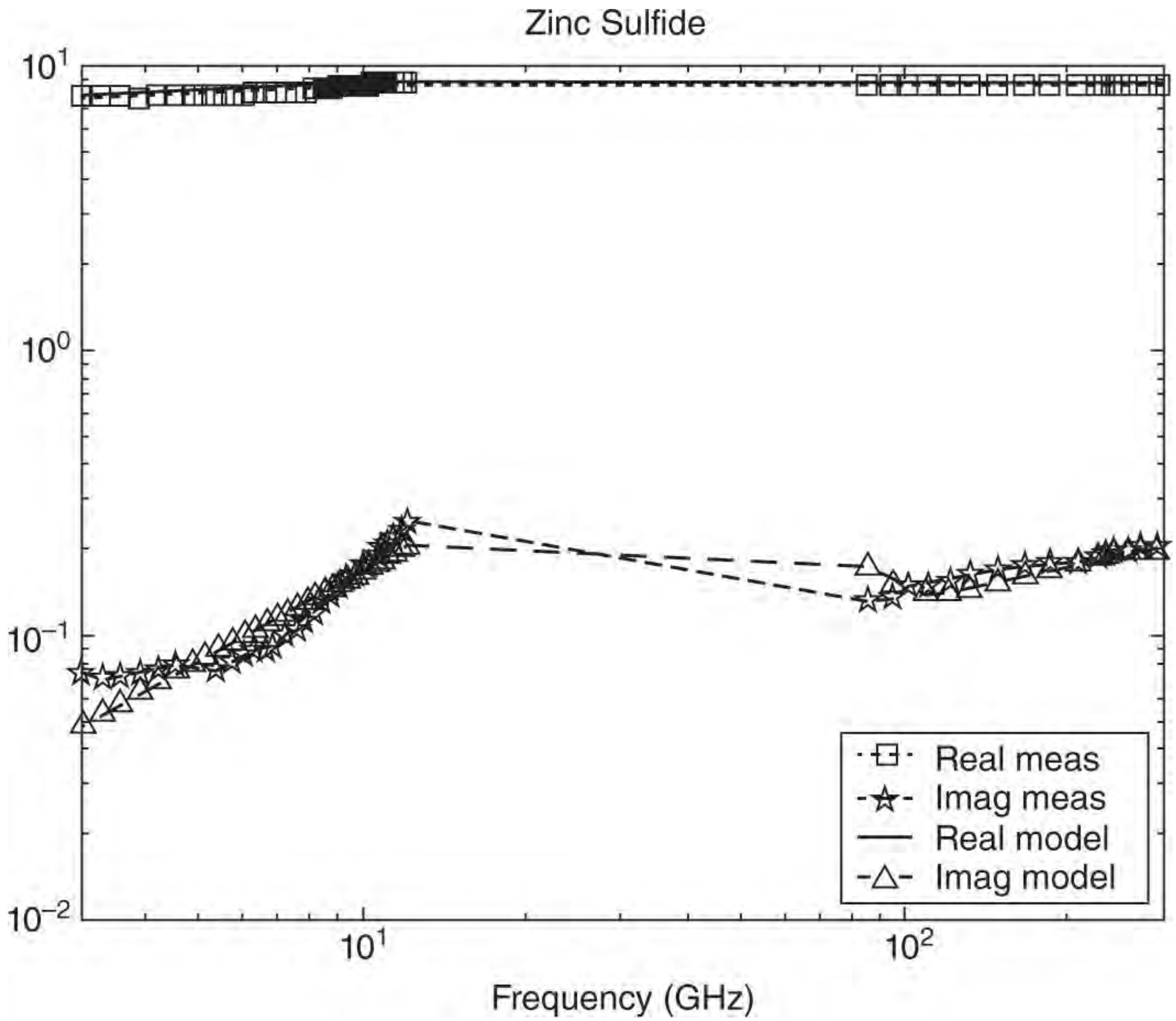


FIGURE 12.9 Measurement and model fit for Zinc Sulfide.

Disclaimer: Data are results obtained by the author on samples prepared in the laboratory. Variations may be observed by other researchers when prepared in their laboratories. Data are not "guaranteed" by a manufacturer or the author. Variations in properties may be observed and users of the products should verify properties. All material properties are guides for engineering design. Materials prepared in the laboratory should be considered as experimental and also guides for engineering design.

12.7 HONEYCOMB AND FOAMS VERSUS FREQUENCY

Table 12.7 shows the parametric fits to permittivity for honeycomb and foam composites. Square test samples were cut from larger production pieces. Test samples were square shapes greater than 30 cm on each side. Thicknesses were typically 2.5 cm. Samples were measured with Fabry–Perot and/or focused beam system. The functional forms are shown at the beginning of the table. Functions are those causal functions that have been derived in Chaps. 2 and 3 for dielectric and magnetic media. Other data are shown when available. These include density, measured frequency span serving as basis for fits, tabulated information, and chemical and/or physical composition. One foam (Fig. 12.10, top) and one honeycomb (Fig. 12.10, bottom) are shown. In the tables exponentials are often shown as bE—which means $b*10^{-a}$. Thus, –2E-004–7.6E-003j is equal to –0.0002–j0.0076. Nominal data from web-accessible external databases (e.g., Le Reseau Composites Network) are shown when available.

TABLE 12.7 Foams/Honeycombs

Sample ID							
0 or 90 degree rotations of the square shape sample (38 × 38 × 1 cm)							
$\varepsilon(f) = B + 2Cf^{D} + G\{1 - J*(f-H)^2 - j2If\}^{-1}$							
	B	C	D	G	H	I	J
Syntactic foam F6555 (20–100 GHz) (nominal $\varepsilon_r = 1.9$, $\tan\delta = .005$, Le Reseau Composites Network, icomposites.com)							
0 degree	0.52–3E-003j	0.5–1E-002j	–0.21+1E-002j	0.63–3E-003j	2E-003–3E-004j	–3E-003j	–2E-005–4E-006j
90 degree	0.63+4E-003j	0.75+2E-002j	–0.14–1E-002j	0.6–1E-004j	1E-003	4E-004–2E-003j	–2E-005–4E-006j
Honeycomb HRH-310 meta-aramid fiber polyimide, 1/8-in. cell (10–60 GHz) (nominal $\varepsilon_r = 1.015–1.043$, $\tan\delta = .0002–.0018$)							
0 degree	0.264–4E-004j	0.266–4E-004j	–3E-002+1E-002j	0.263–7E-004j	2E-003+1E-004j	–8E-004–3E-003j	–7E-005+1E-005j
90 degree	0.254+2E-004j	0.254+2E-004j	2E-004	0.254+2E-004j	–2E-006	–2E-005–7E-004j	–2E-005+1E-006j

Honeycomb HRP ¼-in. cell (30–60 GHz) fiberglass reinforced phenolic (nominal $\varepsilon_r = 1.09$, $\tan\delta = .003$, CEMTACH Group)							
0 degree	0.331+ 4.5E-002j	0.378+ 3.5E-002j	−0.111+ 9E-002j	0.634+ 2E-004j	1.8E-002 + 2E-002j	−2E-002+ 5E-003j	1E-004+ 5E-004j
90 degree	0.33+ 9.8E-002j	0.193+ 4E-002j	0.24− 7E-002j	1.2E-002 −1.5E-002j	0.13− 6E-002j	6E-004− 3E-002j	−9E-004+ 9E-006j
Honeycomb HRP 1/16-in. cell (30–60 GHz) fiberglass reinforced phenolic							
0 degree	0.297+ 4E-003j	0.297+ 4E-003j	−1E-003+ 2E-003j	0.31+ 5E-003j	7E-003+ 8E-004j	−3E-003+ 9E-003j	2E-004+ 1E-004j
90 degree	0.267+ 6E-003j	0.267+ 6E-003j	4E-004+ 1E-004j	0.267+ 6E-003j	4E-004+ 1E-004j	−1E-004− 9E-004j	−4E-005− 5E-006j
Honeycomb HRH-78 meta-aramid ¼-in. cell (18–60 GHz)							
0 degree	0.258+ 7E-004j	0.259+ 7E-004j	2.3E-002 +7E-004j	0.258+ 6E-004j	−1.3E-003− 1E-004j	−1E-004− 1E-003j	−4.6E-005+ 2E-006j
90 degree	0.27− E-004j	0.27− 2E-004j	−6E-003+ 2E-004j	0.27− 4E-004j	1E-003− 5E-004j	1E-004+ 1.5E-003j	6E-005− 3E-006j

Honeycomb HRH-10 1/8-in. cell, meta-aramid fiber phenolic (18–60 GHz)

0 degree	0.258+ 7E-004j	0.259+ 7E-004j	2.5E-002+ 7E-004j	0.258+ 6E-004j	−1.3E-003− 1E-004j	−1E-004− 1E-003j	−5E-005+ 2E-006j
90 degree	0.253+ 3E-004j	0.255+ 3E-004j	2.9E-002+ 4E-004j	0.251+ 3E-004j	−1.5E-003	−2E-005− 5E-004j	−4E-005+ 3E-007j

Honeycomb para-aramid fiber [$-CO-C_6H_4-CO-NH-C_6H_4-NH-]_n$, HRH-49 para (5–40 GHz) (nominal $\varepsilon_r = 1.03–1.07$, $\tan\delta = .001–.003$, Le Reseau Composites Network)

0 degree	0.266+ 6E-004j	0.266+ 6E-004j	2E-003	0.267+ 6E-004j	4E-004	2E-003j	1E-004
90 degree	0.262+ 4E-004j	0.263+ 4E-004j	−1.7E-002	0.262+ 4E-004j	−5E-004	−2E-003j	−3E-005

Honeycomb HRH-327 fiberglass reinforced polyimide 3/16 in. (30–60 GHz)

0 degree	0.267+ 6E-003j	0.267+ 6E-003j	4E-004 +1E-004j	0.267+ 6E-003j	4E-004− 1E-004j	−1E-004− 9E-004j	−4E-005 +4E-006j
90 degree	0.297+ 5E-003j	0.297+ 5E-003j	−1E-003 +2E-003j	0.31+ 5E-003j	7E-003 +8E-004j	−3E-003 +9E-003j	2E-004 +1E-004j

Honeycomb ES PEI-E-glass, 5 lb/ft^3 (18–60 GHz)							
0 degree	0.253–1E-003j	0.257–7E-004j	4.2E-002+1.1E-002j	0.254–2E-003j	–2E-003–1E-003j	–2E-003+7E-004j	8E-007+3E-005j
90 degree	0.271–2E-004j	0.271–2E-004j	–7E-003–2E-003j	0.272+1E-004j	–3E-003+2E-003j	2E-004–4E-003j	–1E-004
PBI Honeycomb (2–100 GHz)							
0 degree incidence (4–100 GHz)	0.286+2E-003j	0.288+2E-003j	–4E-002–8E-003j	0.292+2E-003j	–3E-003–2E-004j	5E-004–3E-003j	–9E-006–3E-006j
20 degree incidence (>70 GHz)	0.41–0.12j	0.4–0.25j	–0.14–0.14j	0.297–7E-002j	8E-003–6E-003j	3E-003–1E-002j	–1E-004–4E-005j
40 degree incidence (>70 GHz)	0.52–3E-002j	0.54–2E-002j	8.3E-002+1.9E-002j	0.462+5E-002j	8E-002+4E-003j	3E-002–7E-002j	–2E-003–8E-004j
60 degree incidence (>70 GHz)	0.32–1E-002j	0.32–1E-002j	–3E-002–1E-002j	0.35+3E-003j	–2E-003–3E-003j	2E-003–1E-003j	2E-005–3E-005j
Honeycomb polycarbonate 1/8-in., 0.149 g/cc (8–26 GHz)							
0 degree	0.293+3E-004j	0.293+3E-004j	8E-003–2E-003j	0.294+3E-004j	–1.4E-003–1.2E-003j	5E-004+3E-003j	6E-005+1E-005j
90 degree	0.304–5E-003j	0.31–5E-003j	–5E-002+2E-002j	0.303–4E-003j	2E-003–8E-004j	–4E-004–3E-003j	–5E-005+6E-006j

Honeycomb polyimide ¼-in. (18–45 GHz)							
0 degree	0.288	0.288	−4E-004	0.287–2E-004j	4E-004–3E-005j	2E-004+5E-003j	2E-004–2E-006j
90 degree							
Polyurethane foam 10 lb/ft^3 (18–100 GHz)							
0 degree	0.293–2E-004j	0.293–2E-004j	7E-003+2E-003j	0.291–1E-004j	−3E-004–1E-004j	2E-005-5j	−1E-005–9E-007j
90 degree							
Polyurethane foam 6 lb/ft^3 (18–100 GHz)							
0 degree	0.278+4E-004j	0.278+4E-004j	1E-004–1E-004j	0.278+4E-004j	5E-007–2E-007j	5E-005+2E-004j	3E-006–6E-007j
90 degree							
Carbon reticulated foam (500 MHz to 6 GHz)							
Sample C	1.55+0.28j	−0.64+1.81j	−0.95+0.16j	0.93+0.86j	0.5+0.46j	−0.41–0.11j	−0.14–5E-003j
Sample B	1.59+0.39j	−0.43+1.61j	−1.1+0.47j	−0.5+1.44j	0.31–0.12j	−0.46–0.11j	−0.11+5E-002j
Sample A	1.28–0.55j	−0.32+2.61j	−0.84+0.11j	1.55+0.44j	−6E-002+0.31j	−0.44+0.17j	−4E-002+0.15j

110 Polymethacrylimide-1 foam (1–100 GHz) 6.9 lb/ ft^3

0.292+ 2E-003j	0.292+ 2E-003j	0	0.292+ 2E-003j	0	0	0

110 Polymethacrylimide-2 foam (1–100 GHz) 6.9 lb/ ft^3

0.321– 3E-003j	0.365– 3E-003j	–0.12+ 1.4E-002j	0.318– 4E-003j	–1E-003+ 2E-003j	–3E-004- 2E-003j	–2E-005+ 4E-006j

200 Polymethacrylimide foam (18–100 GHz) 12.5 lb/ ft^3

0.322+ 3E-003j	0.322+ 3E-003j	7E-004+ 2E-003j	0.322+ 3E-003j	1E-004+ 1E-004j	–5E-004+ 8E-004j	2E-005+ 8E-006j

300 Polymethacrylimide foam (18–60 GHz) 18.7 lb/ ft^3

0.273+ 7E-003j	0.313+ 5E-003j	0.12– 1E-003j	0.161– 8E-003j	3.3E-002+ 2E-003j	–3E-002j	–2E-003

51 Polymethacrylimide foam (8–26 GHz) 3.1 lb/ ft^3

0.289– 2E-003j	0.305– 2E-003j	–8.2E-002 +7E-003j	0.287– 2E-003j	–1E-003+ 3E-004j	–1E-004 –2E-003j	–2E-005+ 1E-006j

71 Polymethacrylimide foam (9–17 GHz) 4.4 lb/ ft^3

0.2753+ 1.7E-003j	0.2753+ 1.7E-003j	2E-003+ 4E-004j	0.2754+ 1.7E-003j	3.8E-003+ 1E-003j	–1.2E-003+ 4.1E-003j	–4E-004+ 1E-004j

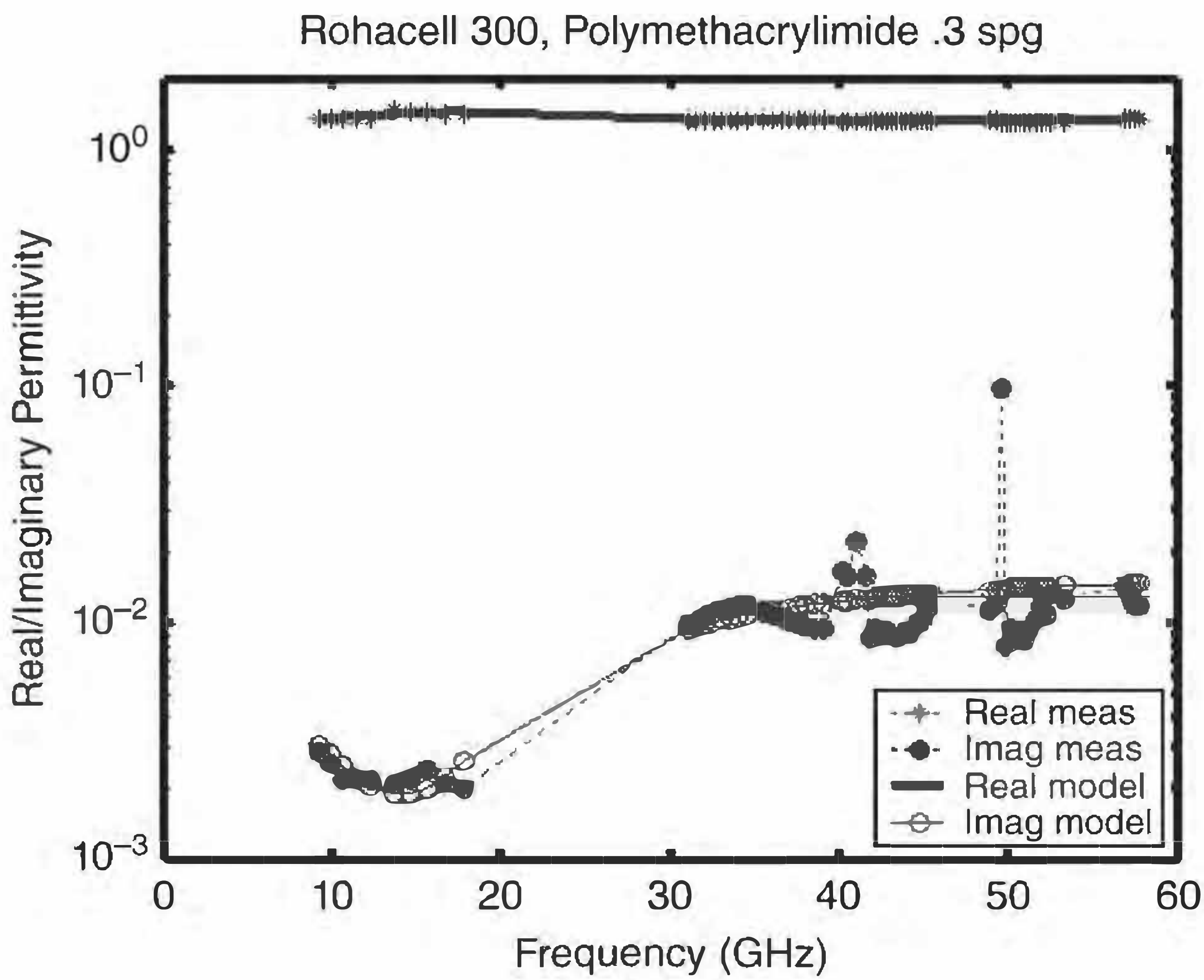
31 Polymethacrylimide foam (8–26 GHz) 1.9 lb/f^{3}							
	0.2625+ 2E-004j	0.2625+ 2E-004j	−5E-004	0.2625+ 2E-004j	0	3E-004j	1E-004
Polystyrene foam 7.8 lb/ft^{3} (9–18 GHz)							
	0.2974+ 3E-004j	0.6337+ 2E-004j	−0.3404+ 2E-004j	0.1091+ 4E-004j	4E-002	4.28E-002j	−2.6E-003
Polystyrene foam 12.1 lb/ft^{3} (9–18 GHz)							
	0.2959+ 1.5E-003j	0.2959+ 1.5E-003j	1.2E-003+ 5E-004j	0.2964+ 1.5E-003j	−1.9E-003 +1.1E-003j	−1E-003+ 5E-003j	−2E-004+ 1E-004j
Polystyrene foam 13.9 lb/ft^{3} (9–18 GHz)							
	0.2457+ 1E-004j	0.2923+ 1E-004j	0.1776+ 1E-004j	3.5E-002 +1E-004j	8.4E-002 +1E-004j	−8.62E-002j	−9.2E-003
Polystyrene foam 15.7 lb/ft^{3} (9–18 GHz)							
	0.2454+ 1E-004j	0.2883+ 1E-004j	0.1733	3.31E-002	8.43E-002 +1E-004j	8.68E-002	−9.1E-003
Polystyrene foam 17.0 lb/ft^{3} (9–18 GHz)							
	0.3977+ 1E-004j	0.8283+ 5E-004j	−0.3271+ 3E-004j	3.02E-002 +2E-004j	3.47E-002 +1E-004j	5.48E-002j	−3.3E-003

