Métodos de Caracterización Dieléctrica

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Agenda

KEYSIGHT TECHNOLOGIES

Unlocking Measurement Insights for 75 Years

- **Introduction**
- **Permittivity and permeability**
- **Measurement techniques and systems**
- **Parallel plate**
- **Coaxial probe**
- **Transmission line**
- **Free space**
- **Resonant cavity**

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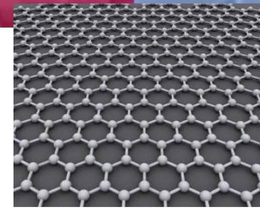
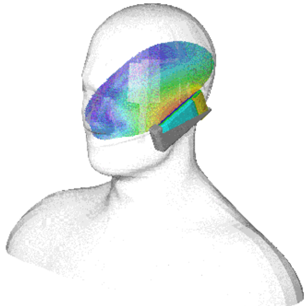
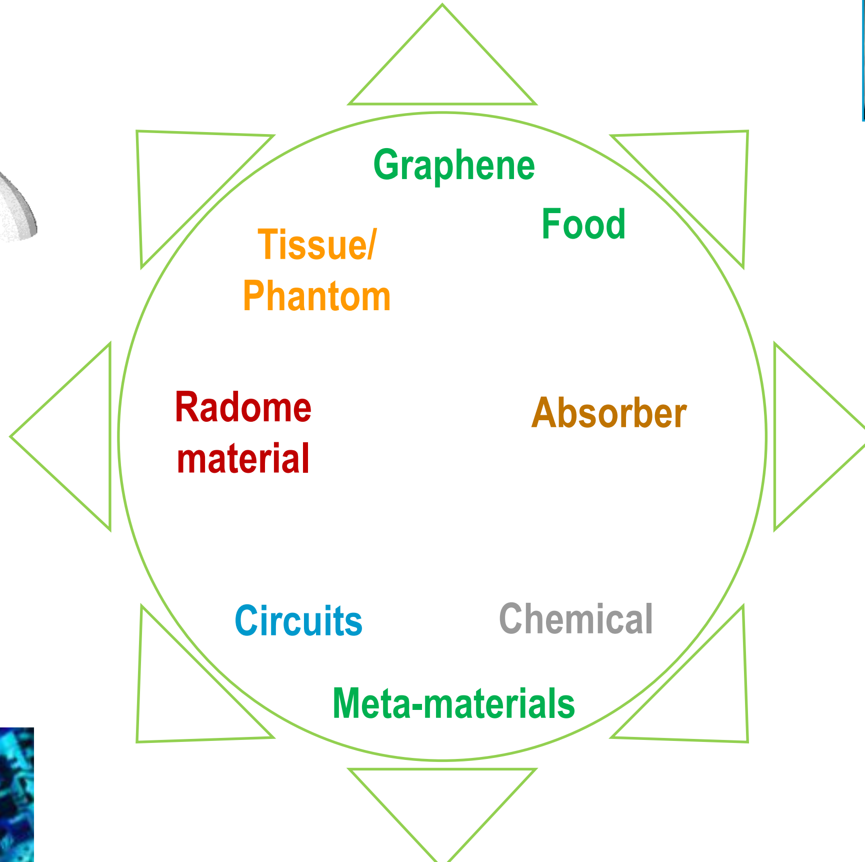
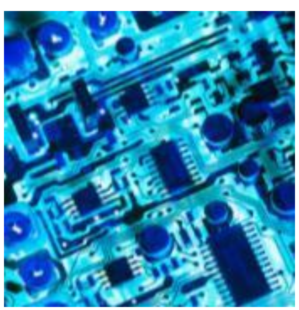
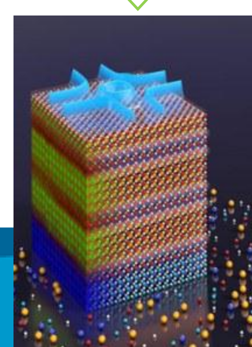
Type of material



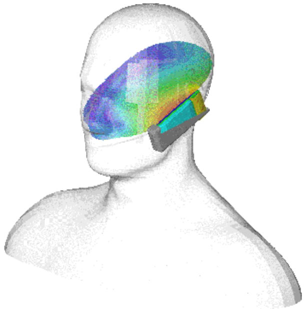


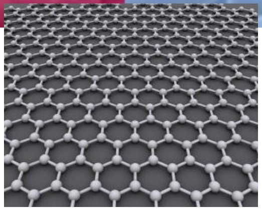




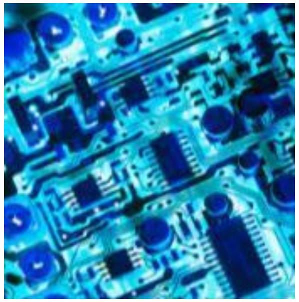


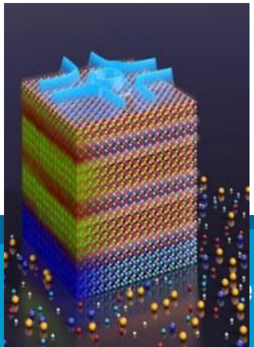
Type of material





Industry	Application/Products
Electronics	Capacitors, substrates, PCB antennas, ferrites, absorbers, SAR phantom materials
Aerospace/ Defense	Stealth, RAM (radiation absorbing materials),radomes
Industrial/ Materials	Ceramics & composites: A/D and automotive components, coatings Polymers & plastics: Fibers, films, Insulation materials Hydrogel: Disposable diaper, soft contact lens Liquid crystal: Displays Other products containing these materials: Tires, paint, adhesives, etc.
Food & Agriculture	Food preservation (spoilage) research, food development for microwave, packaging, moisture measurements
Mining	Moisture measurements in wood or paper, oil content analysis
Pharmaceutical & Medical	Drug research and manufacturing, bio-implants, human tissue characterization, biomass, fermentation





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Permitivity …

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Permittivity (Dielectric Constant)

$$\kappa = \frac{\varepsilon}{\varepsilon_0} = \varepsilon_r = \varepsilon_r^{'} - j\varepsilon_r^{''}$$

interaction of a material in the presence of an external electric field.

Permitivity and Permeability

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Permittivity (Dielectric Constant)

$$\kappa = \frac{\varepsilon}{\varepsilon_0} = \varepsilon_r = \varepsilon_r^{'} - j\varepsilon_r^{''}$$

interaction of a material in the presence of an external electric field.

Permeability

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

interaction of a material in the presence of an external magnetic field.