Polystyrene foam 20.0 lb/ft^3 (9–18 GHz)

	0.3381+ 5E-004j	0.3382+ 5E-004j	5.3E-003+ 2E-004j	0.3386+ 5E-004j	7.3E-003	−1E-004+ 7.9E-003j	−8E-004

$$\varepsilon(f)=B+2Cf^{D}+Ef^{f}+G\{1-J*(f-H)^{2}-j2If\}^{-1}$$

	B	C	D	E	F	G	H	I	J
¼-in. cell, meta-aramid honeycomb, −3-dB/in. transmission loss in X band (200 MHz to 18 GHz)									
Measurement position 1	1.08+ 0.23j	0.21+ 0.21j	−0.37− 0.34j	0.17+ 0.19j	−0.98− 0.5j	9E-002− 0.31j	2.68+ 0.37j	0.77− 0.11j	−8E-002− 0.13j
Measurement position 2	1.175+ 0.18j	−0.16- 2E-002j	−1.12+ 0.56j	−0.17− 2E-002j	−0.93	1.12− 0.1j	0.35+ 0.81j	0.29+ 2E-002j	−9E-002− 1E-002j
Measurement position 3	1.2+ 0.18j	9E-002+ 0.2j	−1.03− 0.56j	9.4E-002 +0.2j	−0.66− 0.48j	0.12− 0.43j	1.97− 1.04j	0.6− 0.5j	−3E-002− 0.18j


Rohacell 300, Polymethacrylimide .3 spg
Real/Imaginary Permittivity
10^0
10^{-1}
10^{-2}
10^{-3}
0
10
20
30
40
50
60
Frequency (GHz)
Real meas
Imag meas
Real model
Imag model

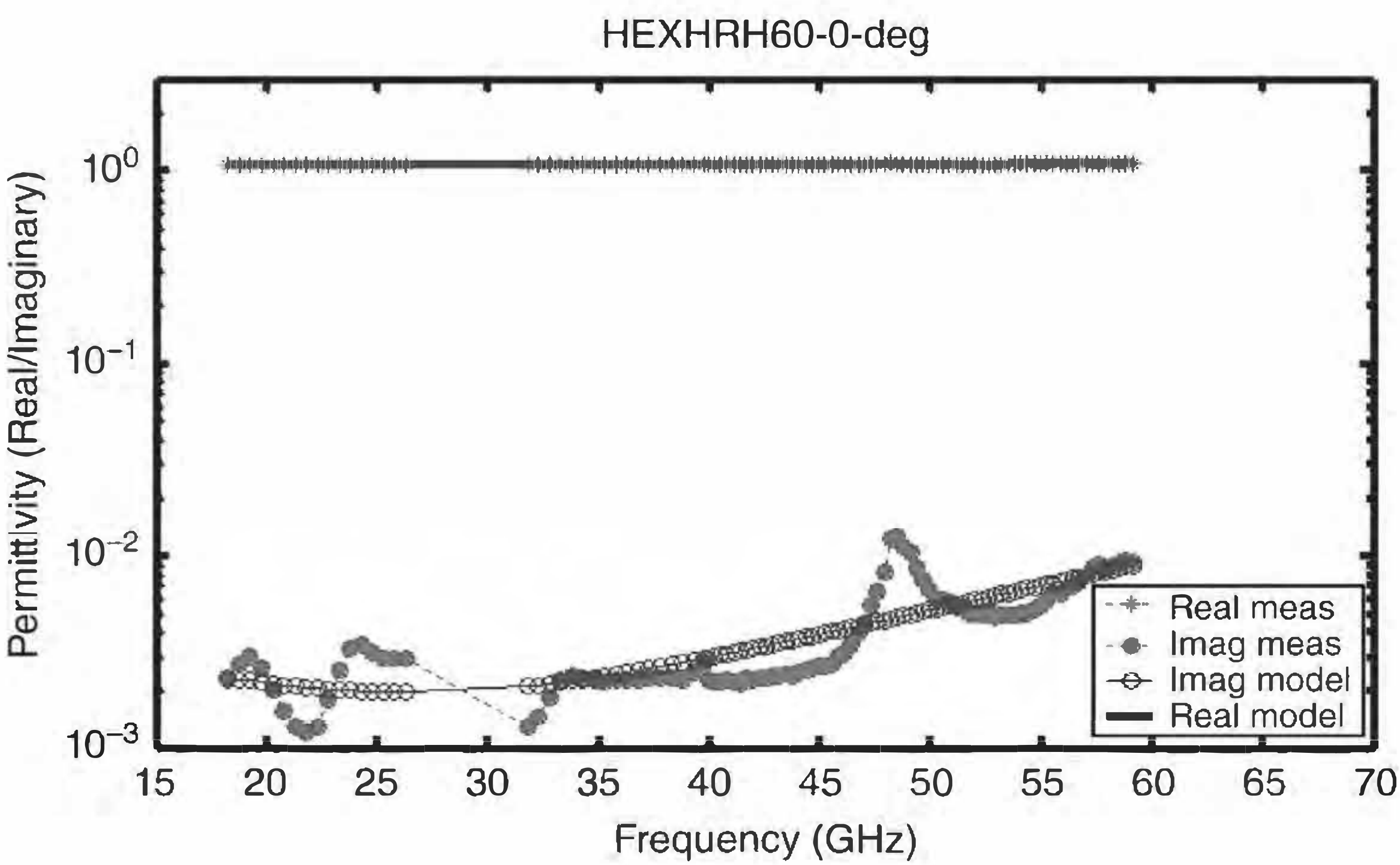

HEXHRH60-0-deg
Permittivity (Real/Imaginary)
10^0
10^{-1}
10^{-2}
10^{-3}
15
20
25
30
35
40
45
50
55
60
65
70
Frequency (GHz)
Real meas
Imag meas
Imag model
Real model

FIGURE 12.10 Measurement and model fit for a foam (upper) and honeycomb (lower) composite.

Disclaimer: Data are results obtained by the author on samples prepared in the laboratory. Variations may be observed by other researchers when prepared in their laboratories. Data are not "guaranteed" by a manufacturer or the author. Variations in properties may be observed and users of the products should verify properties. All material properties are guides for engineering design. Materials prepared in the laboratory should be considered as experimental and also guides for engineering design.

12.8 POLYMERS VERSUS FREQUENCY

Table 12.8 shows the parametric fits to permittivity for various polymers. The functional forms are shown at the beginning of the table. Functions are those causal functions that have been derived in Chaps. 2 and 3 for dielectric and magnetic media. Samples were measured in waveguide, focused beam, and Fabry–Perot systems and data were integrated for processing. Other data are shown when available. These include density, measured frequency span serving as basis for fits, tabulated information, and chemical and/or physical composition. In the tables exponentials are often shown as bE—which means $b*10^{-a}$. Thus, –2E-004–7.6E-003j is equal to –0.0002–j0.0076. Figure 12.11 indicates typical fits to the measurement: the graph at the top shows a very low loss polymer, Rexolite. Measured ε_{imag} shows unphysical rapid ripples in the imaginary permittivity. These are smoothed by a fit to the causal function. The lower graph of the figure is for a higher loss epoxy. In that case the need for smoothing is not strong.

TABLE 12.8 Polymers versus Frequency

Sample ID						
$\varepsilon(f) = B + 2Cf^{D} + G\{1 - J*(f-H)^2 - j2If\}^{-1}$						
B	C	D	G	H	I	J
Bismaleimide BMI F650, 1.27 g/cc (18–60 GHz)						
0.5471+ 3.87E-002j	0.6184+ 3.24E-002j	0.1048− 7.1E-003j	1.7022− 4.33E-002j	1.53E-002+ 2.2E-003j	−1.5E-003 +1.62E-002j	2E-004
Bismaleimide BMI F650, 1.27 g/cc (18–100 GHz)						
0.7982+ 2.17E-002j	0.7982+ 2.17E-002j	5.4E-003+ 3.8E-003j	0.7987+ 2.16E-002j	5E-004+ 5E-004j	−1.9E-003+ 2.6E-003j	5.91E-005+ 2.91E-005j
Celazole polybenzamidazole PBI (75–100 GHz), 1.3 g/cc (nominal ε_r = 4.2 at 1 MHz, Boedeker data sheet)						
0.6934+ 0.1502j	0.6812+ 0.3522j	−0.1589+ 1.96E-002j	0.6014− 4.5E-003j	4.6E-003+ 6.7E-003j	−1E-003− 7.8E-003j	−1E-004
Cyanate ester 561, (20–60 GHz), 1.22 g/cc						
0.707+ 1.3E-003j	0.707+ 1.3E-003j	4E-003− 9E-004j	0.7075+ 1.1E-003j	7E-004− 2E-004j	9E-004+ 3.8E-003j	1E-004
Cyanate ester-2 (30–100 GHz), 1.22 g/cc						
0.6469+ 5.46E-002j	0.6796+ 4.16E-002j	8.81E-002− 1.67E-002j	0.4457+ 8.11E-002j	1.06E-002− 5.5E-003j	−3.4E-003− 1.22E-002j	−6E-004
Epoxy, EAB (2–100 GHz), 1.24 g/cc						
1.0702+ 5.32E-002j	0.8609− 2.38E-002j	−0.5203+ 0.1529j	0.8918− 9.54E-002j	−2E-003+ 1.7E-003j	1E-004− 4.8E-003j	−4.85E-005+ 5.91E-008j
Polyester F141 (18–60 GHz), 1.38 g/cc						
0.7543+ 3.25E-002j	0.7538+ 3.23E-002j	1.1E-003+ 4.7E-003j	0.7653+ 3.51E-002j	7.1E-003+ 3.5E-003j	−6.3E-003+ 6.6E-003j	2E-004+ 2E-004j
Epoxy F161, 1.243 g/cc (18–100 GHz)						
0.8804+ 2.21E-002j	0.9002+ 2.34E-002j	−6.88E-002− 1.24E-002j	0.8758+ 2.13E-002j	−6E-004+ 7E-004j	−1.5E-003j	−1.12E-005+ 1.61E-007j

2555 Meltbond adhesive (20– 60 GHz)

0.7346+ 4.1E-003j	0.7345+ 4.1E-003j	1.2E-003+ 1E-004j	0.7355+ 4.1E-003j	4E-004	−2E-004+ 3.5E-003j	9.70E-005+ 5.53E-006j

Plexiglass acrylic, poly(methyl methacrylate) (PMMA), 1.2 g/cc (26–100 GHz) (nominal $\varepsilon_r \sim 2.5$)

0.6719+ 2E-003j	0.6724+ 2E-003j	1.85E-002+ 6E-004j	0.6692+ 2E-003j	5.2E-003+ 1E-004j	−1E-004+ 6E-003j	8.54E-005+ 2.25E-006j

Polyester, F148 (18–100 GHz), about 1.4g/cc

0.9813+ 8.28E-002j	0.931− 5.15E-002j	6.8E-003+ 2.73E-002j	7E-003+ 1.75E-002j	3.56E-002− 7E-003j	−2.4E-003− 2.89E-002j	−9E-004+ 1E-004j

1422, Cross-linked polystyrene 1.05 g/cc (4–100 GHz) (nominal $\varepsilon_r = 2.53$, 1–500 GHz, Rexolite Data Specs. complast.com)

0.5914+ 5.09E-002j	0.586+ 4.83E-002j	2.24E-002+ 6.8E-003j	0.7488− 0.152j	−2E-004+ 1.3E-003j	−1.4E-003+ 2.1E-003j	2.74E-005+ 1.78E-005j

1000 Polyetherimide (2–60 GHz), 1.28 g/cc (nominal $\varepsilon_r = 3.15$, $\tan\delta = .0013$, Boedeker Ultem Polyetherimide Specifications)

0.7855+ 9E-004j	0.7872+ 8E-004j	−2.93E-002− 7E-004j	0.7851+ 1E-003j	8E-004+ 1E-004j	1E-004− 2.7E-003j	−4.51E-005− 2.27E-006j

Polyimide bismaleimide F178 (18–100 GHz), 1.297 g/cc

0.504−4.24E-002j	0.5854−4.11E-002j	0.1004+5.5E-003j	1.6253+0.1025j	8.6E-003−1.7E-003j	2.1E-003+9.6E-003j	9.82E-005−1.99E-005j

Polyethelene (8–40 GHz), 0.93–0.94 g/cc (nominal $\varepsilon_r = 2.25–2.35$)

0.6329+7E-004j	1.0517−2.1E-003j	−0.2925−2E-004j	0.5377+3E-003j	−2.2E-003+7E-004j	−1E-004−1.11E-002j	−2.67E-004+2.19E-006j

Polytetrafluoroethelene (10–100 GHz), 2.13–2.19 g/cc (nominal $\varepsilon_r = 2.01$)

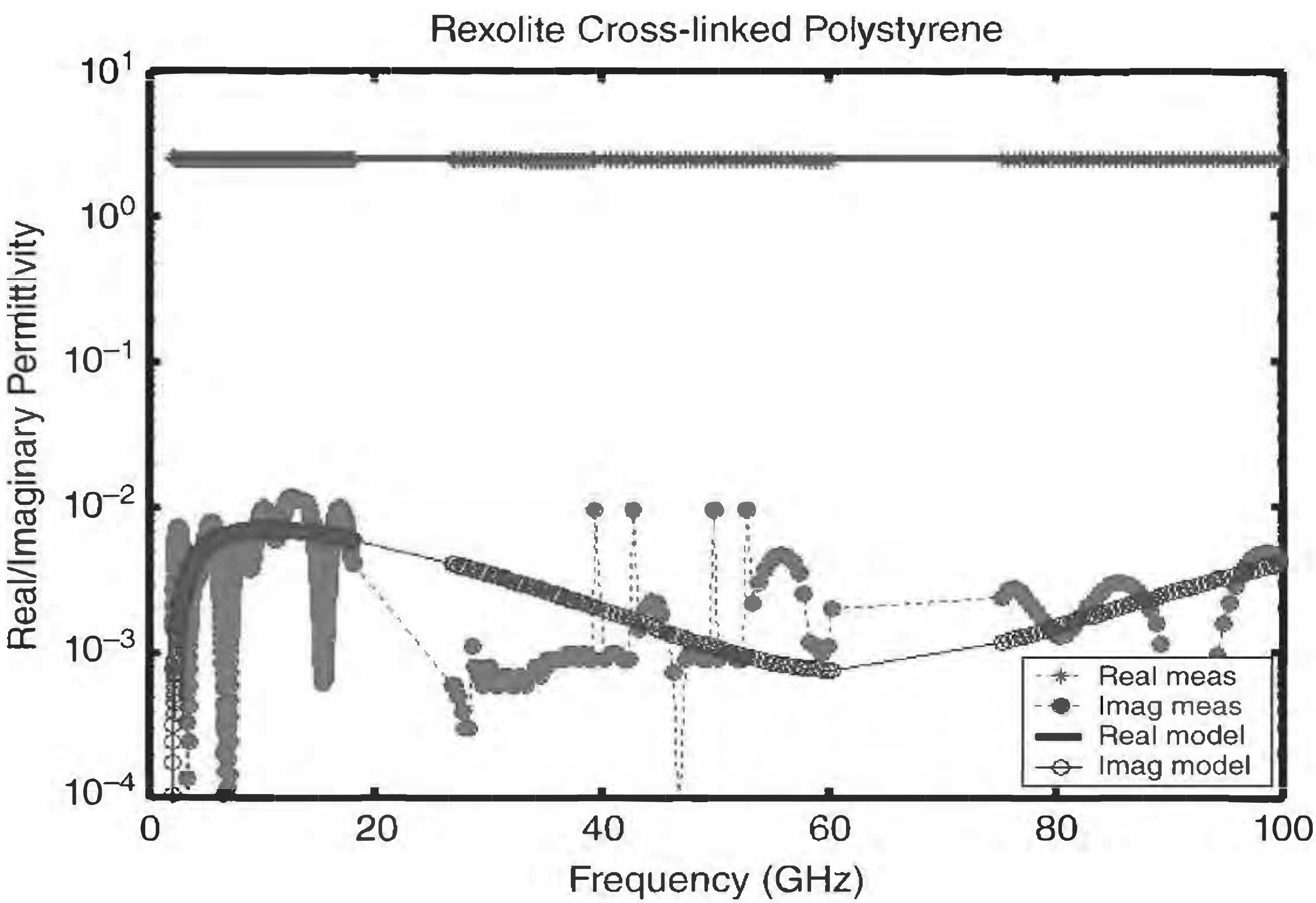
0.5635+2E-004j	0.6481+6E-004j	−0.1309+1E-004j	0.5095−7E-004j	9E-004+2E-004j	−3.4E-003j	−3.40E-005+1.74E-007j

Polyamide 7 (frequency averaged value between 10 and 16 GHz), 1.15–1.25 g/cc

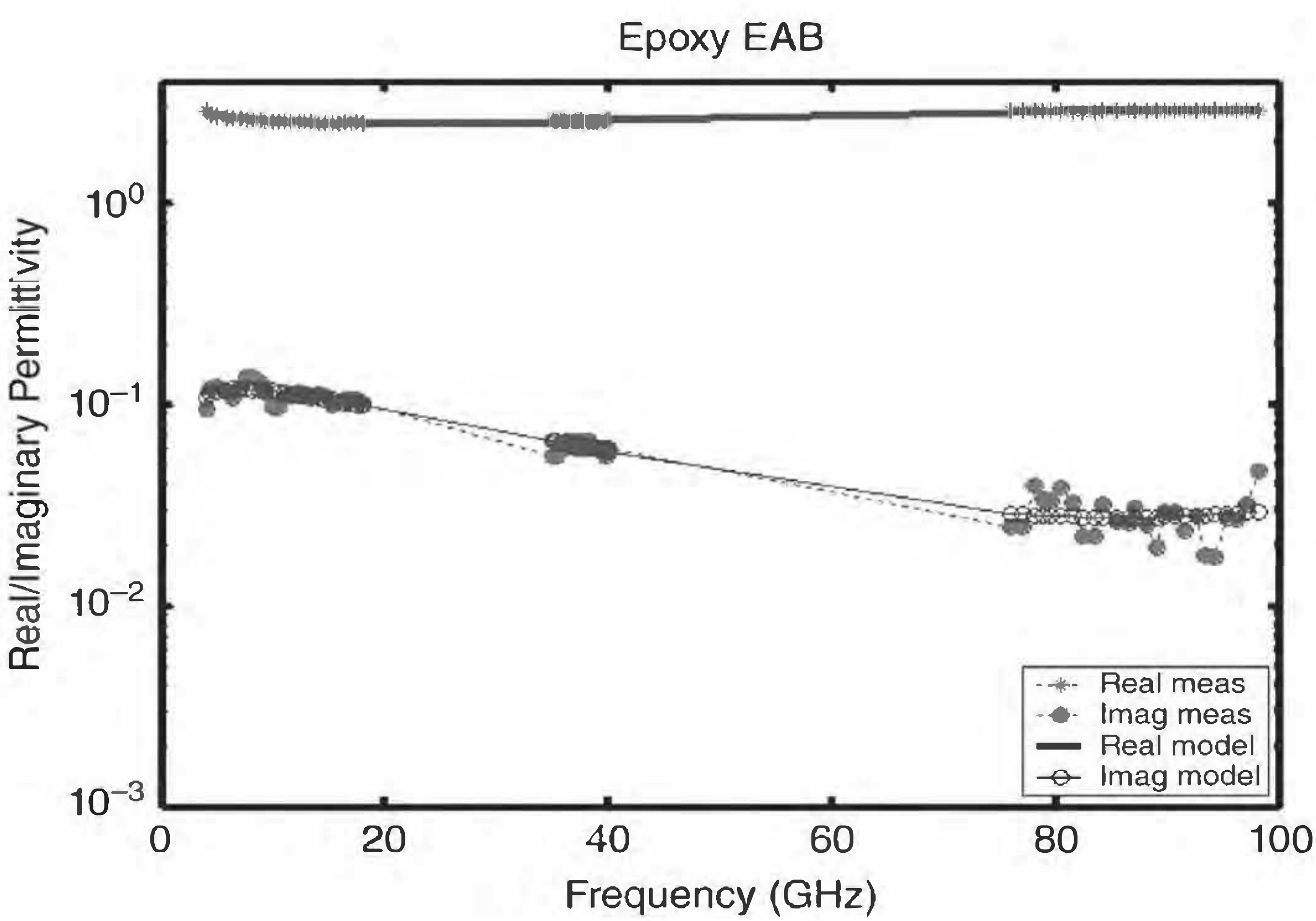
3.1+3E-003j

$$\varepsilon(f) = B + Cf^D + Ef^F + G\{1 - J*(f-H)^2 - j2If\}^{-1}$$

B	C	D	E	F	G	H	I	J
7058 Epoxy with about 40%/volume 52-µm silica hollow spheres, 3–5 µm walls (2–18 GHz)								
0.7275+7.58E-002j	2.4321+0.1323j	−3.8007−0.9919j	1.6261+[illegible].2312j	−3.3603+1.9301j	0.9885−5.86E-002j	−9E-003+1.07E-002j	−2E-004−2.3E-003j	−1.62E-004+1.21E-005j



Rexolite Cross-linked Polystyrene
Real/Imaginary Permittivity
Frequency (GHz)
Real meas
Imag meas
Real model
Imag model



Epoxy EAB
Real/Imaginary Permittivity
Frequency (GHz)
Real meas
Imag meas
Real model
Imag model

FIGURE 12.11 The upper figure illustrates how functional fits can minimize unphysical data characteristics. This often occurs for low loss materials. The lower figure illustrates a higher loss measurement and functional fit.

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12.9 R-CARDS VERSUS FREQUENCY

Table 12.9 shows the parametric fits of equivalent surface impedance for various thin film conductors, R-cards. Samples were cut from large production rolls and were measured in focused beam systems. The fitted functional form is shown at the beginning of the table. Functions are those causal functions that have been derived in Chaps. 2 and 3 for thin conducting films. In the tables exponentials are often shown as bE—which means $b*10^a$. Thus, –2E-004–7.6E-003j is equal to –0.0002 –j0.0076. Other data are shown when available. These include density, measured frequency span serving as basis for fits, tabulated information, and chemical and/or physical composition and DC conductivity as measured by a four-point probe. Figure 12.12 shows examples of two impedance: fits and measurements.

TABLE 12.9 R-Cards: Conductor-Coated Films

Sample ID							
$Z(f) = B + Cf^{D}\{1 + Ef^{f} + jGf^{H}\}^{-1}$							
	B	C	D	E	F	G	H
D-Black polyimide film (carbon), nominal DC 3400 Ω/sq (2–100 GHz), .003", measured DC 3110 Ω/sq							
$Z(f)$	3110	−10−2.81j	0.2944+0.146j	−0.495−4E-003j	1E-004−4E-003j	−4E-003+0.495j	1E-004−4E-003j
D-Black polyimide film (carbon), nominal DC 1300 Ω/sq (2–100 GHz), .003", measured DC 1211 Ω/sq							
$Z(f)$	1211	−9.421−4.064j	0.3953+ 0.144j	−0.4846−2.1E-002j	−1.9E-003−2.06E-002j	−2.1E-002+0.4846j	−1.9E-003 −2.06E-002j
D-Black polyimide film (carbon), nominal DC 780 Ω/sq (2–100 GHz), .003", measured DC 746 Ω/sq							
$Z(f)$	746	−6.444−7.999j	0.5423−6.14E-002j	−0.4834−0.1365j	−5.58E-002−6.94E-002j	−0.1365+0.4834j	−5.58E-002−6.94E-002j
D-Black polyimide film (carbon), nominal DC 400 Ω/sq (2–100 GHz), .003"; measured DC 400 Ω/sq							
$Z(f)$	400	−3.3951−9.142j	0.55−0.8898j	−0.6526−0.3955j	−6E-003−0.1607j	−0.3955+0.6526j	−6E-003−0.1607j
Cp-Ni, nominal DC 288 Ω/sq (2–100 GHz), .003", measured DC 266 Ω/sq							
$Z(f)$	266	2.7632−9.5162j	0.371−0.1786j	−0.1516−0.4655j	−6.98E-002−0.2403j	−0.4656+0.1516j	−6.98E-002−0.2403j
Cp-Ni, nominal DC 178 Ω/sq (2–100 GHz), .003", measured DC 172 Ω/sq							
$Z(f)$	172	5.8926+0.8111j	0.366−1.332j	−0.9−3.98j	−0.4085−0.358j	−3.981+0.9j	−0.4103−0.389j
C-, Ni, nominal DC 71 Ω/sq (2–100 GHz), .003", measured DC 69 Ω/sq							
$Z(f)$	69	5.248−3.077j	7E-002−7E-002j	0.1154−0.671j	6.3E-002	−0.641−1.29j	−0.21+0.18j
Cp-, Ni, nominal DC 45 Ω/sq (2–100 GHz), .003", measured DC 43 Ω/sq							
$Z(f)$	43	19.94−5.1j	−0.79−0.67j	0.5054−1.8E-002j	0.294−0.584j	1.4E-002−0.541j	0.145−1.2j

D-Black polyimide film (carbon), nominal DC 890 Ω/sq (2–18 GHz), .003", measured DC 980 Ω/sq							
$Z(f)$	980	−3.368−9.6212j	0.6835−0.214j	−0.4851−6.8E-002j	−5.12E-002−2.77E-002j	−6.8E-002+0.4851j	−5.12E-002−2.77E-002j
Ni, nominal DC 50 Ω/sq (2–18 GHz), .003", measured DC 40 Ω/sq							
$Z(f)$	40	2.22+0.25j	−0.346−0.623j	0.143+0.157j	9.9E-002−1.26j	0.156−0.142j	9.8E-002−1.25j
Ni-Cr on polyimide film, nominal DC 20 Ω/sq (2–18 GHz), .003", measured DC 19 Ω/sq							
$Z(f)$	19	1.268+0.254j	5.9E-002−5.7E-002j	0.547−0.128j	−1.01−1.69j	−0.396−0.399j	−0.702−3.89j
Cp-Ag on polymer, nominal DC 8 Ω/sq (2–18 GHz), .003", measured DC 8 Ω/sq							
$Z(f)$	8	−8.97−0.635j	9.7E-002−3.25E-002j	−0.288−0.172j	−0.784−1.273j	0.275−0.143j	−0.755+1.454j
ITO on polymer, nominal DC 300 Ω/sq (2–18 GHz), .003", measured DC 313 Ω/sq							
$Z(f)$	313	−8.55−5.61j	0.275+0.103j	−0.431−2.4E-002j	−5E-002−0.146j	−2.4E-002+0.431j	−5E-002−0.146j
Cp-Ag on polymer, nominal DC 4 Ω/sq (2–18 GHz), .003", measured DC 3 Ω/sq							
$Z(f)$	3	−1.417+2.39j	−0.381−0.837j	0.1903+0.1j	−0.227+3.48j	0.1−0.19j	−0.226+3.47j
ITO on polymer, nominal DC 150 Ω/sq (2–18 GHz), .003"; measured DC 145 Ω/sq							
$Z(f)$	145	8.37−0.44j	−4.8E-002−0.674j	−0.522−0.152j	0.274+0.103j	0.202+7.8E-002j	−4E-002−2.03j
Cp-Ag on polymer, nominal DC 2 Ω/sq (2–18 GHz), .003", measured DC 1.5 Ω/sq							
$Z(f)$	1.5	−3.67+3.973j	−0.883−0.893j	−7.9E-002−3.13E-002j	0.422+5.808j	0.112−2.7E-002j	0.639+3.025j

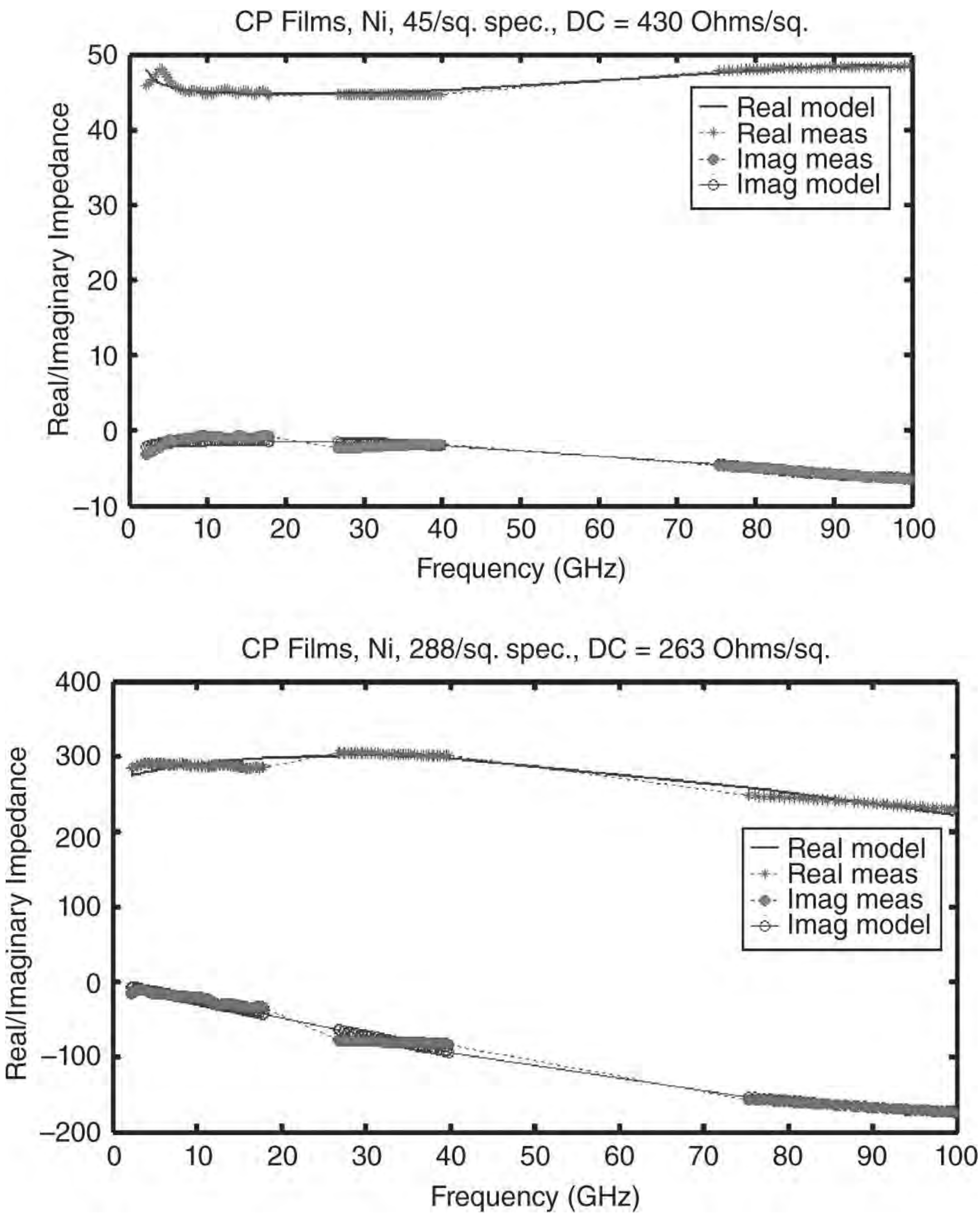


FIGURE 12.12 The upper and lower figures show typical functional fit to measured data.

Disclaimer: Data are results obtained by the author on samples prepared in the laboratory. Variations may be observed by other researchers when prepared in their laboratories. Data are not "guaranteed" by a manufacturer or the author. Variations in properties may be observed and users of the products should verify properties. All material properties are guides for engineering design. Materials prepared in the laboratory should be considered as experimental and also guides for engineering design.

12.10 MICROMETER AND NANOMETER MAGNETITE MAGNETIC COMPOSITES VERSUS FREQUENCY

Table 12.10 shows the parametric fits of susceptibility for various magnetic composites. The functional forms are shown at the beginning of the table. Functions are those causal functions that have been derived in Chaps. 2 and 3 for dielectric and magnetic media. *Note to use the absolute parameter values (i.e., |B|, |C|, |D|) when calculating permeability. Caution should be observed when the derived parameters are over a narrow bandwidth and may not fully encompass the fundamental resonance. In those cases, extrapolation of the parameters outside the original measured band can lead to an error*. Samples were manufactured in the laboratory and cut to fit coaxial or stripline measurement systems. Other data are shown when available. These include density, measured frequency span serving as basis for fits, tabulated information, and chemical and/or physical composition. Figure 12.13 shows typical parameter fits for *magnetic susceptibility* for experimental magnetite–polymer composites of various diameters and volume fraction.

TABLE 12.10 Micrometer and Nanometer Iron Oxide, Fe_3O_4, Particulates and Composites

Sample ID and Information					
$\mu(f)-1=\chi_m(f)=B(1-j*f/D)\{1-(f/C)^2-j*(f/D)\}^{-1}$					
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$ are, respectively, EMT-calculated DC magnetic particle susceptibility; calculated composite resonant frequency, $\lvert C\rvert$; EMT-calculated magnetic particle resonant frequency; calculated composite relaxation frequency, $\lvert D\rvert$; EMT-calculated magnetic particle relaxation frequency. Note to use the absolute parameter values (i.e., $\lvert B\rvert$, $\lvert C\rvert$, $\lvert D\rvert$) when calculating permeability.					
	B	C	D		
5-µm, 5% volume fraction, 0.1–10 GHz					
$\chi_m(f)$	0.14+ 2E-002j	5.21+ 1.94j	−2.03− 0.81j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.141	5.56	2.19		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	15.18	5.56	0.908	2.19	0.378
5-µm, 10% volume fraction, 0.1–10 GHz					
$\chi_m(f)$	0.302+ 2.2E-002j	3.48+ 1.73j	−1.49− 0.77j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.303	3.89	1.68		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	13.46	3.88	0.75	1.65	0.33
5-µm, 15% volume fraction, 0.1–10 GHz					
$\chi_m(f)$	0.5+ 1.6E-002j	2.88+ 1.54j	−1.27− 0.69j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.500	3.27	1.45		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	12.9	3.26	0.671	1.45	0.31
5-µm, 20% volume fraction, 0.1–10 GHz					
$\chi_m(f)$	0.675-7E-003j	2.41+ 1.47j	−1.08− 0.65j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.675	2.82	1.26		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	10.3	2.82	0.653	1.26	0.338

150-nm 10% volume fraction, 0.1–10 GHz,					
$\chi_m(f)$	0.411+ 0.11j	1.29– 3.26j	1.86– 2j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.426	3.51	2.73		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	112	3.51	0.1485	2.73	0.008
150-nm 20% volume fraction, 0.1–10 GHz					
$\chi_m(f)$	0.953-.1j	1.81+0.33j	−0.81−7E-002j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.96	1.84	0.82		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	25.9	1.84	0.29	0.82	0.103
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$					
150-nm 30% volume fraction, 0.1–10 GHz,					
$\chi_m(f)$	1.29– 0.21j	1.21+ 0.83j	−0.51– 0.33j	-	
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	1.31	1.46	0.61		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	11.7	1.46	0.316	0.61	0.164

150 nm 60% volume fraction, 0.1–10 GHz,

$\chi_m(f)$	3.1−0.45j	1.284+0.902j	−0.544−0.412j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	3.13	1.57	0.68		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	9.02	1.57	0.46	0.68	0.31

25-nm 10% volume fraction, 0.1–10 GHz

$\chi_m(f)$	0.179+4E-003j	2.94+1.89j	−1.571−1.01j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.18	3.49	1.87		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	3.63	3.49	1.29	1.87	0.895

25-nm 7.5% volume fraction, 0.1–10 GHz

$\chi_m(f)$	0.155+8.5E-003j	2.91+1.2j	−1.82−0.54j	−0.83−8E-002j	
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.155	3.15	1.89		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	5.14	3.15	1.18	1.89	0.73

17-nm 10% volume fraction, 0.1–10 GHz,					
$\chi_m(f)$	0.257+ 4.5E-002j	1.335– 1.67j	2.29+ 2.3j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.26	2.14	3.24		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	8.42	2.14	1.73	3.24	0.92
12-nm 2.5% volume fraction, 0.1–10 GHz					
$\chi_m(f)$	4.7E-002+ 1.5E-002j	1.71– 0.92j	−0.53+ 1.88j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.049	1.95	1.95		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	5.34	1.945	1.18	1.95	0.714
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$					
12-nm 1.25% volume fraction, 0.1–10 GHz					
$\chi_m(f)$	2.17E-002+ 7E-003j	1.705– 0.3j	−0.45+ 0.21j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.023	1.73	0.496		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	4.49	1.73	0.316	0.496	0.2
7-nm 1.25% volume fraction, 0.1–10 GHz					
$\chi_m(f)$	1.45E-002+ 9E-003j	4– 1.41j	−1.39+ 0.63j		
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.017	4.25	1.53		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	2.4	4.25	1.14	1.53	0.854

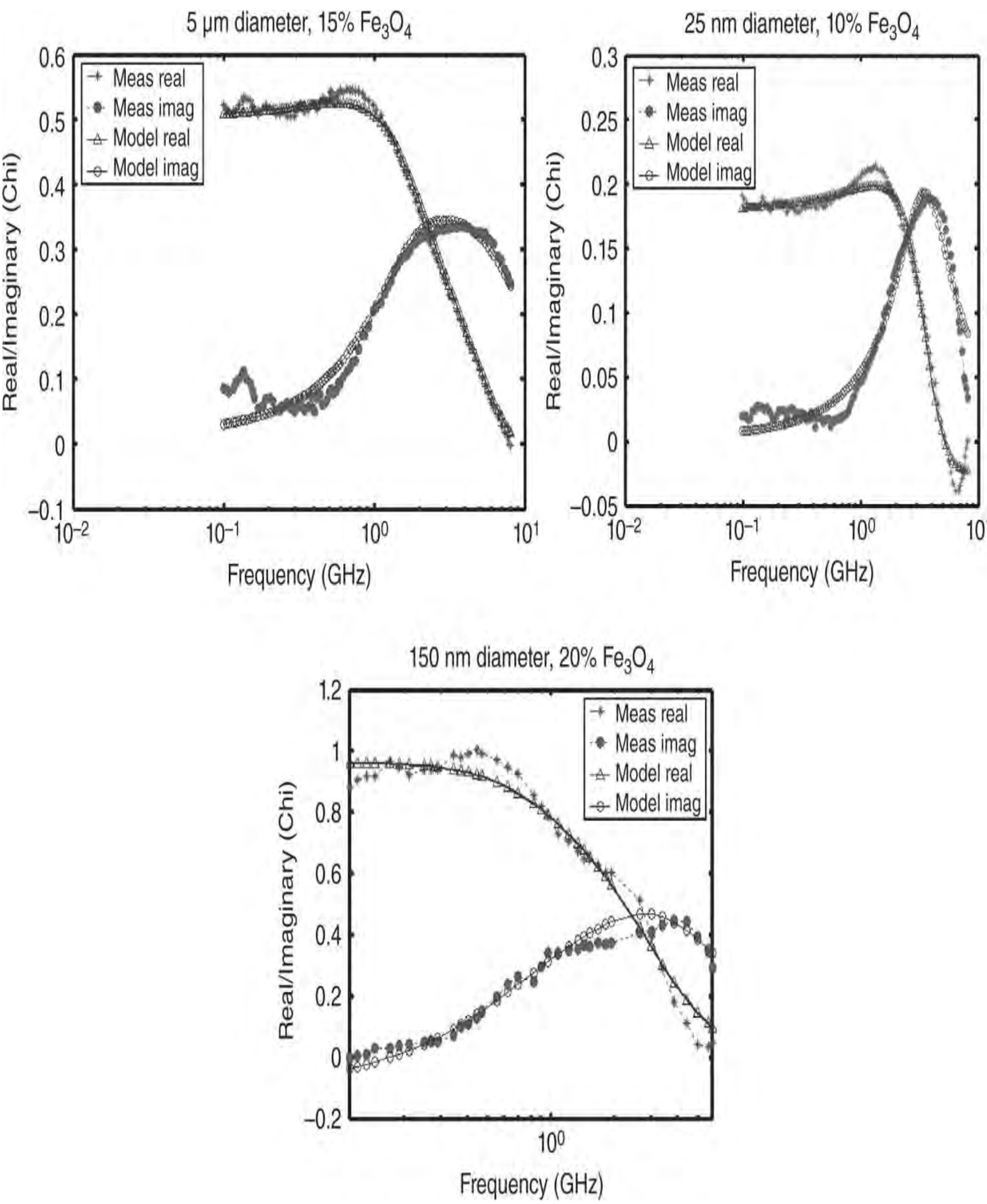


FIGURE 12.13 Typical data and functional fits to magnetite composites.