Electromagnetic field interaction

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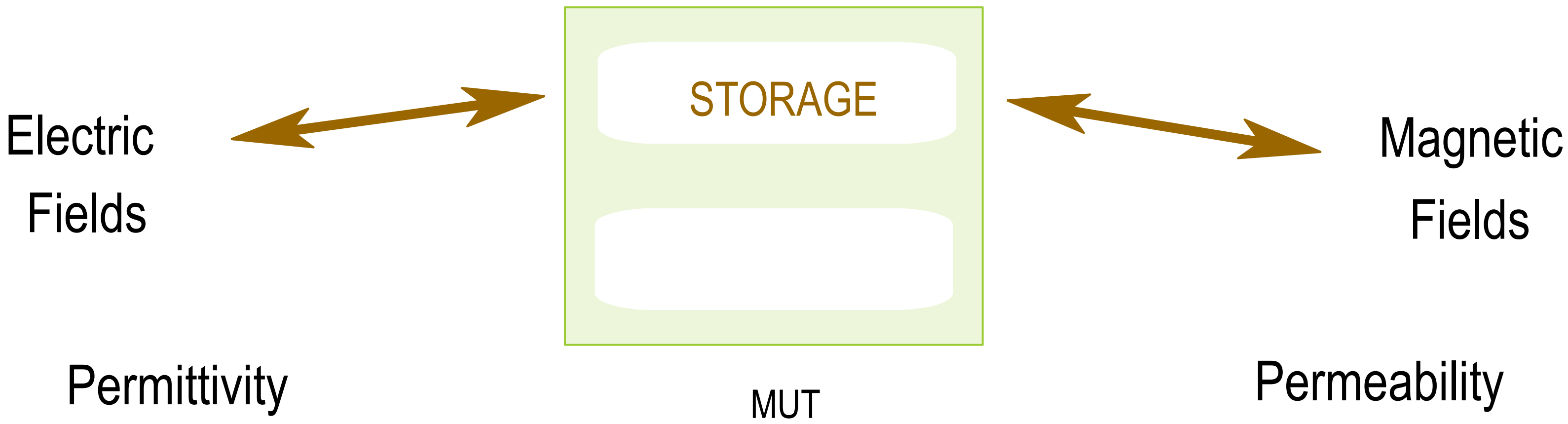

$$\varepsilon_r = \varepsilon_r^{'} - j\varepsilon_r^{''} \qquad \mu_r = \mu_r^{'} - j\mu_r^{''}$$

STORAGE

Electromagnetic field interaction

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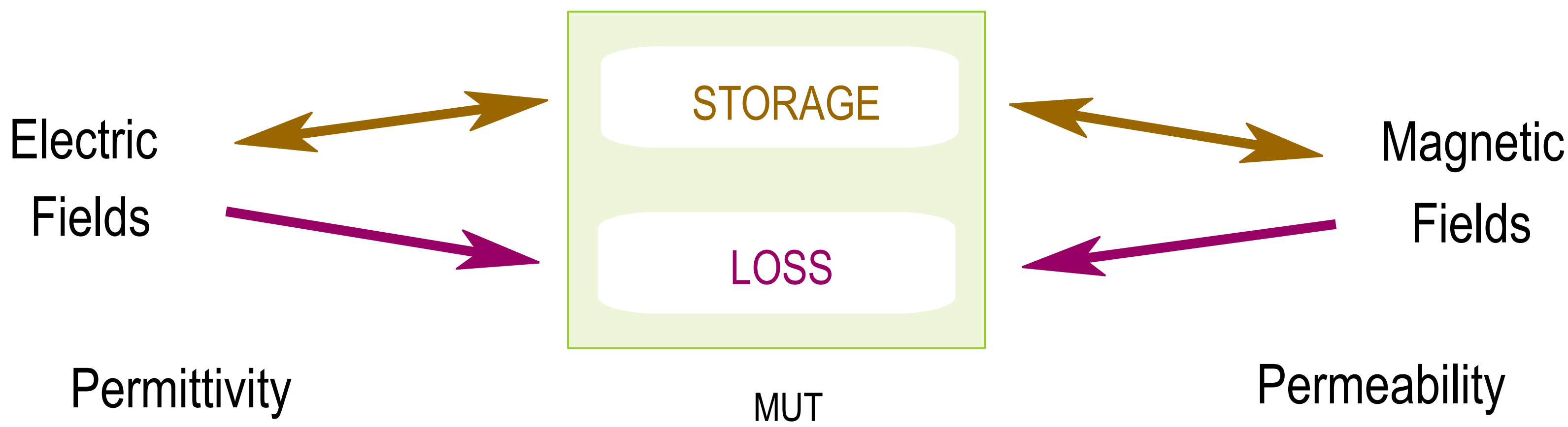

$$\varepsilon_r = \varepsilon_r^{'} - j\varepsilon_r^{''}$$

$$\mu_r = \mu_r^{'} - j\mu_r^{''}$$

STORAGE

LOSS

Loss tangent

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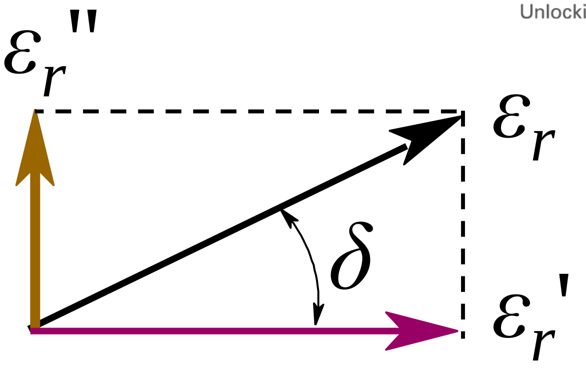
$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'}$$



$$\tan\delta = D = \frac{1}{Q} = \frac{Energy\ Lost\ per\ Cycle}{Energy\ Stored\ per\ Cycle}$$

D Dissipation Factor

Q Quality Factor

Df → D

Relaxation constant

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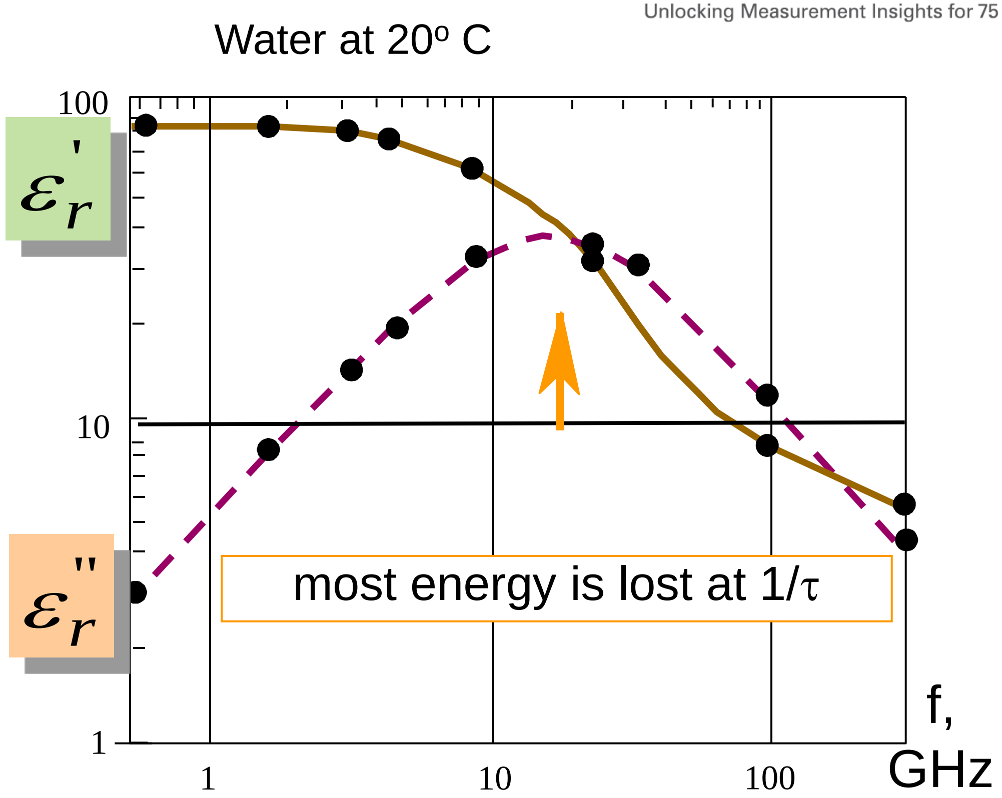
τ = Time required for 1/e of an aligned system to return to equilibrium or random state, in seconds.