Disclaimer: Data are results obtained by the author on samples prepared in the

laboratory. Variations may be observed by other researchers when prepared in their laboratories. Data are not "guaranteed" by a manufacturer or the author. Variations in properties may be observed and users of the products should verify properties. All material properties are guides for engineering design. Materials prepared in the laboratory should be considered as experimental and also guides for engineering design.

12.11 IRON–POLYMER COMPOSITES VERSUS FREQUENCY

Table 12.11 shows the parametric fits of susceptibility and permittivity for various magnetic composites. Details of commercial sample's composition (e.g., A RAM) are not readily available. The author suggests that if a reader wishes to obtain similar samples, he or she should contact firms making electromagnetic interference material and ask for samples with the calculated volume fraction of Fe or the measured density. All data assume "spherical" particulate for inversion to determine particulate properties. The exception, are those whose designation begins with WD., WX.. or Flex. These three are believed to contain flat ferromagnetic platelets and may have anisotropic properties. Samples were measured in waveguide, coaxial line, and free space focused beam systems. The fitted functional forms are shown at the beginning of the table. *Note to use the absolute parameter values (i.e.,* $|B|$, $|C|$, $|D|$*) when calculating permeability*. Functions are those causal functions that have been derived in Chaps. 2 and 3 for dielectric and magnetic media. *Caution should be observed when the derived parameters are over a narrow bandwidth and may not fully encompass the fundamental resonance. In those cases, extrapolation of the parameters outside the original measured band can lead to an error*. In some composites multiple measurements and models are shown for the same compositions or different samples. Data are indicated of variability in composites. Other data such as density, measured frequency span serving as basis for fits, indication as a commercial or laboratory sample, source (if available), and chemical and/or physical composition are included. In the tables exponentials are often shown as bE—which means $b*10^{-a}$. Thus, –2E-004–7.6E-003j is equal to –0.0002–j0.0076. Figure 12.14 shows typical parameter fits for *magnetic susceptibility* (left graphs) and permittivity (right graphs) for one commercial (upper) and one experimental (13% Fe by volume, lower) Fe-polymer composite. Note high-frequency chatter in imaginary susceptibility is smoothed by the complex fit.

TABLE 12.11 Micrometer and Nanometer Iron Particulates and Composites

Sample ID and Information							
$\mu(f)-1=\chi_m(f)=B(1-j*f/D)\{1-(f/C)^2-j*(f/D)\}^{-1}$							
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$ are, respectively, EMT-calculated DC magnetic particle susceptibility; calculated composite resonant frequency, $\|C\|$; EMT-calculated magnetic particle resonant frequency; calculated composite relaxation frequency, $\|D\|$; EMT-calculated magnetic particle relaxation frequency. Note to use the absolute parameter values (i.e., $\|B\|$, $\|C\|$, $\|D\|$) when calculating permeability.							
$\varepsilon_1(f)=B+Cf^D+E\{1-(f/F)^2-2j*(f/G)\}^{-1}$ $\varepsilon_2(f)=B+real(C)f^D+imag(C)f^E+F\{1-(f/G)^2-2j*(f/H)\}^{-1}$							
	B	C	D	E	F	G	H
A RAM (calculated average 24%/volume Fe 2–5 μm in silicone) 0.05–18 GHz (commercial)							
$\chi_m(f)$	2.33+ 0.89j	0.818– 4.63j	1.89– 0.53j				
$\|B\|$, $\|C\|$ and $\|D\|$	2.49	4.70	1.96				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	12.01	4.70	0.112	1.96	0.0064		
$\varepsilon_1(f)$	2.97+ 1E-002j	2.97+ 1E-002j	−2E-003+ 4E-003j	2.98+ 1E-002j	38.7– 5.1j	−146.9– 272.9j	
$\varepsilon_2(f)$	3.31– 1E-002j	3.08– 2E-002j	0.19– 2E-002j	−1.02+ 3E-002j	3.74– 0.11j	8.02– 2.13j	0.62– 4.8j

B RAM (calculated average 34%/volume Fe 2–5 μm in silicone) 0.05–18 GHz (commercial)

$\chi_m(f)$	1.82+.67j	0.348-.34j	0.905+.202j				
$\|B\|$, $\|C\|$ and $\|D\|$	1.94	2.365	0.9273	1.2733			
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	16.13	2.365	0.435	0.927	0.204		
$\varepsilon_1(f)$	4.62+ 5E-002j	4.91+ 4E-002j	−0.15− 2E-003j	4.63+ 4E-002j	56.9− 6.3j	207+ 1778.3j	
$\varepsilon_2(f)$	4.59+ 5E-002j	4.95+ 3E-002j	−0.19+ 2E-002j	−1.45− 0.9j	4.6+ 5E-002j	25.2− 52.7j	−63.7+ 160.6j

ECBSR (calculated 30%/volume assuming Fe in silicone), 0.001–18 GHz (commercial)

$\chi_m(f)$	3.79+ 3.5E-002j	3.3+ 1.38j	−1.23− 0.45j				
$\|B\|$, $\|C\|$ and $\|D\|$	3.79	3.58	1.31				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	104	3.58	0.26	1.31	0.052		
$\varepsilon_2(f)$	3.68+ 0.14j	3.28+ 9E-002j	−5E-003− 1E-002j	−9E-002− 0.72j	3.73+ 0.14j	3.12− 14.7j	−22.4+ 68j

ECMFS (calculated 46%/volume assuming Fe, 4.22 g/cc), 0.05–18 GHz (commercial)							
$\chi_m(f)$	6.23+ 2.17j	0.139– 1.33j	0.252+ 6.8E-002j				
$\|B\|$, $\|C\|$ and $\|D\|$	6.60	1.34	0.26				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	38.73	1.34	0.092	0.26	0.033		
$\varepsilon_1(f)$	5.58+ 9E-002j	6.04– 0.14j	–9.7E-002– 6E-002j	4.49+ 0.31j	16.2+ 33.5j	53.25+ 50.9j	
$\varepsilon_2(f)$	5.69+ 0.11j	5.62+ 2E-002j	–0.13– 5E-002j	–1.6– 1.1j	4.83+ 0.13j	10.43+ 35.9j	42.2+ 64.2j
Γ RAM (calculated 39%/volume assuming Fe, 3.7 g/cc), 0.05–18 GHz (commercial)							
$\chi_m(f)$	2.39+ 1.15j	0.805– 4.86j	1.572– 0.843j				
$\|B\|$, $\|C\|$ and $\|D\|$	2.65	4.93	1.78				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	17.96	4.93	0.83	1.78	0.38		
$\varepsilon_2(f)$	6.99– 0.17j	12.15– 44j	–3E-002– 2E-003j	1.16+ 2E-002j	3.21+ 0.26j	0.28– 20.5j	–0.33+ 22.3j

EcSFU-7, 3.65 g/cc, 37–38%/volume assuming Fe, 0.001–18 GHz (commercial)

$\chi_m(f)$	2.25+6E-002j	5.12+2.8j	−1.94-0.86j	−1.37-0.12j			
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	2.25	5.84	2.12	1.3752			
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	15.59	5.84	1.03	2.12	0.499		
$\varepsilon_2(f)$	2.94+0.24j	2.94+0.24j	−2.4E-002−1E-002j	−2.4E-002−1.1E-002j	3.03+0.36j	0.56+19.6j	95−205j

FeSi 20%/volume in epoxy, 0.05-8 GHz (laboratory made)

$\chi_m(f)$	1.26−0.18j	0.815−8.5E-002j	−.164+3.2E-002j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	1.27	0.82	0.17				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	96.8	0.82	0.032	0.17	0.0062		
$\varepsilon_1(f)$	1.45−5E-002j	2.41+0.4j	0.17−0.13j	1.89−0.63j	3.52+0.1j	1.98−2.87j	
$\varepsilon_2(f)$	2.44+4E-002j	1.94+2E-003j	0.23+2E-003j	3.6−0.68j	1.65+7E-002j	3.84−0.17j	0.34−2.63j

FeSi 30%/volume in epoxy, 0.05–20 GHz (laboratory made)

$\chi_m(f)$	1.395+0.12j	2.22–0.41j	–0.6+0.45j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	1.40	2.26	0.75				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	13.2	2.26	0.369	0.75	0.183		
$\varepsilon_1(f)$	3.31+0.36j	3+0.44j	9E-002–2E-002j	2.39–0.64j	3.41+0.9j	–0.38–2.1j	
$\varepsilon_2(f)$	2.46+0.17j	2.46+0.17j	–7E-002+2E-002j	–7E-002+2E-002j	2.46+0.17j	36.4–11.4j	–118–164j

FeSi 30%/volume in epoxy, 0.05–2 GHz (laboratory made)

$\chi_m(f)$	1.97–0.26j	0.712–4E-002j	–.149+3.6E-002j	–2.28–0.4j			
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	1.99	0.71	0.15	2.3148			
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	25.45	0.71	0.058	0.15			
$\varepsilon_1(f)$	2.35–7E-002j	3.8+1.88j	9E-002–0.25j	2.32–3.05j	0.81+1j	2E-002–1.9j	
$\varepsilon_2(f)$	2.4+0.1j	3.03+1.6E-002j	0.31+0.1j	0.3–0.2j	2.4+0.37j	0.14+1.1j	18.4–0.82j

WDHO010, 0.001–18 GHz, about 15%/volume (commercial)

$\chi_m(f)$	18.42−0.26j	1.11+0.58j	−0.35−0.171j			
$\|B\|$, $\|C\|$ and $\|D\|$	18.42	1.25	0.39			
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$		1.25		0.39		
$\varepsilon_1(f)$	466.8+ 30j	−0.1+ 1E-005j	2E-003+ 1E-006j	326− 207j	0.48+ 0.41j	7E-02− 3E-002j

WDHVOp010, 15%, 0.001–18 GHz (commercial)

$\chi_m(f)$	51.12+0.51j	0.15+5E −004j	−4E-002 +4E-003j			
$\|B\|$, $\|C\|$ and $\|D\|$	51.12	0.15	0.041			
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$		0.15		0.041		
$\varepsilon_1(f)$	362+ 11.3j	3E-002+ 5E-002j	3E-003− 7E-004j	222− 2036j	0.3− 0.22j	−2E-002− 5E-003j

WDHVOp020, 15%, 0.001–18 GHz (commercial)

$\chi_m(f)$	44.7+1.8j	0.14–3E-002j	–4E-002+2E-002j	–1.62–0.4j		
$\|B\|$, $\|C\|$ and $\|D\|$	44.74	0.14	0.045	1.6687		
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$		0.14		0.045		
$\varepsilon_1(f)$	282+13j	–10–7j	0.8–0.1j	197–2146j	1.18–0.93j	–0.24+4E-002j

WXAO10, 15%, 0.001–18 GHz (commercial)

$\chi_m(f)$	27.62–0.9j	0.18+2.6E-002j	–4.8E-002–1.2E-002j			
$\|B\|$, $\|C\|$ and $\|D\|$	27.63	0.18	0.05			
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$		0.18		0.05		
$\varepsilon_1(f)$	318+13j	–7.6–1.8j	0.3+2.1j	762–2770j	2.6E-002–8E-002j	–1E-003+2E-003j

WXAO20, 15%, 0.001–18 GHz (commercial)

$\chi_m(f)$	22.34–0.52j	0.188+3.4E-002j	–5E-002–1.4E-002j			
$\|B\|$, $\|C\|$ and $\|D\|$	22.35	0.19	0.052			
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$		0.19		0.052		
$\varepsilon_1(f)$	227–3j	1.4–1.4j	0.9+1.2j	228–2414j	4E-002–0.24j	1E-003+1.4E-002j

Flex -S, 3.1 g/cc, 0.01–1.0 GHz (commercial)							
$\chi_m(f)$	64.1-2.3j	8.3E-002+ 9E-003j	−2E-002− 6E-003j	−1.8+ 0.32j			
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	64.14	0.084	0.021	1.8282			
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$		0.084		0.021			
$\varepsilon_1(f)$ (not available)							
Fe S2-1, 20.21%/volume, average 5-μm size, 0. 2–18 GHz (laboratory made)							
$\chi_m(f)$	0.53+0.54j	7.1–13.4j	7.68–18.6j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.76	15.16	20.12				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	12.92	15.16	9.6	20.12	4.54		
$\varepsilon_1(f)$	6.79– 3.98j	7.45– 3E-002j	−0.62– 0.44j	2.11– 0.93j	−7.7+ 52.7j	1.13+ 0.58j	0.28– 0.14j
$\varepsilon_2(f)$	13.38+ 1.88j	6.34+ 1.5j	−0.42– 1.12j	−9E-003+ 1.54j	10.28– 4.84j	0.5– 0.5j	−0.23+ 5E-002j
Fe S6-1, 43%/volume, average 5-μm size, 0.2–18 GHz (laboratory made)							
$\chi_m(f)$	1.02+ 3.47j	0.36+ 7.3j	2.76– 0.8j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	3.62	7.31	2.87				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	21.4	7.31	1.23	2.87	2.87		
$\varepsilon_2(f)$	13.13– 0.22j	8.54+ 1.9j	0.54– 0.23j	0.94+ 0.57j	0.69– 6.2j	0.32+ 5.54j	1.27+ 3.32j
Fe 2-1, 20.2%/volume, average 10-μm size, 0.1–2 GHz (laboratory made)							
$\chi_m(f)$	1.617– 0.1j	1.83+ 0.99j	−1.05– 0.21j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	1.62	2.08	1.07				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	−405	2.08		1.07			
$\varepsilon_2(f)$	3.1+ 5.31j	2.92+ 4.79j	−0.53+ 1E-002j	0.38– 0.62j	−5.6– 5.58j	0.46+ 0.83j	0.83– 9E-002j

Fe 4-1, 33.6%/volume, average 10-μm size, 0.1–2 GHz (laboratory made)

$\chi_m(f)$	2.28+0.13j	0.786+2.82j	−0.61−1.36j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	2.28	2.93	1.49				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	21.8	2.93	1.21	1.49	0.26		
$\varepsilon_2(f)$	8.78+1.92j	8.39+2.47j	−6.8E-002−0.22j	0.55−1.8j	−4.14−5.35j	−0.45−8E-002j	−0.36−1.8E-002j

Fe 6-1, 43%/volume, average10-μm size, 0.1–2 GHz (laboratory made)

$\chi_m(f)$	3.81−0.18j	1.65+0.98j	−0.84−0.29j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	3.81	1.92	0.89				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	22.99	1.92	0.83	0.89	0.17		
$\varepsilon_2(f)$	6.52−0.61j	6.53−0.61j	1.8E-002−9.3E-002j	−3.8E-002+0.46j	6.6−0.66j	0.25−0.36j	0.26−9E-002j

Fe 6-1, 43%/volume, average 4-μm size, 0.1–2 GHz (laboratory made)

$\chi_m(f)$	3.45−7E-002j	2.56+1.77j	−1.35−0.67j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	3.45	3.11	1.51				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	20.1	3.11	1.42	1.51	0.31		
$\varepsilon_2(f)$	5.93+0.47j	6.06+0.48j	0.58+2E-002j	−0.89−1E-002j	6.14+0.35j	−3.5E-003+77j	3E-002−0.3j

Fe T 2:1, 20.2%/volume, 2.39 g/cc, average 500-nm size, 0.3–18 GHz (laboratory made)

$\chi_m(f)$	1.27+0.72j	0.414−3.14j	0.77+0.34j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	1.46	3.17	0.84				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	348	3.17	0.07	0.84	0.01		
$\varepsilon_2(f)$	2.18+0.36j	2.15+0.44j	−0.52−2E-002j	−0.52+2E-002j	2.19+0.4j	8.35−18.6j	−21.9+27.1j

Fe T 4:1, 33.6%/volume, 3.32 g/cc, average 500-nm size, 0.3–18 GHz (laboratory made)

$\chi_m(f)$	2.74–3E-002j	3.86+0.71j	−1.24–0.25j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	2.74	3.92	1.27				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	29.73	3.92	0.465	1.27	0.17		
$\varepsilon_2(f)$	2.83+0.3j	4.22+0.32j	−0.46+0.32j	−0.46–1E-002j	2.65+0.4j	2.34–22.1j	−3.12+31.1j

Fe T6-1 43%/volume, average 500-nm size, 0.4–18 GHz (laboratory made)

$\chi_m(f)$	4.25+4.22j	0.865+3.11j	1.03–0.17j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	5.99	3.23	1.044				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	41.5	3.23	0.35	1.044	0.12		
$\varepsilon_2(f)$	5.82+0.37j	3.05+2.29j	6.4E-002–8E-002j	−2.2–0.34j	4.61+0.42j	12.9–30.8j	−78+174j

Fe Q 4:1, 33.6%, average 10-μm size, 0.5–18 GHz (laboratory made)

$\chi_m(f)$	3.18−0.45j	3.08+1.41j	−1.02−0.77j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	3.21	3.39	1.28				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	39.24	3.39	0.41	1.28	0.132		
$\varepsilon_2(f)$	4.77−0.26j	7.4+0.33j	−0.24+1E-002j	7.4+0.33j	−0.24+1E-002j	1.01+0.26j	−78+174j

Fe average 500-nm size, 12.8%/volume in epoxy, 1.96 g/cc, 0.001–18 GHz (laboratory made)

$\chi_m(f)$	0.849+7E-004j	4.331−0.11j	−1.69+0.55j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.85	4.33	1.78				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	33	4.33	1.46	1.78	0.33		
$\varepsilon_2(f)$	1.63+0.15j	1.72+0.17j	4E-002-0.33j	4E-002-0.33j	1.74+0.16j	4+4.9j	8.1+2.7j
	5.06						

Fe average 500-nm size, 13.2%/volume in epoxy, 1.99 g/cc, 0.05–10 GHz (laboratory made)							
$\chi_m(f)$	0.815–0.17j	3.5+1.6j	−1.32–0.5j				
$\|B\|$, $\|C\|$ and $\|D\|$	0.83	3.85	1.41				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$		3.85		1.41			
$\varepsilon_2(f)$	1.59+1E-002j	1.6–2E-003j	−1.9E-002–7E-002j	−1.8E-002–7E-002j	1.59+1E-003j	15.6+26.9j	37.5+38.8j
	4.78						
Fe average 500-nm size, 19.3%/volume in epoxy, 2.41 g/cc, 0.05–10 GHz (laboratory made)							
$\chi_m(f)$	1.44+0.23j	4.59+2.35j	−1.53–0.76j				
$\|B\|$, $\|C\|$ and $\|D\|$	1.46	5.16	1.71				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	122.2	5.16	0.896	1.71	0.052		
$\varepsilon_2(f)$	2.56+3E-002j	1.99+0.15j	2E-002–0.14j	−0.63+0.64j	1.87–1E-002j	9.13+12.7j	29.6+7j

Fe average 500-nm size, 23.3%/volume in epoxy, 2.66 g/cc, 0.05–10 GHz (laboratory made)							
$\chi_m(f)$	1.63–6E-002j	3.95–2.8j	−1.51+1.65j				
$\lvert B\rvert, \lvert C\rvert$ and $\lvert D\rvert$	1.63	4.84	2.24				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	62.5	4.84	0.55	2.24	0.132		
$\varepsilon_2(f)$	2.55+6E-003j	2.55+6E-003j	−3E-003–1E-003j	−3E-003–1E-003j	2.55+6E-003j	23.1+1.4j	17–164j
Fe average 500-nm, 25.6%/volume in epoxy, 2.803 g/cc, 0.005–18 GHz (laboratory made)							
$\chi_m(f)$	1.71+5E-002j	4.4+0.58j	−1.45+4E-002j	−1.51–0.24j			
$\lvert B\rvert, \lvert C\rvert$ and $\lvert D\rvert$	1.71	4.4381	1.4506	1.5290			
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	37.5	4.44	1.38	1.45	0.14		
$\varepsilon_2(f)$	2.5+2E-002j	2.51+2E-002j	−4E-002–0.13j	−4E-002–0.13j	2.51+2E-002j	14.1+18.5j	32.4+14.8j
Fe average 500-nm size, 38–39%/volume in epoxy, 3.7–3.8 g/cc, 0.001–18 GHz (laboratory made)							
$\chi_m(f)$	4.92+0.64j	3.85+2.95j	−0.139–0.94j				
$\lvert B\rvert, \lvert C\rvert$ and $\lvert D\rvert$	4.96	4.85	0.95				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	46.2	4.85	1.5	0.95	0.161		
$\varepsilon_2(f)$	6.87+9E-002j	7.16–7E-002j	−0.18–5E-002j	−1.3–0.22j	6.12+0.69j	5.82+14.2j	7.7+16.5j
Fe average 500-nm size, 36.3%/volume in epoxy, 3.56 g/cc, 0.05–10 GHZ (laboratory made)							
$\chi_m(f)$	3.5+8E-002j	3.62+1.1j	−1.32–0.34j				
$\lvert B\rvert, \lvert C\rvert$ and $\lvert D\rvert$	3.50	3.78	1.361				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	33.8	3.78	0.48	1.36	0.17		
$\varepsilon_2(f)$	6.92–0.81j	8.01–0.54j	−0.17–2E-002j	−0.73–0.1j	2.4+1.64j	4–7.5j	−7.7+9.3j
	17.33						

Fe average 500-nm size, 41–43%/volume in epoxy, 3.95–4.0 g/cc, 0.001–18 GHz (laboratory made)							
$\chi_m(f)$	5.6+ 0.64j	3.32+ 2.1j	−1.1− 0.59j				
$\|B\|$, $\|C\|$ and $\|D\|$	5.64	3.93	1.25				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	48.2	3.93	1.2	1.25	0.12		
$\varepsilon_2(f)$	6.98− 0.51j	8.09− 0.58j	−6E-002+ 0.13j	−0.57+ 0.43j	4.97+ 1.06j	4.2− 6.2j	−19.9− 2.2j
Fe average 500-nm size, 13.0%/volume in epoxy, 2.05 g/cc, 0.001–18 GHz (laboratory made)							
$\chi_m(f)$	0.85+ 6E-004j	4.33− 0.1j	−1.7+ 0.55j				
$\|B\|$, $\|C\|$ and $\|D\|$	0.85	4.33	1.79				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$		4.33		1.79			
$\varepsilon_2(f)$	4.09− 0.15j	1.5− 0.95j	0.16+ 2E-002j	0.1− 3E-002j	0.66+ 0.29j	1.17− 0.31j	0.1− 0.71j
Fe average 500-nm size, 20.5%/volume in epoxy, 2.3 g/cc, 0.001–18 GHz (laboratory made)							
$\chi_m(f)$	1.44+ 0.23j	4.59+ 2.35j	−1.53− 0.77j				
$\|B\|$, $\|C\|$ and $\|D\|$	1.46	5.16	1.71				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	209	5.16	0.23	1.71	0.03		
$\varepsilon_2(f)$	2.71+ 0.37j	1.05− 0.71j	0.68+ 1E-002j	0.57− 7E-002j	3.64− 0.21j	6.41+ 3.21j	−0.36− 1.03j
	7.4						

Fe average 500-nm size, 27.0%/volume in epoxy, 2.85 g/cc, 0.001–18 GHz (laboratory made)							
$\chi_m(f)$	1.71+ 5E-002j	4.4+ 0.58j	−1.45+ 4E-002j				
$\|B\|$, $\|C\|$ and $\|D\|$	1.71	4.44	1.45				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	28.7	4.44	0.51	1.45	0.18		
$\varepsilon_2(f)$	3.82+ 0.23j	1.27− 0.68j	0.44+ 0.17j	0.44− 0.14j	3.54+ 0.12j	12.5− 5.9j	−16.7− 2.92j
Fe average 500-nm size, 38.4%/volume in epoxy, 3.75 g/cc, 0.001–18 GHz (laboratory made)							
$\chi_m(f)$	4.92+ 0.65j	3.85+ 2.96j	−1.4− 0.94j				
$\|B\|$, $\|C\|$ and $\|D\|$	4.96	4.86	1.69				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	46.6	4.86	0.52	1.69	0.16		
$\varepsilon_2(f)$	8.98+ 0.33j	4.1− 0.22j	−6E-002+ 6E-002j	−0.35+ 0.16j	6.15+ 0.15j	7.1− 6.7j	−35.4− 36j
Fe average 500-nm size, 40%/volume in epoxy, 3.8 g/cc, 0.001–18 GHz (laboratory made)							
$\chi_m(f)$	5.59+ 0.64j	3.32+ 2.1j	−1.1− 0.59j				
$\|B\|$, $\|C\|$ and $\|D\|$	5.63	3.93	1.25				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	48.2	3.93	0.38	1.25	0.12		
$\varepsilon_2(f)$	9+ 0.24j	4.17− 0.33j	−8E-002+ 9E-002j	−0.39+ 0.19j	6.13+ 5E-002j	6.73− 7.43j	−59.5− 34j
Fe average 500-nm size, 51%/volume in epoxy, 4.5 g/cc, 0.001–18 GHz (laboratory made)							
$\chi_m(f)$	7.08− 0.15j	1.06+ 0.17j	−0.28− 9E-002j				
$\|B\|$, $\|C\|$ and $\|D\|$	7.08	1.07	0.29				
$\chi_{DCP}, f_{rc}, f_{rp}, f_{cd}, f_{pd}$	32.5	1.07	0.12	0.29	0.05		
$\varepsilon_2(f)$	6.03− 0.16j	10.96− 0.43j	1.7E-002+ 3E-002j	1.18− 4E-002j	2.83+ 0.29j	11.29+ 18.6j	14.5+ 28.6j

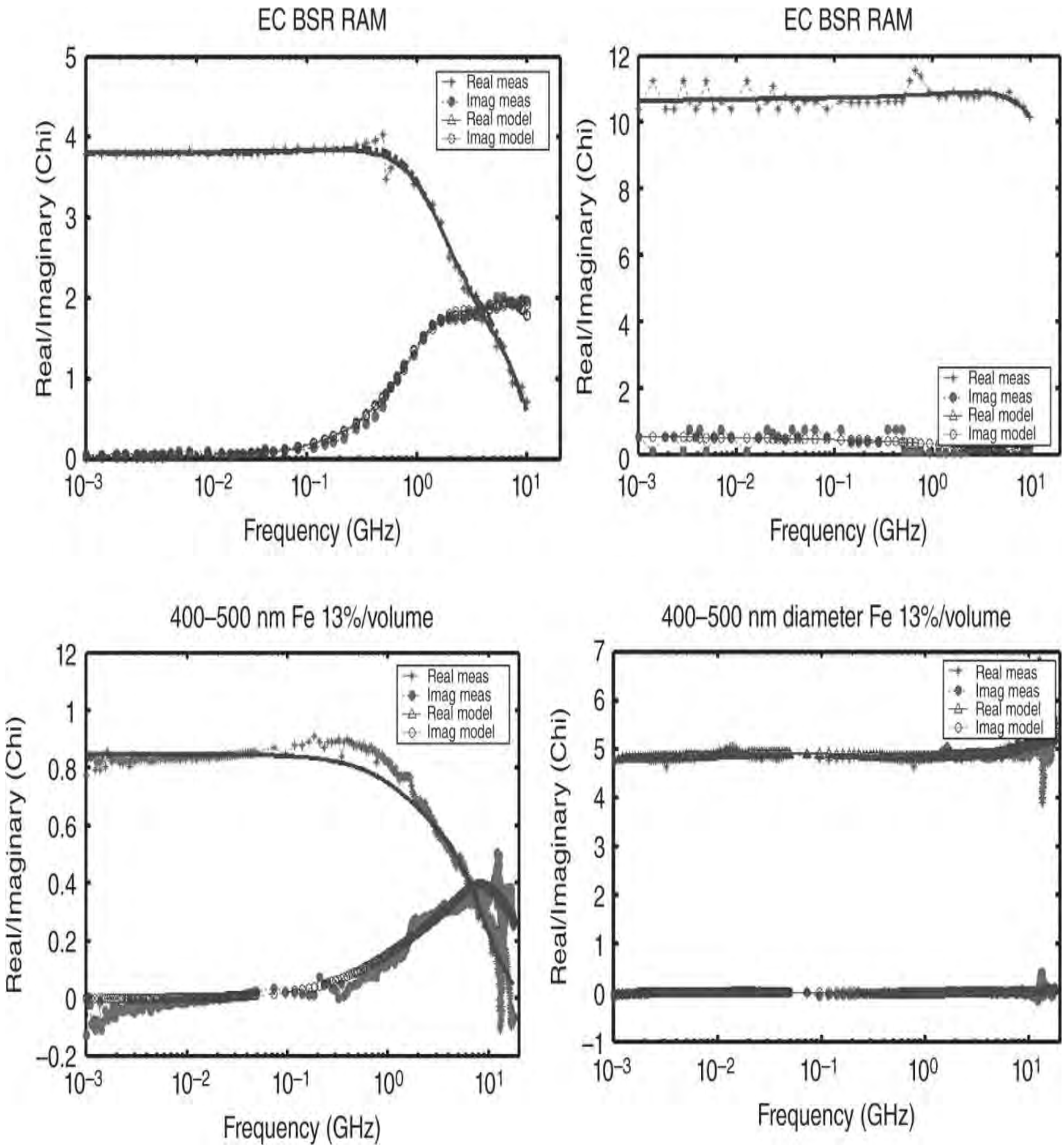


FIGURE 12.14 Measured and functional fit examples of magnetic susceptibility for a commercial (upper) and laboratory (lower) iron polymer composite.

Disclaimer: Data are results obtained by the author on samples prepared in the laboratory. Variations may be observed by other researchers when prepared in their laboratories. Data are not "guaranteed" by a manufacturer or the author. Variations in properties may be observed and users of the products should verify properties. All material properties are guides for engineering design. Materials prepared in the

laboratory should be considered as experimental and also guides for engineering design.

12.12 CERAMIC POLYMER FIBER VERSUS FREQUENCY

Table 12.12 shows the parametric fits of permittivity for various fiber and fiber blends. Test samples were cut from long commercial tow samples that had been purchased. Measurements used TE_{10N} cavities and therefore samples were typically less than 2 in. in length. The fitted functional form is shown at the beginning of the table. Functions are those causal functions that have been derived in Chaps. 2 and 3 for dielectric and magnetic media. When available additional data are shown; these may include density, measured frequency span serving as basis for fits, tabulated information, and chemical and/or physical composition. Figure 12.15 shows frequency fit and measured data that are typical. Fiber frequency measurements were restricted to 2 to 18 GHz and were performed with a rectangular cavity test fixture. In most cases, frequency dispersion is small over the measured bandwidth.

TABLE 12.12 Ceramic and Polymer Fibers versus Frequency 2 to 18 GHz

$\varepsilon_r(f)=B+Cf+Df^2;\ \varepsilon_i(f)=B+Cf^{-D}$			
	B	C	D
SiC fiber (1% O, 69% Si, 30% C)-1, 2.5 g/cc			
$\varepsilon_r(f)$	6.73	−0.043	−0.003
$\varepsilon_i(f)$	0.035	0.0005	−1.86
SiC fiber (5% O, 62% Si, 31% C)-2, 2.7 g/cc			
$\varepsilon_r(f)$	5.34	0.186	−0.0076
$\varepsilon_i(f)$	0.045	1.65	4.1
SiC fiber (12% O, 57% Si, 31% C)-2, regular grade, 2.55 g/cc			
$\varepsilon_r(f)$	8.01	−0.126	0.007
$\varepsilon_i(f)$	0.161	0.573	0.99
Ceramic, 62% Al_2O_3, 24% SiO_2, 14% B_2O_3, 2.7 g/cc (nominal $\varepsilon_r = 5.2$)			
$\varepsilon_r(f)$	6.05	−0.061	0.022
$\varepsilon_i(f)$	0.003	0.009	0.69
Ceramic #1, 70% Al_2O_3, 28% SiO_2, 2% B_2O_3, 3.05 g/cc (nominal $\varepsilon_r = 5.7$)			
$\varepsilon_r(f)$	7.42	−0.2154	0.0094
$\varepsilon_i(f)$	0.0002	0.0005	1.86

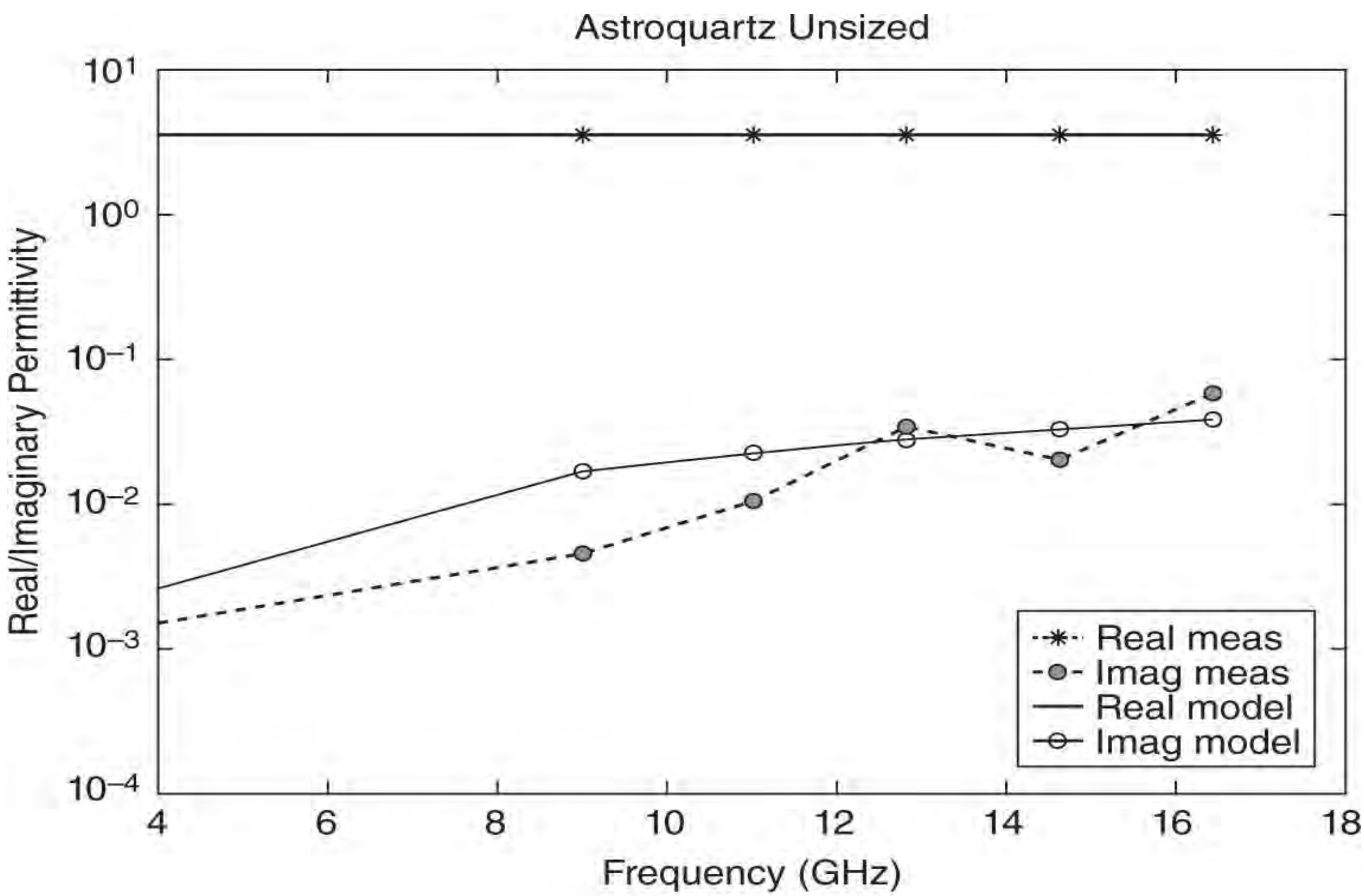
Ceramic #2, 70% Al_2O_3, 28% SiO_2, 2% B_2O_3, 3.05 g/cc (nominal $\varepsilon_r = 5.7$)			
$\varepsilon_r(f)$	7.31	−0.183	0.0081
$\varepsilon_i(f)$	0.0001	0.044	0.291
Ceramic, 97–99% Almax, Al_2O_3, 3.60–3.88 g/cc			
$\varepsilon_r(f)$	9.37	−0.077	0.0038
$\varepsilon_i(f)$	0.001	0.71	0.041
#1, 59% Si, 10% C, 28% N, 3% O (400 filaments), 2.23–2.27 g/cc			
$\varepsilon_r(f)$	6.21	0.043	−0.0031
$\varepsilon_i(f)$	0.116	0.116	0.08
$\varepsilon_r(f)$	5.62	0.1042	−0.0062
$\varepsilon_i(f)$	0.159	0.158	−0.0431
#3 59% Si, 10% C, 28% N, 3% O, 14N (400fil), 2.4 g/cc			
$\varepsilon_r(f)$	6.98	0.004	−0.0025
$\varepsilon_i(f)$	0.001	0.221	−0.087
#4 59% Si, 10% C, 28% N, 3% O, −03 (200 filaments), 2.59–2.64 g/cc			
$\varepsilon_r(f)$	7.52	−0.02	0.0013
$\varepsilon_i(f)$	0.038	0.189	0.773

SiN fiber (2% O, 57% Si, 32–39% N, <1% C)-1. 2.32 g/cc			
$\varepsilon_r(f)$	4.35	−0.28	0.013
$\varepsilon_i(f)$	0.001	0.102	−0.24
SiN fiber (2% O, 57% Si, 32–39% N, <1% C)-2, 2.45 g/cc			
$\varepsilon_r(f)$	3.28	−0.08	0.0032
$\varepsilon_i(f)$	0.004	0.011	0.162
SiN fiber (2% O, 57% Si, 32–39% N, <1% C)-3, 2.48 g/cc			
$\varepsilon_r(f)$	3.08	−0.04	0.0018
$\varepsilon_i(f)$	0.001	0.001	0
Silicon nitride (Si_3N_4, 2.5 g/cc)			
$\varepsilon_r(f)$	4.77	0.0005	0.0008
$\varepsilon_i(f)$	0.01	0.01	−0.434
Steel (about 3%), nylon blend (σ DC about 1.3 Mho-m fiber)			
$\varepsilon_r(f)$	7.49	−0.998	0.039
$\varepsilon_i(f)$	0.001	23.38	0.995