$$\tau = \frac{1}{\omega_c} = \frac{1}{2\pi f_c}$$



$$\text{Debye equation:}\quad \varepsilon(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau}$$

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Material evaluation measurement system

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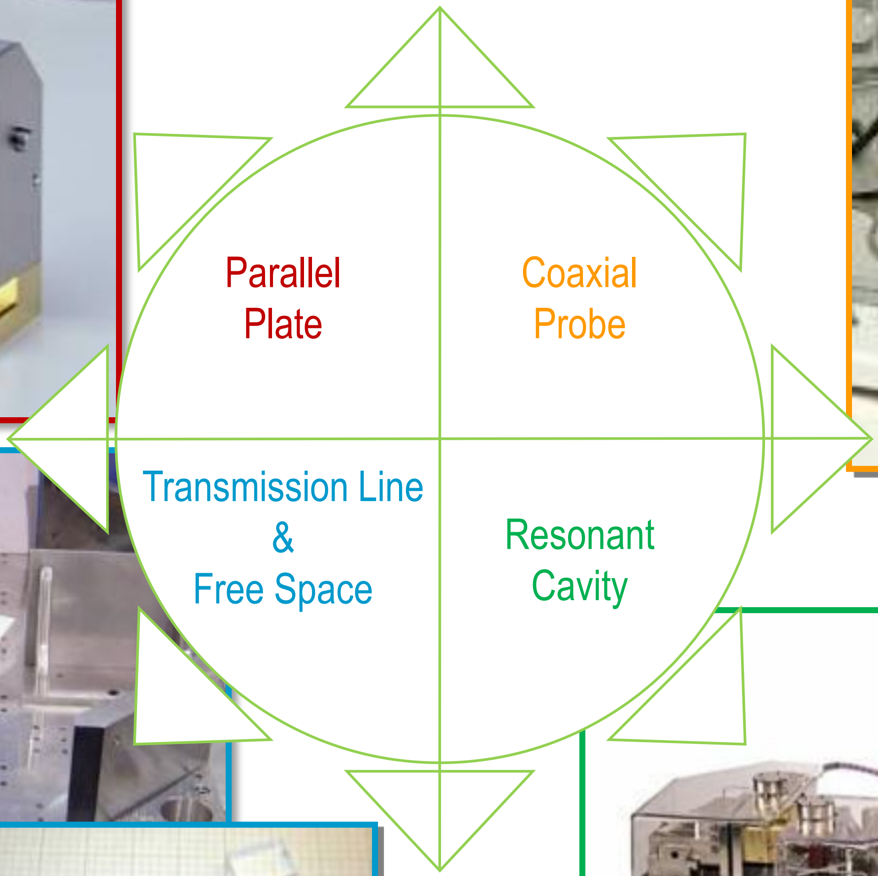
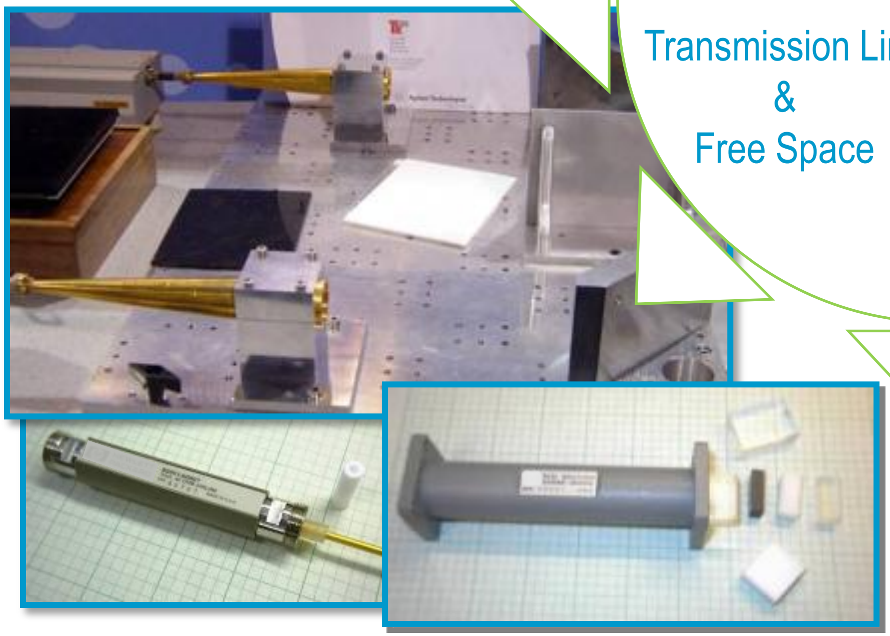
Composed by 3 main pieces:

- Precise measurement instruments
- Test fixtures that hold the MUT
- Software that can calculate & display basic material parameters

The measurement instrument and the test fixtures are determined by the **measurement technique** chosen.

Measurement techniques





Which method is best?

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It Depends…

Which method is best?

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It Depends… on

- ✓ Frequency of interest
- ✓ Expected value of ε_r and μ_r
- ✓ Required measurement accuracy

Which method is best?

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It Depends… on

- ✓ Frequency of interest
- ✓ Expected value of ε_r and μ_r
- ✓ Required measurement accuracy
- ✓ Material properties (i.e., homogeneous, isotropic)
- ✓ Form of material (i.e., liquid, powder, solid, sheet)
- ✓ Sample size restrictions

Which method is best?

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It Depends… on

- ✓ Frequency of interest
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- ✓ Material properties (i.e., homogeneous, isotropic)
- ✓ Form of material (i.e., liquid, powder, solid, sheet)
- ✓ Sample size restrictions
- ✓ Destructive or non-destructive
- ✓ Contacting or non-contacting
- ✓ Temperature