Glass (astroquartz) unsized, 2.2 g/cc, silicon oxide			
$\varepsilon_r(f)$	3.73	−0.022	0.001
$\varepsilon_i(f)$	0.001	0.0026	−1.04
Glass (astroquartz) with sizing, 2.2 g/cc			
$\varepsilon_r(f)$	3.72	−0.020	0.001
$\varepsilon_i(f)$	0.001	0.0066	−0.7231
Si-Ti-C-O fiber (55%-2%-32%-10%), 2.48 g/cc			
$\varepsilon_r(f)$	7.98	−0.064	0.0032
$\varepsilon_i(f)$	0.63	2.48	1.24
Fiber permittivity at selected frequencies			
Si_3N_4, 2.5 g/cc; 12.7, 14.4, 16.4 GHz; pre-heat treatment (average three samples)	12.7 GHz	14.4 GHz	16.4 GHz
$\varepsilon_r(f)$	6.41	6.5	6.59
$\varepsilon_i(f)$	0.39	0.29	0.31
Si_3N_4, 2.5 g/cc; 14.4, 16.4 GHz; post-heat treatment at 1041 K	14.4 GHz	16.4 GHz	
$\varepsilon_r(f)$	4.46	4.55	
$\varepsilon_i(f)$	0.001	0.001	

Para-aramid [$-CO-C_6H_4-CO-NH-C_6H_4-NH-]_n$	12.7 GHz	14.4 GHz	16.4 GHz
$\varepsilon_r(f)$	4.52	4.57	4.48
$\varepsilon_i(f)$	0.29	0.24	0.28
PBI (polybenzimidazole)	12.7 GHz	14.4 GHz	16.4 GHz
$\varepsilon_r(f)$	3.59	3.58	3.64
$\varepsilon_i(f)$	0.11	0.12	0.11
PBT (polybutylene terephthalate)	12.7 GHz	14.4 GHz	16.4 GHz
$\varepsilon_r(f)$	6.37	6.46	6.24
$\varepsilon_i(f)$	0.07	0.04	0.04
Meta-aramid fiber	12.7 GHz	14.4 GHz	16.4 GHz
$\varepsilon_r(f)$	3.83	3.87	3.95
$\varepsilon_i(f)$	0.13	0.13	0.1

Single fiber, Ni plated 8-µm graphite, nominal 0.5-µm coating, 2.5–3.0 g/cc (average 4–18 GHz)		
$\varepsilon_r, \varepsilon_i$	1.56 * 10 ^13, 3.46 * 10 ^ 9	
S-glass, 2.49 g/cc Nominal ε_r is about 4.5 to 5.0; 64% silicon oxide, 25% aluminum oxide, .01% Ca oxide, 10% mg oxide, .01% Boron oxide,	10 GHz	16 GHz
$\varepsilon_r(f)$	5.21–5.41	5.4
$\varepsilon_i(f)$	0.04–0.07	0.06–.08
E-glass, nominal ε_r is about 6.0 to 6.3, 2.54 g/cc, 54% silicon oxide, 15% aluminum oxide, 17% calcium oxide, 10% magnesium oxide, 4% barium oxide	10 GHz	16 GHz
$\varepsilon_r(f)$	6.13	6.25
$\varepsilon_i(f)$	.02–0.04	0.08
Single Ni-coated glass fiber, about 0.5-µm Ni-coating thickness (average 4 to 18 GHz)		
$\varepsilon_r, \varepsilon_i$	$\varepsilon_r = 1.12\times10^{13}$ $\varepsilon_i = 4.02\times10^{9}$	


Astroquartz Unsized
Real/Imaginary Permittivity
Frequency (GHz)
Real meas
Imag meas
Real model
Imag model
10^1
10^0
10^-1
10^-2
10^-3
10^-4
4
6
8
10
12
14
16
18

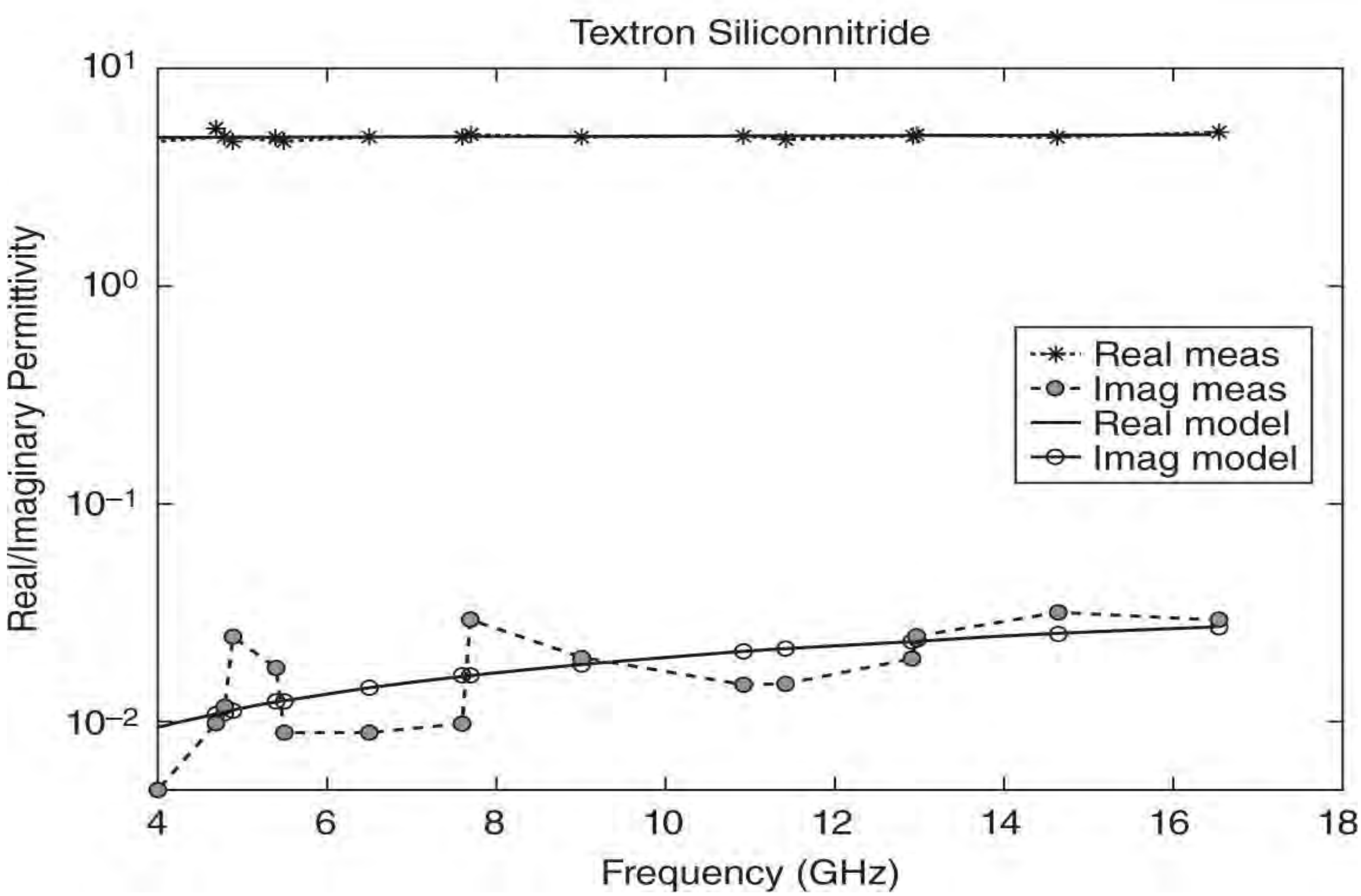

Textron Siliconnitride
Real/Imaginary Permittivity
Frequency (GHz)
Real meas
Imag meas
Real model
Imag model
10^1
10^0
10^-1
10^-2
4
6
8
10
12
14
16
18

FIGURE 12.15 The upper and lower figure show measured and functional fitted permittivity for two ceramic fibers.

Disclaimer: Data are results obtained by the author on samples prepared in the laboratory. Variations may be observed by other researchers when prepared in their laboratories. Data are not "guaranteed" by a manufacturer or the author. Variations in properties may be observed and users of the products should verify properties. All material properties are guides for engineering design. Materials prepared in the laboratory should be considered as experimental and also guides for engineering design.

12.13 DENSE FERRITES VERSUS FREQUENCY

Table 12.13 shows the parametric fits of susceptibility and permittivity for dense magnetic ferrite materials. All samples were machined to fit 7-mm or 14-mm coaxial line. The fitted functional forms are shown at the beginning of the table. Fitted functions are those causal functions that have been derived in Chaps. 2 and 3 for dielectric and magnetic media. *Note to use the absolute parameter values (i.e., |B|, |C|, |D|) when calculating permeability. Caution should be observed when the derived parameters are over a narrow bandwidth and may not fully encompass the fundamental resonance. In those cases, extrapolation of the parameters outside the original measured band can lead to an error*. Most ferrites show nondispersive permittivity and thus a single value may be shown. Some permittivities could not be obtained or measured and for those samples (e.g., $Ni_{.96}Co_{.036}Mn_{.02}Fe_{1.9}O_4$) permittivity is left as an unknown. Physical data are supplied when available in the identifier cell. Data may include density, measured frequency span serving as basis for fits, tabulated information (i.e., magnetization, resonance, anisotropy, density), and chemical composition. In the tables exponentials are often shown as bE—which means b*10^{-a}. Thus, –2E-004 –7.6E-003j is equal to –0.0002–j0.0076. Figure 12.16 shows typical fit and measured data for ferrites with a coaxial gap (high frequency data variation) and for a very wide-band measurement.

TABLE 12.13 Solid Ferrite Parameters

$\mu(f)-1=\chi_m(f)=B(1-j*f/D)\{1-(f/C)^2-j*(f/D)\}^{-1}$ Note to use the absolute parameter values (i.e., $|B|$, $|C|$, $|D|$) when calculating permeability.

$\varepsilon_1(f)=B+C\{1-(f/D)^2-2j*(f/E)\}^{-1}$

$\varepsilon_2(f)=B+real(C)f^D+imag(C)f^E+F\{1-(f/G)^2-2j*(f/H)\}^{-1}$

$Mn_{.6}Zn_{.4}Fe_2O_{3.6}-Mn_{.53}Zn_{.37}Fe_{2.1}O_4$

1 MHz to 2 GHz, $\mu_{DC}=5000$, $T_C=160$, $4\pi M_s=5150$, $f_r=.25$ MHz, 4.9g/cc, $\sigma^{-1}=1$ Ohm-m, $H_k^s\sim 1$ Oe, $\varepsilon_r\simeq 38-25$, $\varepsilon_i\simeq 1-10$ relaxation

$\chi_m(f)$	4860+ 80j	1.6E-003– 5E-004j	−1.1E-003– 7E-004j	
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	4860.66	0.0017	0.0013	
$\varepsilon_1(f)$	20.85+ 0.59j	18.35+ 0.2j	5.39+ 2.04j	4.56– 0.34j

$Mn_{.54}Zn_{.36}Fe_2O_{3.6}-Mn_{.55}Zn_{.38}Fe_{2.07}O_4$,~4.9 g/cc, 1 MHz to 2 GHz, $\mu_{DC}=7500$, $T_C=135$, $4\pi M_S=5152$, $f_r=.3$ MHz, $\sigma^{-1}=$ 1 Ohm-m, $H_k^s\sim 0.7$ Oe, $\varepsilon_r\simeq 35-25$, $\varepsilon_i\simeq 1-8$ relaxation

$\chi_m(f)$	6851+ 332j	4.4E-004– 6E-004j	3.2E-003– 3E-003j	
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	6859.04	0.0007	0.0044	
$\varepsilon_1(f)$	19.62+ 0.6j	15.92+ 8E-003j	7.11+ 2.64j	6.34– 0.33j

$Ni_{.4}Mn_{.02}Fe_{1.9}O_4$, 5.2 g/cc, 0.001–10 GHz, $\mu_{DC}=800$, H_k^s about 5 Oe, $4\pi M_S=4058$, $\varepsilon_r\sim 13.5$

$\chi_m(f)$	781-39j	9.5E-003+ 4E-004j	−3.7E-003– 1E-003j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	781.97	0.0095	0.0038

$Sm_2O_33(Fe_{1.9}O_5)$, 5.1 g/cc, 0.001–10 GHz, $\mu_{DC}=35$, $H_K=162$ Oe., $4\pi M_S=1683$

$\chi_m(f)$	30.5– 2j	1.52E-002– 3E-003j	−5.1E-003– 9E-004j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	30.57	0.0155	0.0052

$Ni_{.97}Co_{.027}Mn_{.02}Fe_{1.9}O_4$, 5.1 g/cc, 0.001–10 GHz, $\mu_{DC} = 20$, $H_K = 165$ Oe., $4\pi M_S = 3317$

$\chi_m(f)$	18.55– 1.4j	0.444+ 0.28j	–0.17– 0.17j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	18.60	0.5249	0.2404

$Ni_{.96}Co_{.036}Mn_{.02}Fe_{1.9}O_4$, 5.1 g/cc, 0.001–10 GHz, $\mu_{DC} = 13.$, $H_K = 160$ Oe, $4\pi M_S = 3405$

$\chi_m(f)$	15– 0.7j	0.608– 4E-002j	–0.415+ 1.6E-002j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	15.02	0.6093	0.4153

$Ni_{.99}Co_{.01}Mn_{.02}Fe_{1.9}O_4$, 5.1 g/cc, 0.001–10 GHz, $\mu_{DC} = 13.7$, $H_K = 155$ Oe, $4\pi M_S = 3279$

$\chi_m(f)$	15.62– 1.1j	0.47+ 0.212j	–0.18– 0.13j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	15.66	0.5156	0.2220

$Ni_{.8}Zn_{.2}Fe_{1.9}O_{4.8}$, 0.05–18 GHz, $\mu_{DC} \sim 80$, $4\pi M_S = 4000$, $H_k^s \sim 50$ Oe, $\varepsilon_r = 12.3$, $\tan\delta < .002$

$\chi_m(f)$	–9.9+ 128j	7.4E-002+ 4.9E-002j	5.2E-002– 9E-003j	
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	128.38	0.0888	0.0528	
$\varepsilon_1(f)$	8.56+ 0.46j	–1.38– 0.31j	1.08+ 0.15j	6E-002– 0.18j

$Ni_{.58}Zn_{.25}Fe_{2.17}O_4$, 4.9–5.1 g/cc, 0.05–18 GHz, $\mu_{DC} = 60$, $H_k^s \sim 84$ Oe, $4\pi M_S = 4058$, $\varepsilon_r \simeq 13.5-15, \varepsilon_i \simeq 1-3$

$\chi_m(f)$	47.9–4.3j	0.2097+9.3E-002j	−9.2E-002−5E-002j	
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	48.09	0.2294	0.1047	
$\varepsilon_1(f)$	7.35+9E-002j	6.39+0.4j	−3E-002+7E-002j	0.45–0.21j

Ni $Al_{.5}Mn_{.02}Fe_{1.5}O_4$, 4.98 g/cc, 0.005 –10 GHz, $\mu_{DC} \sim 6$, $H_k = 800$ Oe, $4\pi M_S = 1043$, $\varepsilon_r = 10 \pm 0.8$

$\chi_m(f)$	3.59+0.34j	0.779+0.33j	−0.21–0.14j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	3.61	0.8460	0.2524

$NiMn_{.02}Fe_{1.9}O_4$, 5.13 g/cc, 0.001–10 GHz, $\mu_{DC} = 28$, $H_k = 260$ Oe, $4\pi M_S = 3230$, $\varepsilon_r \approx 12.5 \pm 10\%$

$\chi_m(f)$	27.2–1.6j	0.194+3E-002j	−7.22E-002–3.4E-002j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	27.25	0.1963	0.0798

$NiMn_{.02}Fe_{1.9}O_4$, 4.85 g/cc, 5.45% voids, .001–10 GHz, $\mu_{DC} = 17$, $H_k = 260$ Oe, $4\pi M_S = 3230$, $\varepsilon_r \approx 11.9 \pm 10\%$

$\chi_m(f)$	15.77–0.8j	0.451+9E-002j	−0.215–8E-002j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	15.79	0.4599	0.2294

$NiMn_{.02}Fe_{1.9}O_4$, 4.6 g/cc, 10.5% voids, 0.001–10 GHz, $\varepsilon_r \approx 11.2 \pm 10\%$, $\mu_{DC} = 13$, $H_k = 260$ Oe, $4\pi M_S = 3230$

$\chi_m(f)$	12–0.69j	0.524+0.12j	−0.24–0.1j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	12.02	0.5376	0.2600

$NiMn_{.02}Fe_{1.9}O_4$, 3.8 g/cc, 25.7% voids, 0.001–10 GHz, $\varepsilon_r \approx 10.7 \pm 10\%$, $\mu_{DC} = 6.5$, $H_k = 260$ Oe, $4\pi M_S = 3230$

$\chi_m(f)$	5.62–0.37j	0.8+0.41j	−0.335–0.23j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	5.63	0.8989	0.4064

$NiMn_{.02}Fe_{1.9}O_4$, 4.96 g/cc, 3.3% voids, 0.001–10 GHz, $\mu_{DC} = 20.5$, $H_k = 260$ Oe, $4\pi M_S = 3230$, $\varepsilon_r \approx 12.1 \pm 10\%$

$\chi_m(f)$	19.18–1.14j	0.323+9E-002j	−0.12–7E-002j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	19.21	0.3353	0.1389

Ni $Al_{.4}Mn_{.02}Fe_{1.6}O_4$, 5.0 g/cc, 0.005–5 GHz, $\mu_{DC} \sim 10$, $H_k = 590$ Oe, $4\pi M_S = 1495$, $\varepsilon_r \approx 11 \pm 10\%$

$\chi_m(f)$	12.54+2.2j	1.6E-002–4E-002j	2.3E-003+4E-003j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	12.73	0.0431	0.0046

Ni $Al_{.2}Mn_{.02}Fe_{1.8}O_4$, 4.8 g/cc, 0.005–5 GHz, $\mu_{DC} = 20$, $H_k = 450$ Oe, $4\pi M_S = 2186$, $\varepsilon_r \approx 10.7 \pm 10\%$

$\chi_m(f)$	18.56+0.32j	0.19–1E-002j	–8.2E-002–3.1E-002j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	18.56	0.1903	0.0877

Ni $Al_{.4}Mn_{.02}Fe_{1.6}O_4$, 5.0 g/cc, 0.005–5 GHz, $\mu_{DC} \sim 10$, $H_k = 590$ Oe, $4\pi M_S = 1495$, $\varepsilon_r \approx 11 \pm 10\%$

$\chi_m(f)$	12.54+2.2j	1.6E-002–4E-002j	2.3E-003+4E-003j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	12.73	0.0431	0.0046

$Ni_{.8}Mn_{.02}Zn_{.2}Fe_{1.9}O_{5.6}$, 5.14 g/cc, 0.001–10 GHz, $\mu_{DC} = 82$, $H_k = 90$ Oe, $4\pi M_S = 4888$, $\varepsilon_r \approx 13.5 \pm 10\%$

$\chi_m(f)$	81.18–4.8j	0.107+2.7E-002j	–3.6E-002–2.4E-002j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	81.32	0.1104	0.0433

$Ni_{.925}Co_{.068}Mn_{.02}Fe_{1.9}O_4$, 4.83 g/cc, 0.001–10 GHz, $\mu_{DC} = 8.5$, $H_k = 620$ Oe, $4\pi M_S = 3480$

$\chi_m(f)$	7.25–0.33j	0.942+0.625j	–0.331–0.285j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	7.26	1.1305	0.4368

$Mg_{.15}Mn_{.01}Fe_2O_4$, 4.4 g/cc, 0.01–10 GHz, $\mu_{DC} \sim 35$, $4\pi M_S \sim 2000–3000$, $\varepsilon_r \approx 13 \pm 10\%$

$\chi_m(f)$	34.88–1.53j	0.105+1E-002j	–4E-002–2E-002j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	34.91	0.1055	0.0447

Li Ferrite A-5000, 0.2–2 GHz, $4\pi M_S = 5000$, $\varepsilon_r \approx 14 \pm 10\%$

$\chi_m(f)$	31.5+36.6j	2.2E-002–0.3j	0.156+0.11j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	48.29	0.3008	0.1909				
$\varepsilon_2(f)$	4.14–8E-002j	3.67–4E-002j	–0.42–0.15j	–0.4–0.14j	4.23–3E-002j	1.43+15.2j	4+23.4j

$Er_2O_3 5(Fe_2O_3)$, 6.3 g/cc, 0.001–10 GHz, $\mu_{DC} = 38$, $H_k = 102$ Oe, $4\pi M_S = 1306$, $\varepsilon_r \approx 15 \pm 10\%$

$\chi_m(f)$	36.5–0.3j	2.1E-002+1E-003j	–6.1E-003–2E-003j
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	36.50	0.0210	0.0064

Li_xZn_y ferrite, 0.2–2 GHz, $4\pi M_S = 4800$, $\varepsilon_r = 14.5$, $\tan\delta < .0015$, $T_C = 400$

$\chi_m(f)$	27.5+54.22j	2E-003–0.28j	0.13+0.16j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	60.80	0.2800	0.2062				
$\varepsilon_2(f)$	4.7-0.15j	4.7-0.15j	–9E-002+2E-003j	–1.5+0.63j	4.71–0.15j	3.97+0.43j	15.6+3.4j

Li_xTi_y ferrite (NIST 72-1700), 0.01–10 GHz

$\chi_m(f)$	9.88+9.41j	0.24–0.45j	0.4+0.27j				
$\|B\|$, $\|C\|$ and $\|D\|$	13.64	0.5100	0.4826				
$\varepsilon_2(f)$	4.39+0.22j	4.39+0.23j	−3E-002+3E-002j	−3E-002+3E-002j	4.39+0.18j	9.86–4.27j	−23.1–20.9j

$Ni_xZn_yFe_2O_4$ (Fair-Rite 43), 0.00001–5 GHz

$\chi_m(f)$	768+64j	5E-003–2E-003j	−1.6E-003+9E-004j				
$\|B\|$, $\|C\|$ and $\|D\|$	770.66	0.0054	0.0018				
$\varepsilon_2(f)$	3.7–7E-002j	3.46–5E-003j	−0.16–0.19j	−0.64–0.61j	3.65–5E-002j	5.52+13.92j	12.8+14.9j

$Ni_{.36}Mn_{.02}Zn_{.64}Fe_{1.9}O_{3.2}$-$Ni_{.37}Zn_{.63}Fe_2O_4$ –St26, 5 g/cc, 0.05–18 GHz, $\mu_{DC} = 1100$, $T_C = 140$, $4\pi M_S$ = unknown, f_r = 1.5 MHz, $\varepsilon_r \approx 12-15, \varepsilon_i \approx 1-2$

$\chi_m(f)$	1168+140j	4E-003–1E-003j	−1.5E-003+4E-004j				
$\|B\|$, $\|C\|$ and $\|D\|$	1176.36	0.0041	0.0016				
$\varepsilon_2(f)$	4.34+9E-002j	4.33+9E-002j	−2E-002–6E-003j	−0.23+0.42j	4.63–2E-003j	1.6+17.19j	20.65+56.8j

$3(Y_2O_3)5(Fe_2O_3)$, 4.95 g/cc, 0.001–10 GHz, $\mu_{DC} = 101$, H_k = 60 Oe, $4\pi M_S = 1734$

$\chi_m(f)$	98.7–8.1j	3.03E-002+1E-002j	−9.7E-003–7.5E-003j
$\|B\|$, $\|C\|$ and $\|D\|$	99.03	0.0319	0.0123

$YGd_{.1}Fe_2O_{6.8}$ T-4259, 0.2–14 GHz, $\mu_{DC} = 116$, $T_C = 280$, $4\pi M_s = 1600$, $\varepsilon_r = 15.1$

$\chi_m(f)$	−0.77+ 5.66j	1.7E-002− 0.78j	1.1− 0.66j				
$\|B\|$, $\|C\|$ and $\|D\|$	5.71	0.7802	1.2828				
$\varepsilon_2(f)$	4.4+ 0.17j	3.81+ 4E-002j	−0.18− 0.13j	0.46+ 0.36j	4.67+ 0.43j	3.4+ 20j	8.75+ 33.4j

$YGd_{.2}Fe_2O_{7.4}$ 0.05–2 GHz

$\chi_m(f)$	5.89+ 8.84j	0.315− 0.419j	5.6E-002+ 0.64j				
$\|B\|$, $\|C\|$ and $\|D\|$	10.62	0.5242	0.6424				
$\varepsilon_2(f)$	4.14+ 0.31j	4.35+ 0.32j	−7E-002− 0.24j	−0.78+ 0.35j	4.05+ 0.21j	1.52+ 16.2j	7.5+ 23.2j

$Y_3Si_3Fe_2O_{12}$, Yittrium Garnett, TTG113, unknown g/cc, 0.1–10 GHz, $\mu_{DC} \sim 25–70$, $H_k \sim 4–7$, $4\pi M_s \sim 1000$, $T_C \sim 280$, $\varepsilon_r \approx 15 \pm 10\%$

$\chi_m(f)$	18.17+ 24.8j	9.15E-002− 0.29j	0.473+ 0.317j				
$\|B\|$, $\|C\|$ and $\|D\|$	30.74	0.3041	0.5694				
$\varepsilon_2(f)$	4.59− 3E-002j	4.59− 3E-002j	4E-002− 2E-002j	3.1E-002− 6E-003j	4.61− 4E-002j	10.55+ 12.8j	33.6− 14.2j

$3(Yb_3O_3)3.5(Fe_2O_3)$, 6.1 g/cc, 0.001–10 GHz, $\mu_{DC} = 64$, $H_k = 53$ Oe, $4\pi M_s = 1696$, $\varepsilon_r \approx 15 \pm 10\%$

$\chi_m(f)$	69.8−5.4j	2.68E-002+4E-003j	−1E-002−5E-003j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	70.01	0.0271	0.0112				

Ni $Mn_{.02}Al_{.65}Fe_{1.35}O_4$, 4.9 g/cc, 0.01–10 GHz

$\chi_m(f)$	0.723+0.33j	2+2.86j	−0.755−0.94j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	0.79	3.4899	1.2057				
$ZnO_3(TiO_2).06(Fe_{1.9}O_4)$ (TiaTan), 0.1–10 GHz	3.1+4.9j	0.21−j	0.44−0.64j				
$\chi_m(f)$	4.19+5.36j	0.313-1.31j	0.72−1.18j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	6.80	1.3469	1.3823				
$\varepsilon_2(f)$	4.12+0.12j	4.12+0.12j	7E-003+3E-002j	−1.3E-003+4E-002j	4.12+0.12j	7.1−6j	50.3−4.2j

$MgZn_{.2}Mn_{.1}O_3Fe_2O_{6.4}$ T-3000, ~5 g/cc, 0.01–18 GHz, $\mu_{DC} = 54$, $H_k = 3.4$, $4\pi M_s = 3000$, $T_C = 240$, $\varepsilon_r = 13.0$, $\tan\delta < .001$

$\chi_m(f)$	7.45+10.21j	0.4−0.7j	0.49+0.71j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	12.64	0.8062	0.8627				
$\varepsilon_2(f)$	2.46+0.14j	2.77+0.2j	0.22+1E-002j	0.91−5E-002j	7.92+0.12j	0.62+5.2j	−0.23−2.64j

$Ni_{.72}Fe_2O_{4.8}$-$Ni_{.79}Mn_{.06}Fe_{2.15}O_4$, 4.6 g/cc, $4\pi M_s = 3140$, 0.05–18 GHz, $\mu_{DC} = 250$, $\varepsilon_r \approx 11-12 \pm 10\%$, $\varepsilon_i \leq 1$

$\chi_m(f)$	16.54–0.28j	0.263+5.1E-002j	−7.7E-002–1E-002j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	16.54	0.2679	0.0776				
$\varepsilon_2(f)$	3.94–5E-002j	3.94–7E-002j	−1E-003–2E-002j	1.14+0.14j	3.99–7E-002j	17.54+13.58j	444.13+6.3j

$Ni_{.26}Zn_{.34}Fe_{1.9}O_{4.8}$-$Ni_{.29}Zn_{.42}Fe_{2.29}O_4$, 4.5 g/cc, 0.05–18 GHz, $\varepsilon_r \approx 11-12 \pm 10\%$, $\varepsilon_i \leq 1$

$\chi_m(f)$	76.02+55.26j	4.1E-002–0.12j	4.5E-002+6.6E-002j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	93.98	0.1268	0.0799				
$\varepsilon_2(f)$	3.81+3E-002j	3.88–8E-002j	−9E-002–6E-002j	1.69+0.34j	3.66+6E-002j	5.87+18.66j	9.01+20.22j

$Ni_{.31}Zn_{.58}Cu_{.08}Fe_{2.03}O_4$-$Ni_{.30}Zn_{.59}Cu_{.08}Fe_{2.03}O_4$, 4.9 g/cc, 0.00001–18 GHz, $\mu_{DC} = 850$, $T_C > 175$, $4\pi M_s = 4100$, $f_r = 2$ MHz, $\sigma^{-1} = 10^5$ Ohm-cm, $\varepsilon_r \approx 15-17 \pm 10\%$, $\varepsilon_i \sim 5-20$ dispersive

$\chi_m(f)$	866+102j	1.03E-002+8E-004j	−3E-003–7E-004j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	871.99	0.0103	0.0031				
$\varepsilon_2(f)$	4.62+0.98j	4.28+1.24j	−0.41–0.31j	−0.41–0.31j	4.62+0.99j	4.23+17.7j	13.85+32.78j

$Ni_{.56}Zn_{.24}Cu_{.04}Fe_2O_{4.6}$-$Ni_{.61}Zn_{.26}Fe_{2.13}O_4$, 5.0 g/cc, 0.05–18 GHz, $\mu_{DC} = 130$, $T_C = 225$, $4\pi M_s = 3600$, $f_r = 15$ MHz, $\sigma^{-1} = 10^6$ Ohm-cm, $\varepsilon_r \approx 10-15 \pm 10\%$, $\varepsilon_i \sim 5-15$ dispersive							
$\chi_m(f)$	118.2+ 14j	4.9E-002+ 3.4E-003j	−1.2E-002– 5E-003j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	119.03	0.0491	0.0130				
$\varepsilon_2(f)$	3.3+ 0.32j	2.36+ 0.35j	−0.64– 0.23j	0.54+ 4E-002j	3.37+ 0.32j	0.61+ 5.46j	1.22+ 9.47j
EC F 116, 0.1–18 GHz							
$\chi_m(f)$	3.12– 4E-002j	3.99+ 1.27j	−1.67– 0.53j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	3.12	4.1872	1.7521				
$\varepsilon_2(f)$	3.79+ 0.18j	3.77+ 0.2j	−9.6E-002+ 6E-003j	−9.6E-002+ 6E-003j	3.81+ 0.18j	8.77- 33.6j	−18.78 +72.2j
$Ni_{.8}Zn_{.2}Fe_{1.9}O_{4.8}$, 0.05–18 GHz, $\mu_{DC} \sim 80$, $4\pi M_s = 4000$, $H_k^s \sim 50$ Oe, $\varepsilon_r = 12.3$, $\tan\delta < .002$							
External DC field 0 Gauss, $\chi_m(f)$	−9.9+ 128j	7.4E-002+ 4.9E-002j	5.2E-002– 9E-003j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	128.38	0.089	0.053				
$\varepsilon_1(f)$	8.56+ 0.46j	−1.38– 0.31j	1.08+ 0.15j	6E-002– 0.18j			
External DC field 150 Gauss, $\chi_m(f)$	−11.2+ 133.9j	7.23E-002 +5E-002j	5.2E-002– 9E-003j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	134.4	.0088	.053				
$Ni_{.8}Zn_{.2}Fe_{1.9}O_{4.8}$, 0.05–18 GHz, $\mu_{DC} \sim 80$, $4\pi M_s = 4000$, $H_k^s \sim 50$ Oe, $\varepsilon_r = 12.3$, $\tan\delta < .002$							
External DC field 300 Gauss, $\chi_m(f)$	−12.6+ 137.6j	7.33E-002 +4.7E-002j	5.1E-002– 1E-002j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	138.2	.0087	.052				
External DC field 600 Gauss, $\chi_m(f)$	−12.2+ 143.1j	8E-002+ 5E-002j	5.2E-002– 1.25E-002j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	143.6	.094	.054				
External DC field 900 Gauss, $\chi_m(f)$	−0.28+ 136j	9.7E-002 + 5.7E-002j	5.6E-002– 2E-002j				
$\lvert B\rvert$, $\lvert C\rvert$ and $\lvert D\rvert$	136.0	.112	.06				

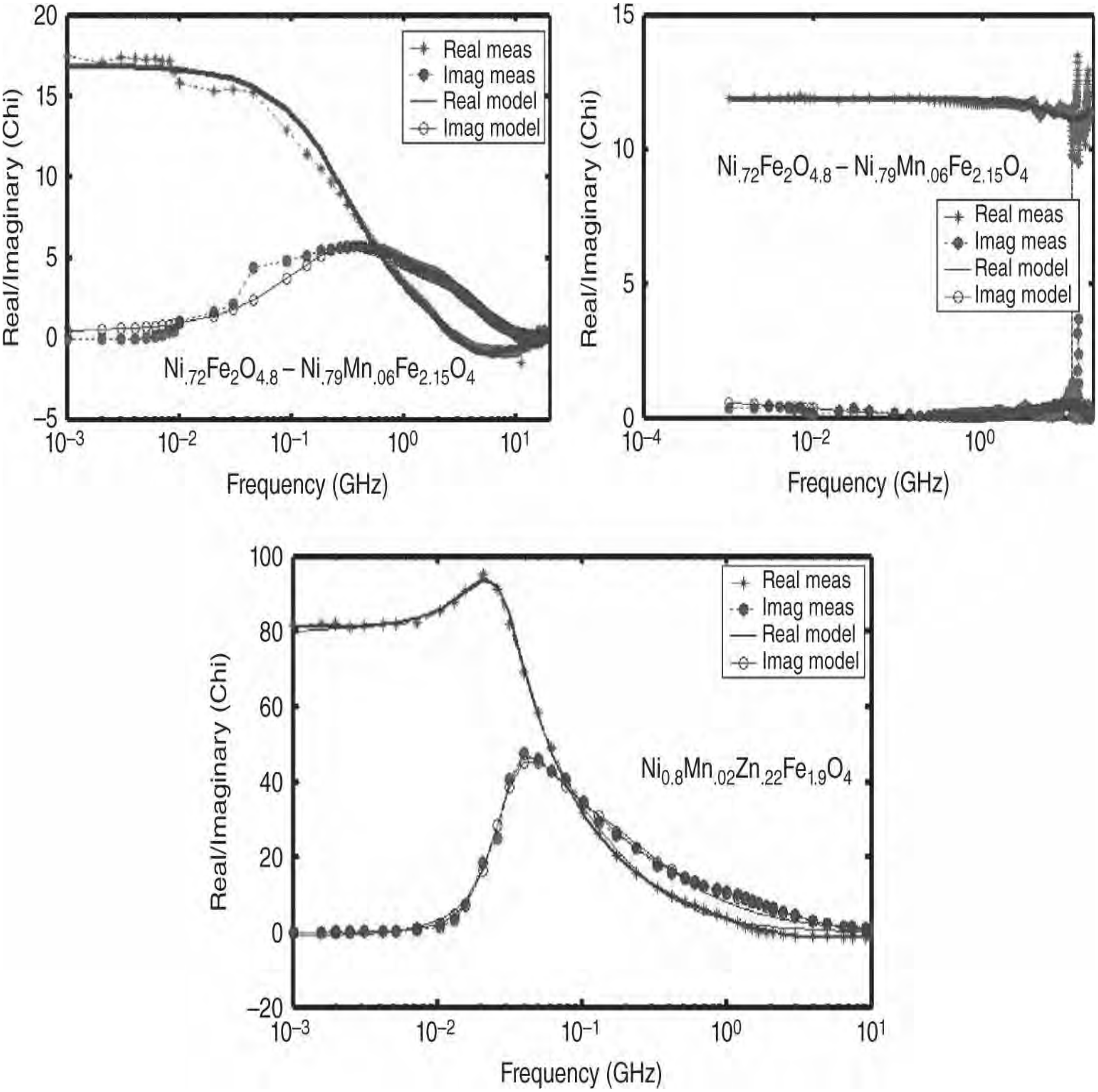


FIGURE 12.16 Examples of measured and functional fits to ferrite susceptibility and permittivity.

Disclaimer: Data are results obtained by the author on samples prepared in the laboratory. Variations may be observed by other researchers when prepared in their laboratories. Data are not "guaranteed" by a manufacturer or the author. Variations in properties may be observed and users of the products should verify properties. All material properties are guides for engineering design. Materials prepared in the laboratory should be considered as experimental and also guides for engineering design.

12.14 FIBER–POLYMER COMPOSITES VERSUS FREQUENCY

Table 12.14 shows the parametric fits of permittivity for various fiber–polymer composites and polymers. Test samples were square- or disk-shaped with cross-sectional dimension typically less than 30 cm. The thickness was between 0.5 and 1 cm. The fitted functional forms are shown at the beginning of the table. Functions are those causal functions that have been derived in Chaps. 2 and 3 for dielectric and magnetic media. Other data are shown when available. These may include density, measured frequency span serving as basis for fits, and chemical and/or physical composition. In the tables exponentials are often shown as bE—which means $b*10^{-a}$. Thus, –2E-004–7.6E-003j is equal to –0.0002–j0.0076. Figure 12.17 shows a typical permittivity fit for a high-loss (top) and low-loss (bottom) composite. Again, unphysical low loss variations are smoothed by the fit to a physical model.