Measurement methods vs. frequency and material loss

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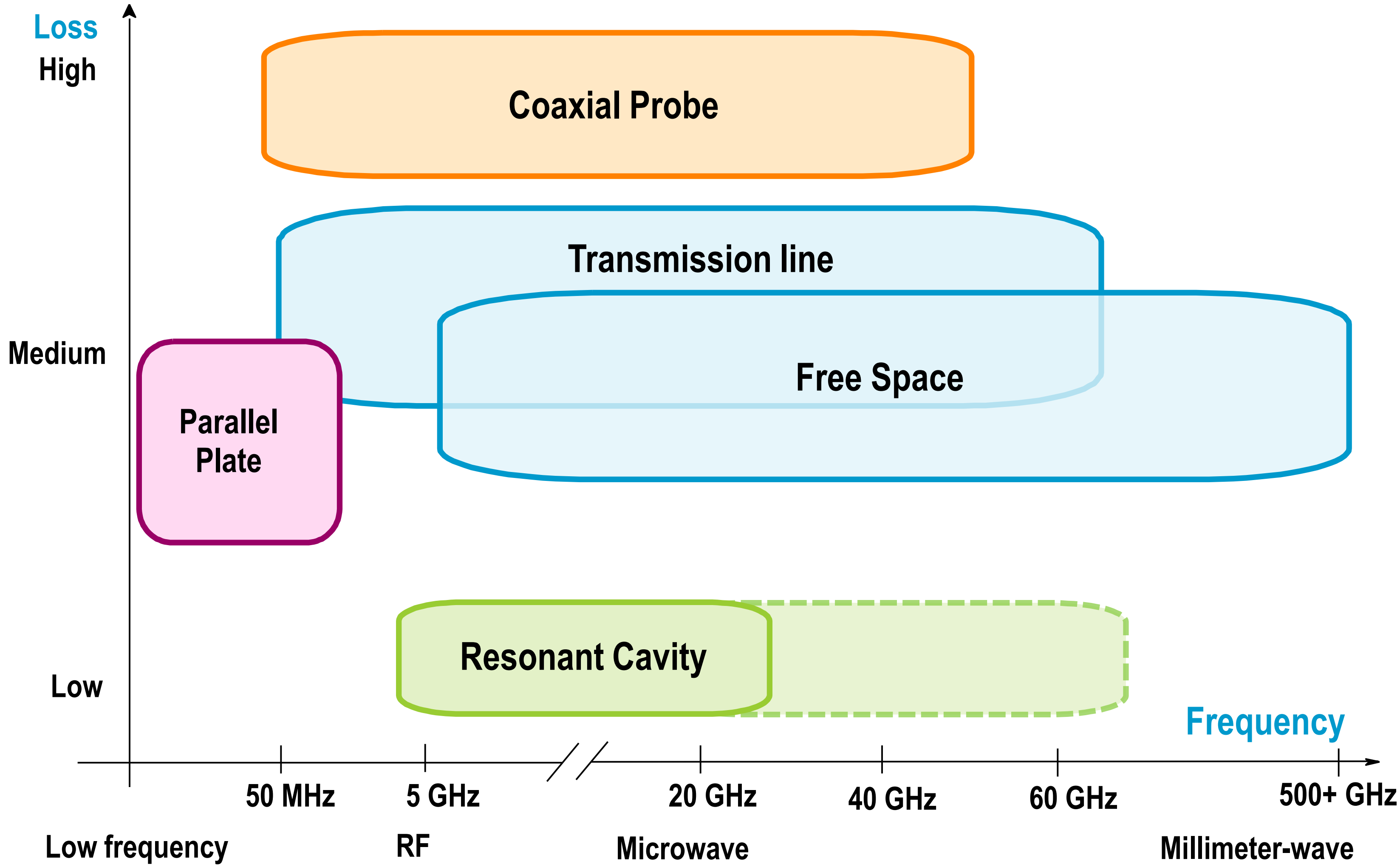

Measurement methods
vs. frequency and material loss

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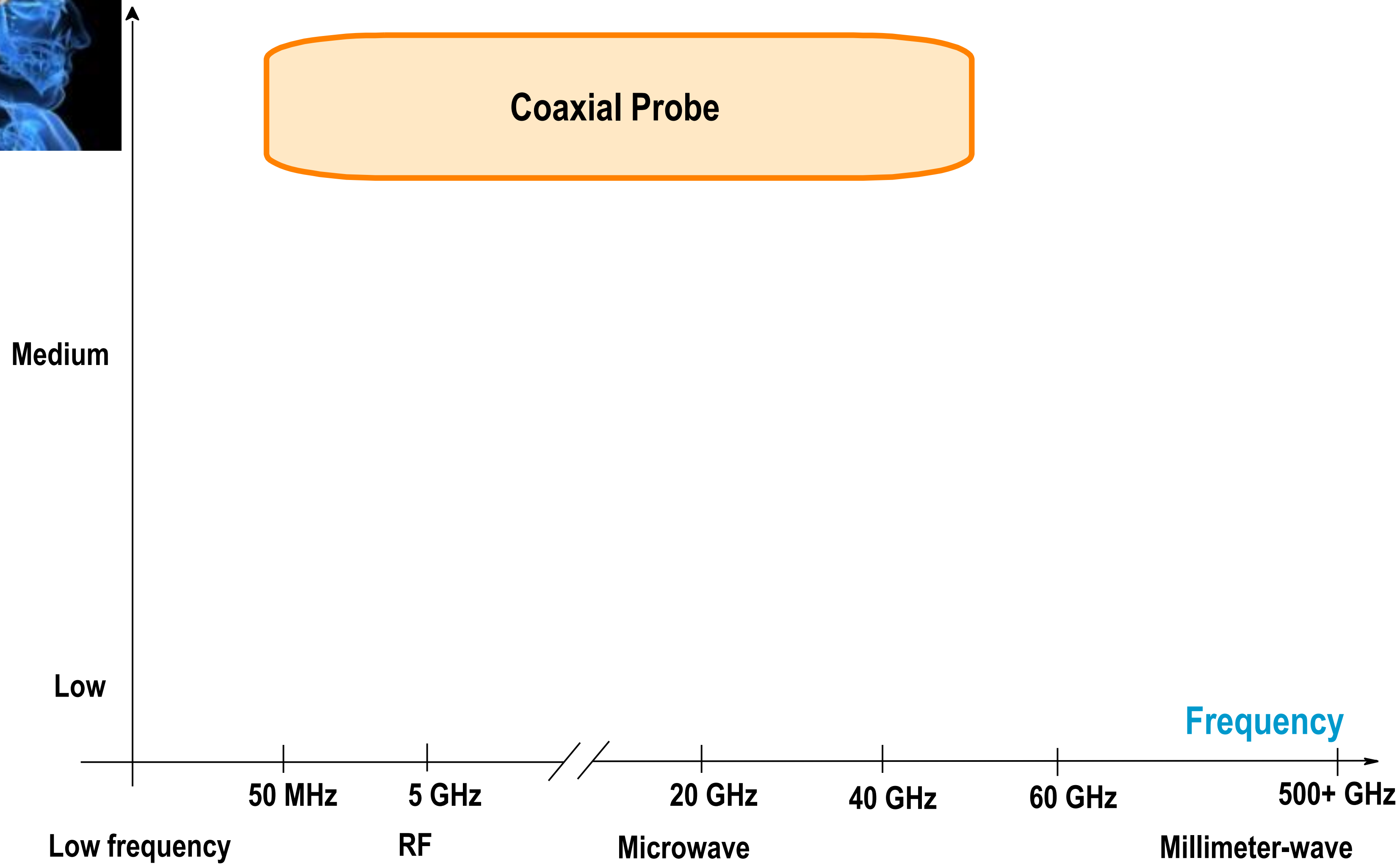
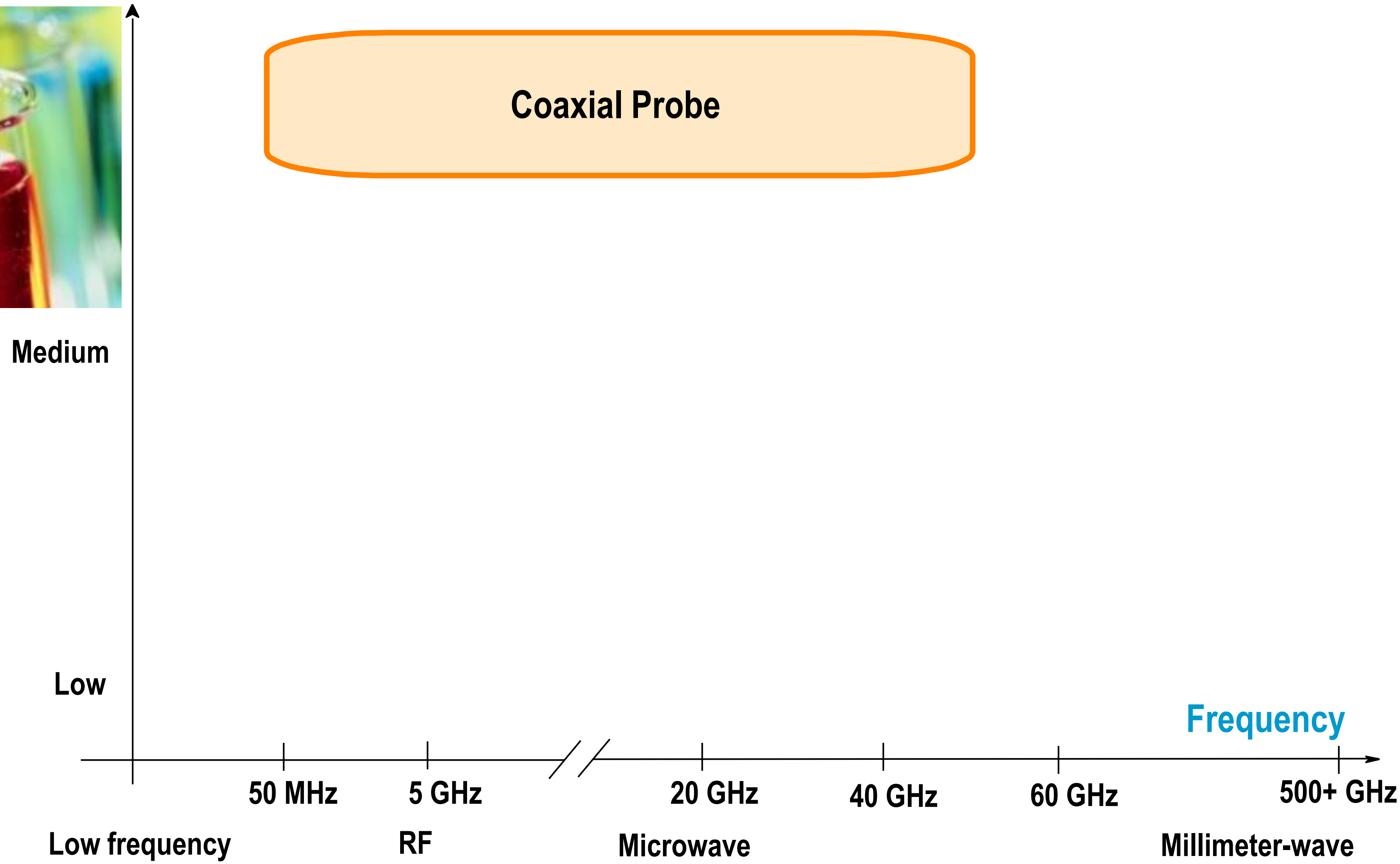
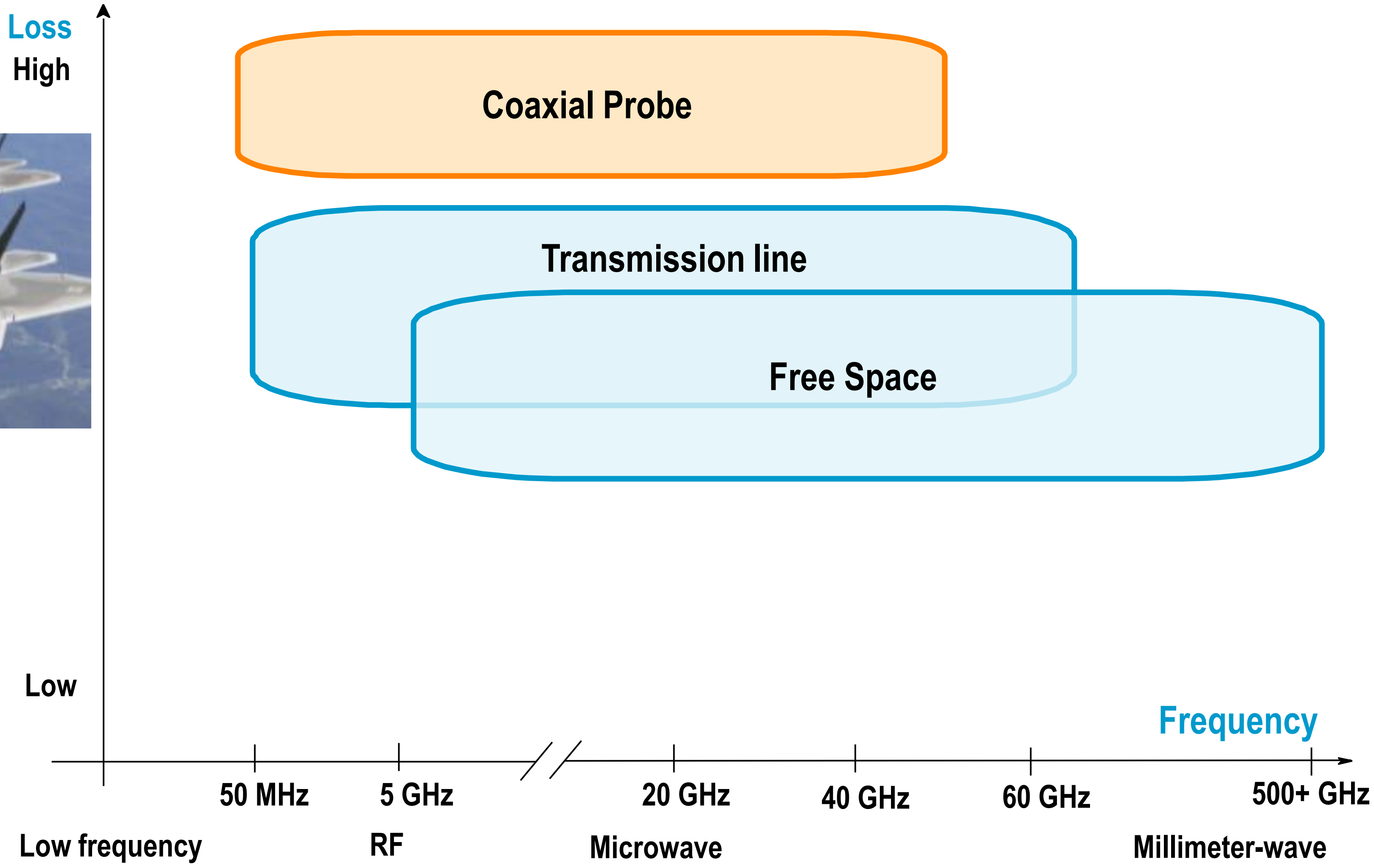