TABLE 12.14 Fiber–Polymer Composites

Sample ID							
$\varepsilon(f) = B + 2Cf^{D} + G\{1 - J*(f-H)^2 - j2/f\}^{-1}$							
	B	C	D	G	H	I	J
E-glass (40–100 GHz), (polyphenylsulfone)							
	0.7015–0.3069j	4.4739–0.8763j	−0.4446+9.95E-002j	0.3187+6.4E-003j	7E-004+1.9E-003j	−1E-004–8.3E-003j	−8.72E-005+2.55E-006j
PTFE-glass fiber (5500), 2.2 g/cc (10–100 GHz)							
	0.6637–5.1E-003j	0.664–4.8E-003j	5.6E-003+1.07E-002j	0.68 – 7.3E-003j	4E-004+9E-004j	−8E-004+2.1E-003j	3.84E-005+9.97E-006j
PTFE-glass fiber 5870, 2.20 g/cc (10–100 GHz) (nominal ε_r = 2.33, tanδ = .0005, Rogers Corp. data sheet 1.5000)							
	0.8126–2.7E-003j	0.748+1.2E-003j	1.82E-002+5E-004j	1.26E-002	2.67E-002–1E-003j	2E-004–2.76E-002j	−8.75E-004–1.34E-005j
PTFE-glass fiber 5880, 2.2 g/cc (1–100 GHz) (nominal ε_r = 2.20, tanδ = 0.0004, Rogers Corp. data sheet 1.5000)							
	0.5326–1.14E-002j	0.5367–9E-003j	4.28E-002–1.01E-002j	0.5721+4.75E-002j	1.4E-003–4E-004j	1.6E-003+2.3E-003j	1.84E-005–1.41E-005j
PTFE-glass fiber 6010, 2.7 g/cc (10–100 GHz) (nominal ε_r = 10.2–10.8, tanδ = .0023, Rogers Corp. data sheet 1.6000)							
	1.4903–2.85E-002j	2.2234–1.27E-002j	0.1901+2.1E-003j	0.9597+4.31E-002j	1.91E-002–2E-004j	−2E-004–1.99E-002j	−6.74E-004+1.21E-006j
PTFE-glass fiber 6002 (10–100 GHz)							
	0.7404+6E-004j	0.7415+6E-004j	2.12E-002+2E-004j	0.7434+3E-004j	2E-003	−1E-004+4.1E-003j	5.58E-005+1.09E-006j
S-Glass- Epoxy7781 (18–60 GHz)							
	1.0287+0.698j	1.0708+0.5054j	8.11E-002–0.147j	1.3393+1.0644j	8.64E-002+8.84E-002j	−5.17E-002–3.5E-002j	−1.5E-003+7E-004j

E-glass bismaleimide BMI 7781-5250-247, 50% fiber/volume (30–100 GHz)							
	1.1699+ 2.2E-003j	1.169+ 2.3E-003j	1.56E-002+ 6E-004j	1.2184+ 2E-004j	−1.9E-003− 8E-004j	3.7E-003j	1.84E-005+ 7.58E-007j
E-glass bismaleimide BMI 7781 F178, 39% polymer/wt., 45% fiber/volume							
	1.1429− 4E-003j	1.1429− 4E-003j	−2E-003+ 4.8E-003j	1.1443− 4.2E-003j	0	5E-004j	1.51E-005− 2.94E-006j
S-glass bismaleimide BMI F650, 1.8 g/cc (18–100 GHz)							
	1.0131− 1.2E-003j	1.0264− 2.4E-003j	0.1149+ 1.5E-003j	0.375+ 2.56E-002j	1.53E-002− 2.7E-003j	−6E-004− 1.15E-002j	−5.57E-004+ 8.39E-006j
S-glass bismaleimide BMI 7781-F655-2709, 50–54% fiber/volume (18–100 GHz)							
	1.0425+ 2.59E-002j	1.0585+ 2.55E-002j	5.98E-002− 1.52E-002j	1.01+ 4.33E-002j	−1.4E-003− 1E-004j	−1.3E-003j	−6.17E-005+ 1.58E-005j
S-glass 7781, 63% fiber/volume (30–100 GHz)							
	1.0473+ 2.9E-003j	1.0483+ 2.8E-003j	1.61E-002− 6.1E-003j	1.0467+ 3.7E-003j	8E-004	7E-004+ 1E-003j	1.26E-005− 7.10E-006j
E-glass cyanate ester fib 7781 (18–60 GHz)							
	1.1695− 7E-004j	1.1713− 6E-004j	−3.38E-002− 5E-004j	1.3056+ 6.2E-003j	2.4E-003− 3E-004j	3E-004+ 4.3E-003j	1.65E-004− 6.75E-006j

E-glass cyanate ester-581 (30–100 GHz)						
1.1348+4.2E-003j	1.1348+4.2E-003j	1.39E-002+2.9E-003j	1.1392+2.9E-003j	2E-004–6E-004j	−6E-004+2.4E-003j	1.89E-005+6.77E-006j
E-glass cyanate ester 7781 (26–100 GHz)						
1.2354–1E-004j	1.1244–3.1E-003j	6.41E-002+1.9E-003j	6.25E-002–5E-003j	1.55E-002–E-004j	7E-004–1.68E-002j	−3.86E-004–2.31E-005j
S-glass epoxy 7781, 35.4% polymer/wt., 47.5% fiber/volume						
1.0451–7.6E-003j	1.0575–6.5E-003j	5.79E-002+4E-004j	1.0354+2.29E-002j	−5E-004+3.1E-003j	6E-004+3.6E-003j	6.97E-007–7.80E-006j
E-glass polyester 7781, 34.1% polymer/wt., 49% fiber/volume (18–100 GHz)						
1.3041–7E-003j	1.4184–1.32E-002j	−0.1491+7.2E-003j	1.2589–8E-004j	3.2E-003–2E-004j	−3.7E-003j	−4.39E-005+4.60E-008j
S-Glass-2 (18–60 GHz) in polyether ether ketone (PEEK)						
0.8137+0.2848j	0.9236+0.1898j	0.1484–3.15E-002j	0.7541+0.6118j	−1.77E-002+0.112j	−4.28E-002–2.52E-002j	−1E-004+1.2E-003j
Para-aramid fiber, - epoxy F161 (18–100 GHz), 45% polymer/wt., 52% fiber/volume (nominal ε_r = 2.8–3.2 $\tan\delta$ = .027-.033, Le Reseau Composites Network)						
0.8647–2.59E-002j	0.8684–2.38E-002j	3.7E-002+1.94E-002j	0.8134–8.1E-003j	−1.5E-003–4E-004j	−1E-004–1.9E-003j	−5.33E-005–9.99E-006j

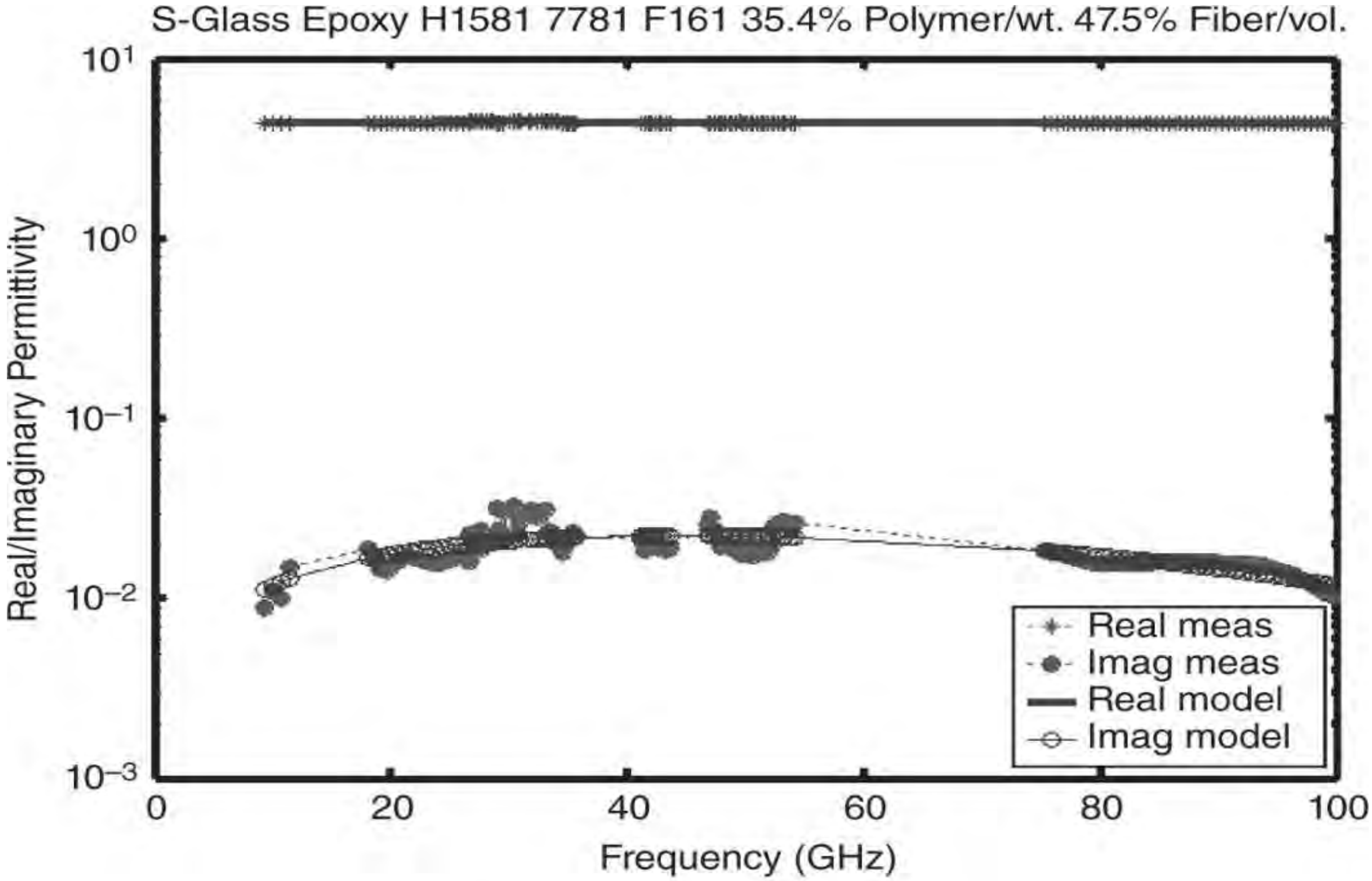
Para-aramid fiber polyester F148-2045, 59% polymer/wt., 38–39% fiber/volume (18–100 GHz)						
0.8937+1E-003j	0.9219−4E-004j	−8.98E-002+5E-004j	0.869+6.2E-003j	3E-003−6E-004j	1E-004−4.8E-003j	−5.83E-005−1.90E-006j
Quartz (10% chopped fiber) PTFE (18–100 GHz)						
0.5819−1E-003j	0.6209−1.2E-003j	0.1002+1.9E-003j	0.492+5.9E-003j	1.5E-003−3E-004j	−1.9E-003j	−2.91E-004−1.17E-005j
Quartz (20% chopped fiber) PTFE (20–100 GHz)						
0.619+9.2E-003j	0.6634+1.12E-002j	9.35E-002+4.32E-002j	0.5967−1.64E-002j	7.5E-003+1.15E-002j	−1.14E-002−8E-004j	2.56E-005+1.27E-004j
Quartz bismaleimide BMI, 1.72 g/cc (10–100 GHz)						
0.5785−5.7E-002j	0.6747−3.56E-002j	0.1212+2.07E-002j	1.7191+0.1308j	1.92E-002+1.1E-003j	−9E-004+1.97E-002j	1.73E-004−2.74E-005j
Quartz bismaleimide BMI 581, 1.68 g/cc (12–100 GHz) (nominal $\varepsilon_r = 3.2$, $\tan\delta = .0043$, Le Reseau Composites Network)						
0.7516	0.7821+1.3E-003j	8.68E-002+8E-004j	0.7091+2.1E-003j	−3.6E-003−4E-004j	−1E-004+3.1E-003j	−1.59E-004+4.87E-007j
Quartz bismaleimide BMI-581, 41% polymer/wt, 46% fiber/volume (10–100 GHz)						
0.9377−5.9E-003j	0.9427−6E-003j	−3.92E-002+8.9E-003j	0.9276−1.7E-003j	−2.2E-003+9E-004j	−4E-004+5E-004j	9.65E-006+5.25E-006j

Quartz bismaleimide BMI 581, 34% polymer/wt., 54–55% fiber/volume (18–100 GHz)	0.7361+ 5E-004j	0.7835+ 2.1E-003j	0.1141+ 8E-004j	0.6229+ 5E-004j	1.5E-003+ 1E-004j	3E-004– 6E–003j	−2.69E-004– 2.06E-006j
Quartz bismaleimide BMI 581 (26–100 GHz)	0.8373+ 1.5E-003j	0.8373+ 1.5E-003j	2E-003– 1E-004j	0.8373+ 1.5E-003j	0	−7E-004j	−2.69E-004– 2.06E-006j
Quartz bismaleimide BMI 581 (26–100 GHz)	0.7557– 2.54E-002j	1.4083+ 5.6E-003j	−3.78E-002+ 2.9E-003j	8.7E-003– 1.9E-003j	7.8E-003+ 1.3E-003j	1E-004– 1.07E-002j	−1E-004
Quartz cyanate ester 581 (26–100 GHz)	0.694+ 2E-003j	0.7048+ 2E-003j	5.9E-002– 6E-004j	0.6773+ 2.5E-003j	1.3E-003	−1E-004– 2.4E-003j	−6.48E-005+ 1.12E-006j
Quartz cyanate ester 581 (30–100 GHz)	0.8273– 6E-004j	0.8273– 6E-004j	−2.5E-003	0.8273– 6E-004j	−1E-004– 3E-004j	2E-004– 1E–004j	9.7635E-007– 4.42E-006j

Quartz epoxy F161, 30.7% polymer/wt., 56.6% fiber/volume (10–100 GHz)						
0.4275+0.1019j	0.5822+5.56E-002j	0.1709−4.18E-002j	2.1098−0.2026j	3.05E-002+2.3E-003j	1.8E-003+2.67E-002j	2.18E-004+1.72E-004j
Quartz epoxy B 5815575, 1.64 g/cc (10–100 GHz)						
0.8579+2.7E-003j	0.8787+2.9E-003j	−7.2E-002−1.9E-003j	0.832+2.6E-003j	1.5E-003−1E-004j	1E-004−3.5E−003j	−4.33E-005−8.76E-007j
Quartz epoxy 581-8625 (18–60 GHz)						
1.1004+0.6744j	1.1894+0.5776j	−5.23E-002−0.1633j	0.7283+0.3971j	9.49E-002+8.32E-002j	−4.45E-002−5.25E-002j	−1.9E-003+7E-004j
Quartz polybutadiene 581 (20–100 GHz)						
0.6775−6.61E-002j	0.6851−2.74E-002j	9.12E-002+8.65E-002j	0.533−0.1782j	2.7E-003+6.9E-003j	−5.7E-003−3.5E-003j	−2.52E-005+6.7E-005j
Quartz polyester 581-F148-2705, 36%/wt. polymer, about 51.3% fiber/volume (10–100 GHz)						
0.9351+6.22E-002j	1.2932+3.05E-002j	−0.1241−3.15E-002j	0.533+7.39E-002j	4.5E-003+2E-004j	−1E-004−4.8E-003j	−5.36E-005+1.76E-006j
Quartz polyester F141–482104, 1.7 g/cc, 581 (26–100 GHz)						
0.1626+0.3806j	0.2892+6.32E-002j	0.3151−0.1254j	2.8966−0.6313j	8.3E-003−7E-003j	4.4E-003+2.06E-002j	3E-004+2E-004j
Quartz polyimide (18–100 GHz)						
0.1709−0.3138j	0.4335−0.2461j	0.2561+7.98E-002j	2.8297+0.5251j	2.77E-002−1.22E-002j	1.63E-002+1.67E-002j	2.98E-004−7.18E-006j
S-Glass epoxy 7781 (18–60 GHz)						
1.032+0.6465j	1.082+0.4818j	8.14E-002−0.1379j	1.3115+1.0102j	8.49E-002+8.77E-002j	−5.15E-002−3.28E-002j	−1.4E-003+7E-004j

$$\varepsilon(f)=B+Cf^{D}+Ef^{F}+G\{1-J*(f-H)^{2}-j2If\}^{-1}$$

B	C	D	E	F	G	H	I	J
Cyanate ester with carbon prepreg fiber (18–100 GHz)								
2.7563+0.3392j	3.9366+0.6446j	0.2443−0.2749j	3.8449+0.6528j	0.2756+0.1624j	−1.3375−0.3695j	−2.9E-002+7E-002j	4E-004−4.2E-002j	−4E-004+2E-004j


S-Glass Epoxy H1581 7781 F161 35.4% Polymer/wt. 47.5% Fiber/vol.
Real/Imaginary Permittivity
Frequency (GHz)
Real meas
Imag meas
Real model
Imag model

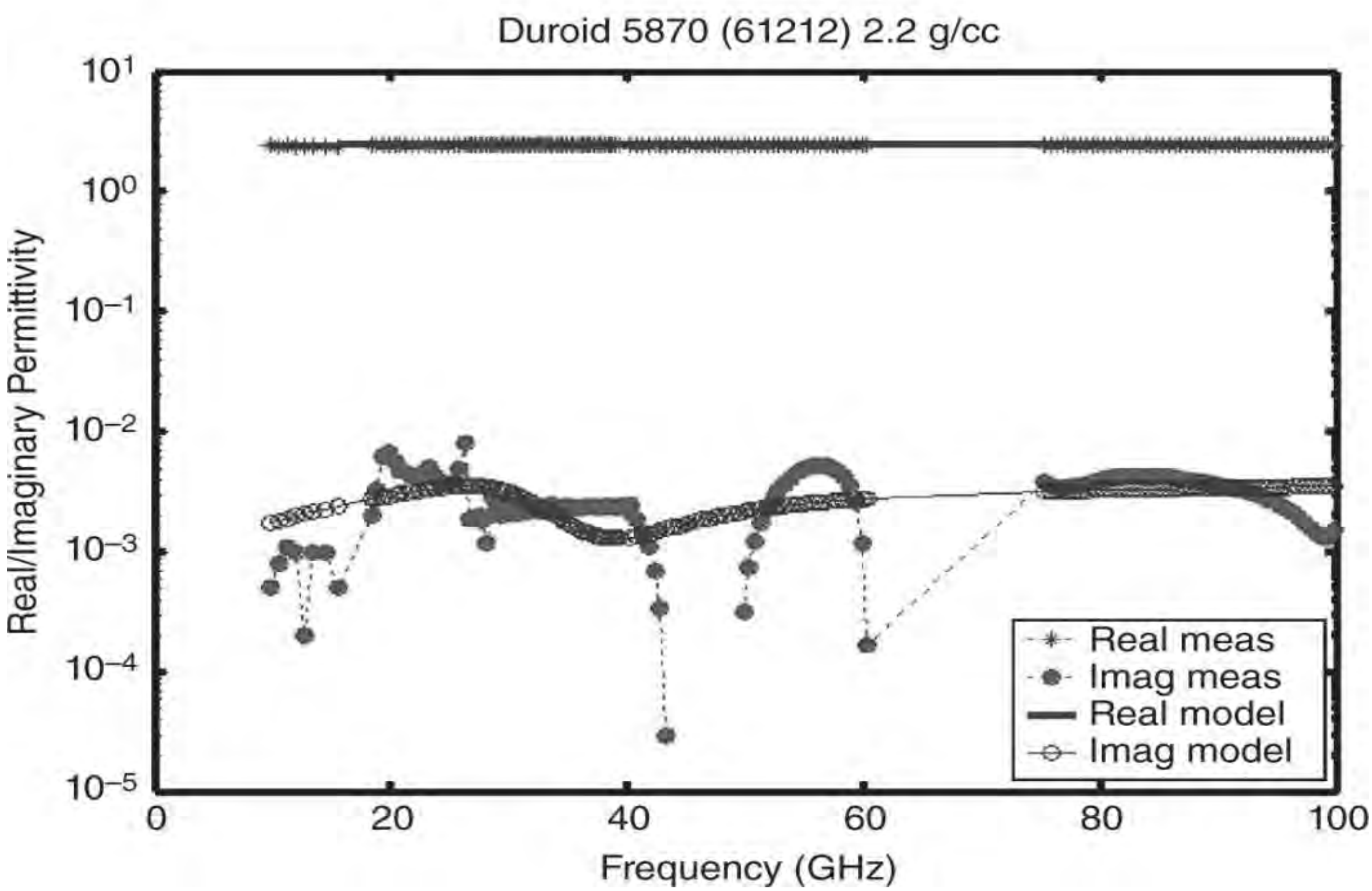

Duroid 5870 (61212) 2.2 g/cc
Real/Imaginary Permittivity
Frequency (GHz)
Real meas
Imag meas
Real model
Imag model

FIGURE 12.17 Example permittivity fits and measured data for a high loss (upper) and low loss (lower) composite.

Disclaimer: Data are results obtained by the author on samples prepared in the laboratory. Variations may be observed by other researchers when prepared in their laboratories. Data are not "guaranteed" by a manufacturer or the author. Variations in properties may be observed and users of the products should verify properties. All material properties are guides for engineering design. Materials prepared in the laboratory should be considered as experimental and also guides for engineering design.