Measurement methods
vs. frequency and material loss



Measurement methods
vs. frequency and material loss



Measurement methods
vs. frequency and material loss

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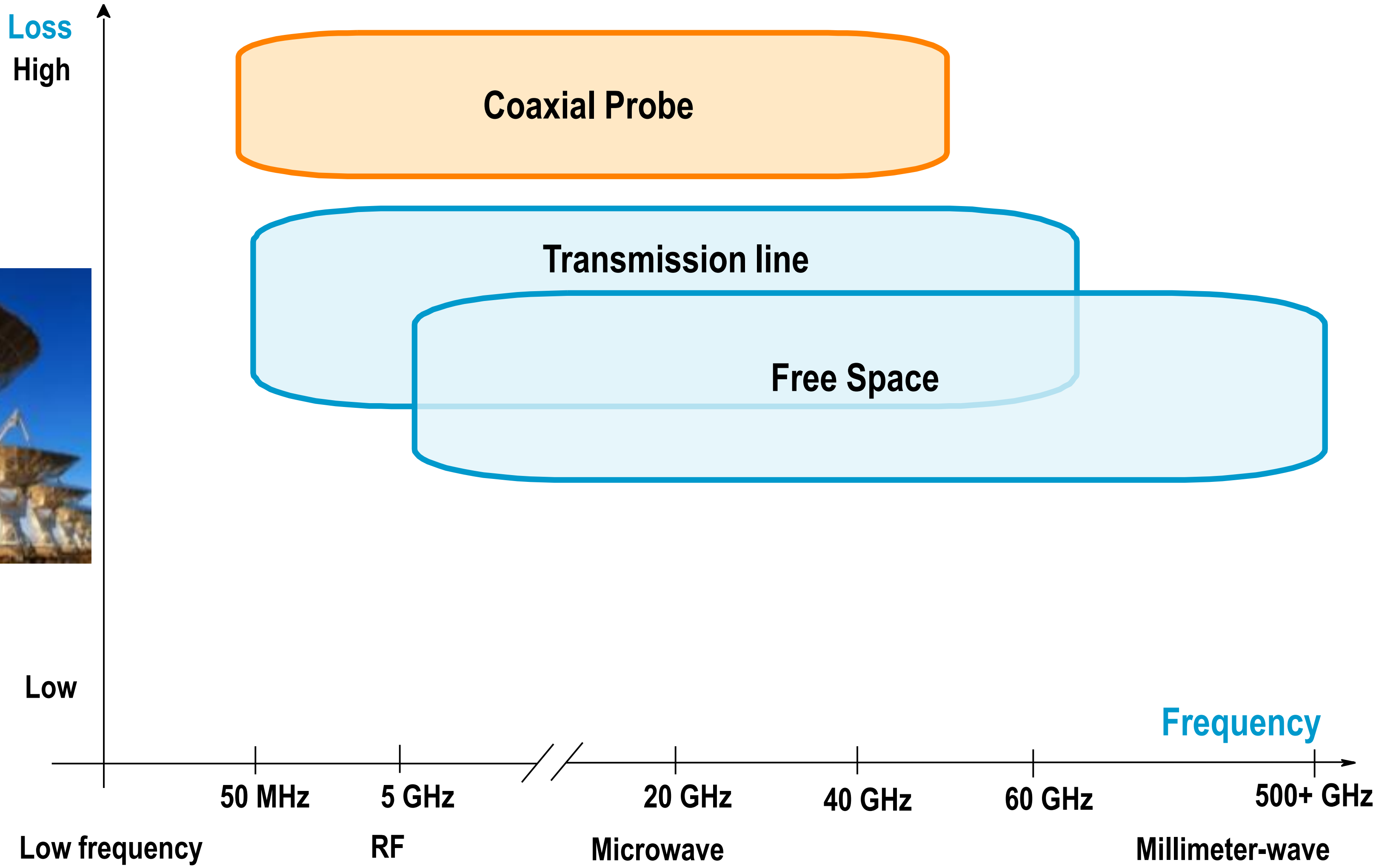

Measurement methods

vs. frequency and material loss

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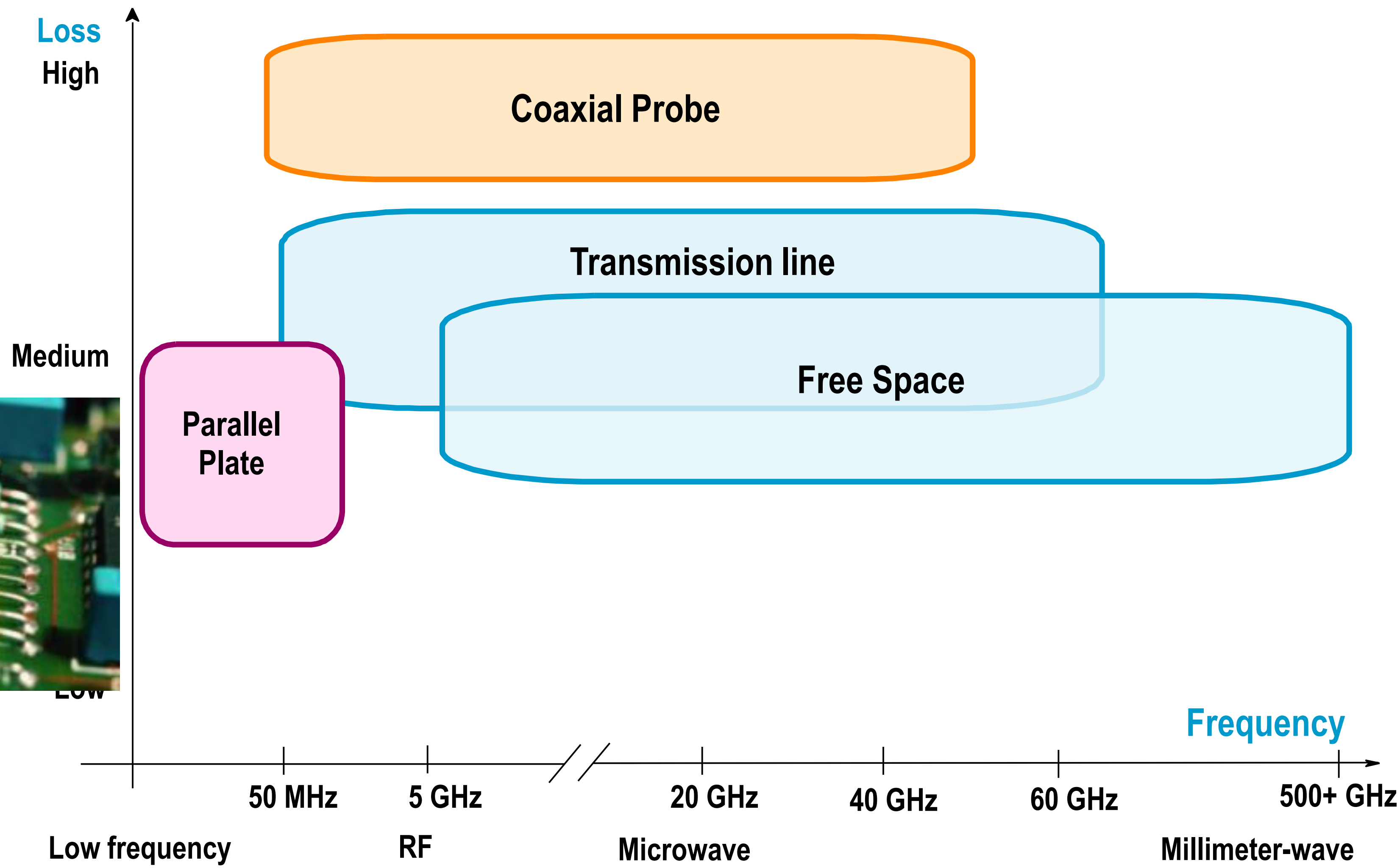

Measurement methods
vs. frequency and material loss

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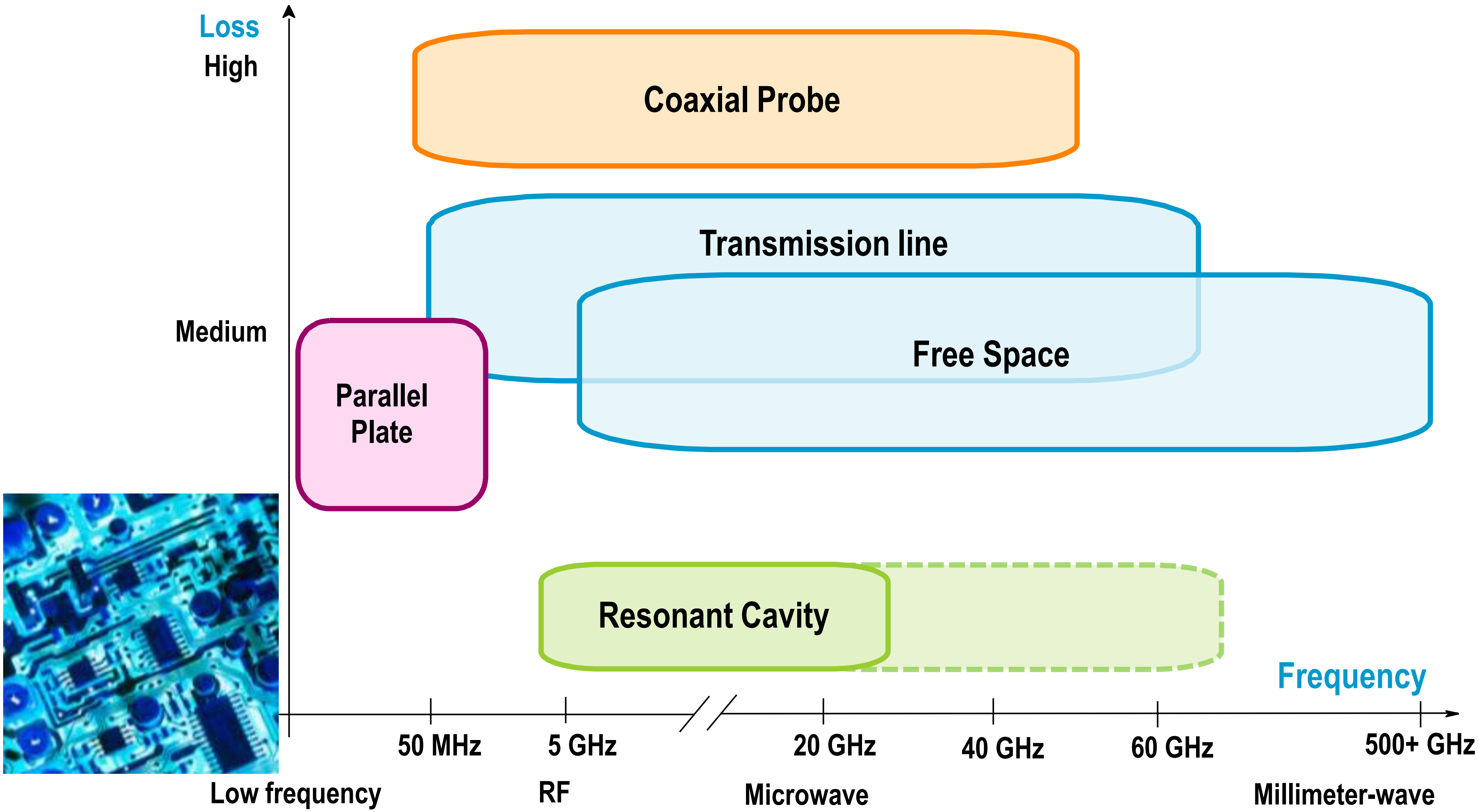

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Parallel plate capacitor system

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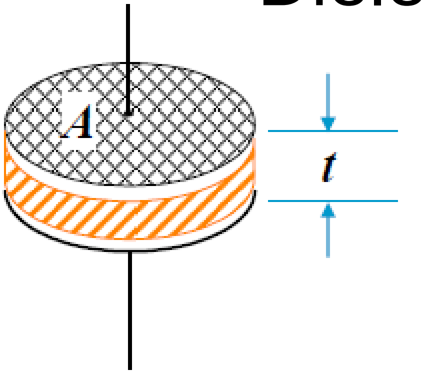
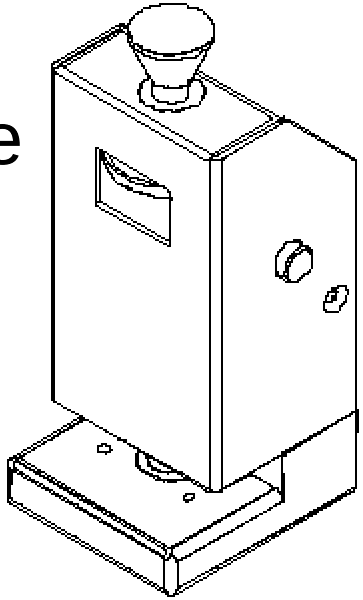
$$\varepsilon'_r = \frac{C}{\varepsilon_0 \frac{A}{t}}$$

$$\tan \delta = D$$

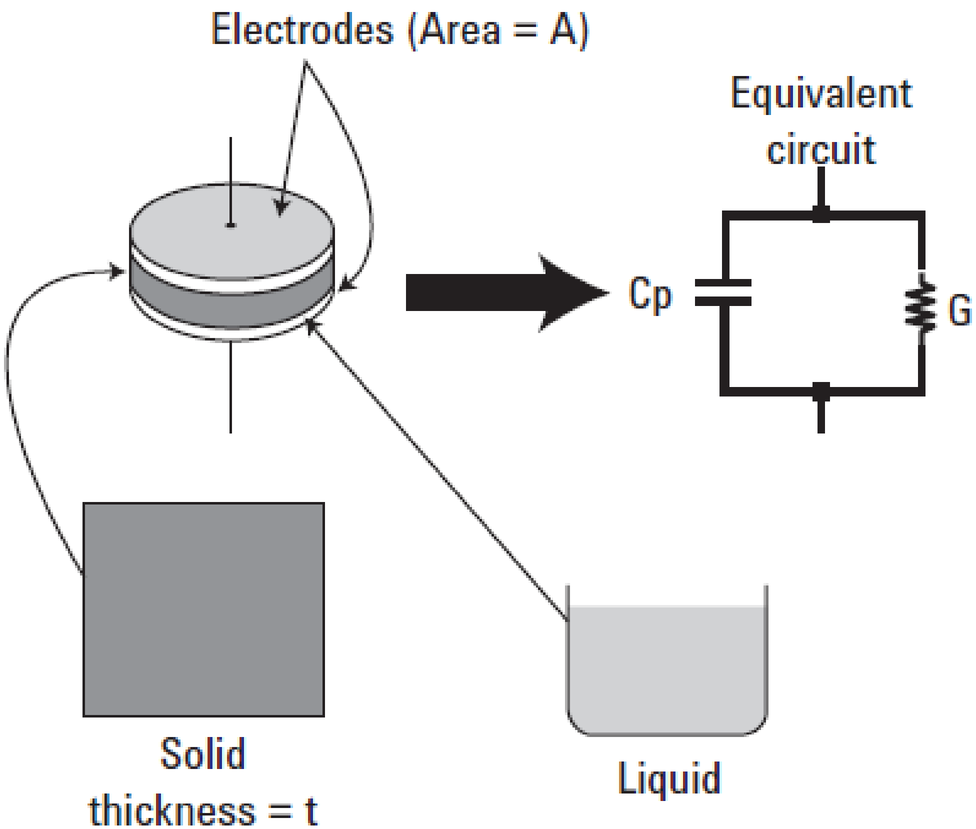
Dielectric Test Fixture



(magnetic fixture also available)



Parallel capacitor technique



$$Y = G + j\omega C_p$$

$$= j\omega C_o \left(\frac{C_p}{C_o} - j\frac{G}{\omega C_o} \right)$$

C_o : Air capacitance

$$\varepsilon_r^* = \left(\frac{C_p}{C_o} - j\frac{G}{\omega C_o} \right)$$

$$\varepsilon_r' = \left(\frac{t * C_p}{A * \varepsilon_o} \right)$$

$$\varepsilon_r'' = \left(\frac{t}{\omega * R_p * A * \varepsilon_o} \right)$$

Effect of guard electrode

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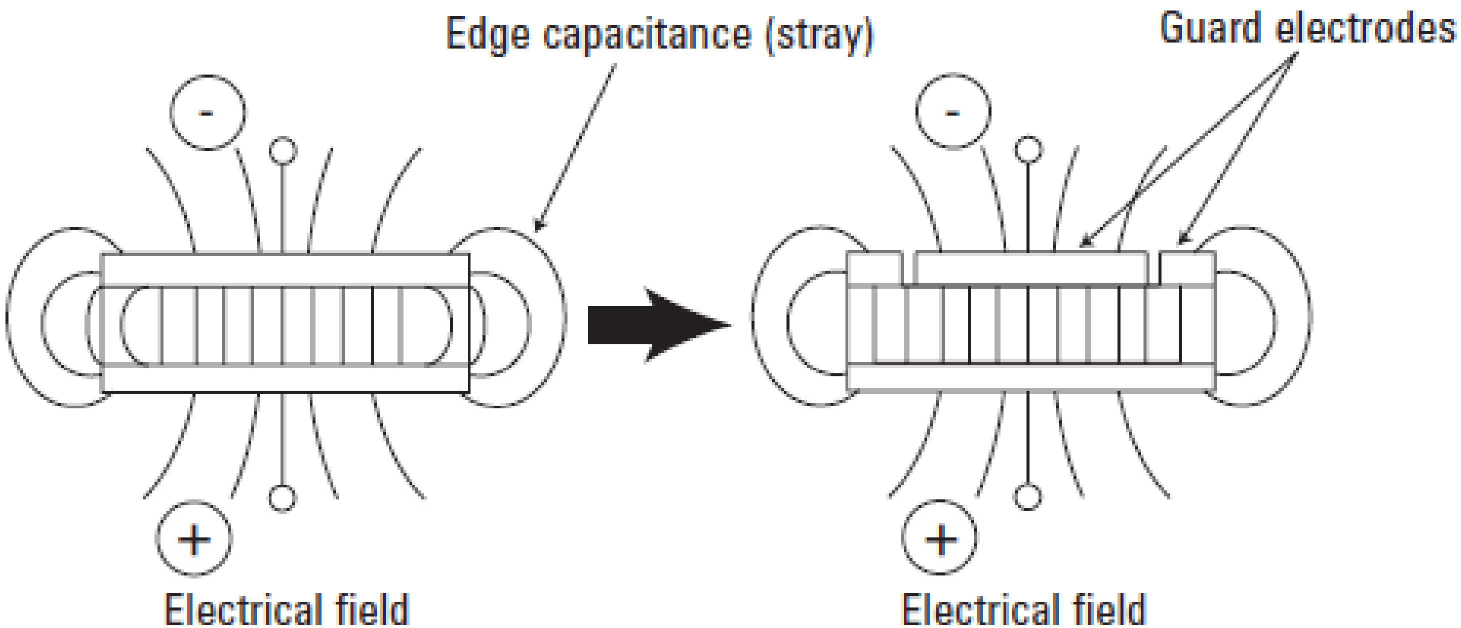

Contacting electrode method

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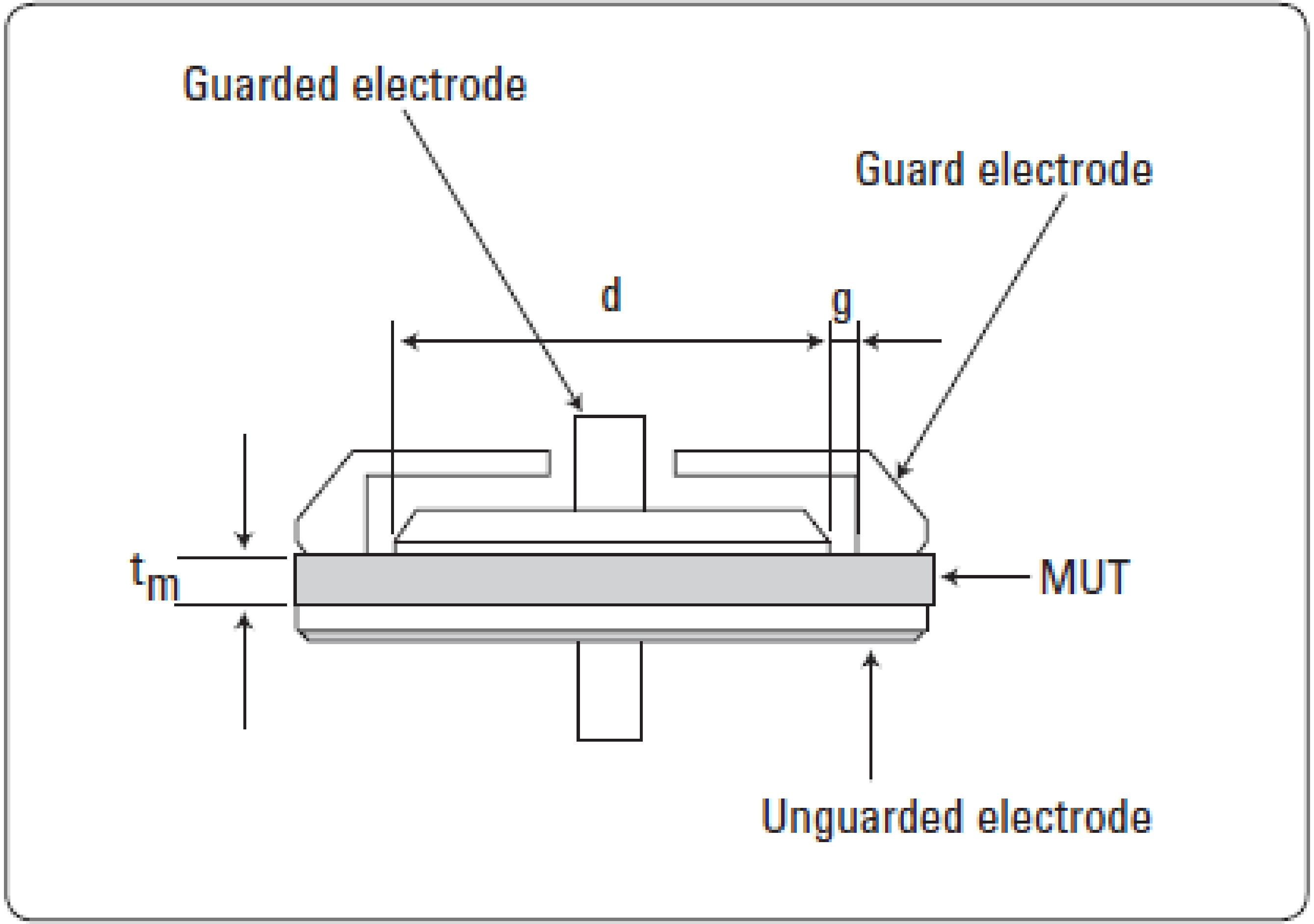
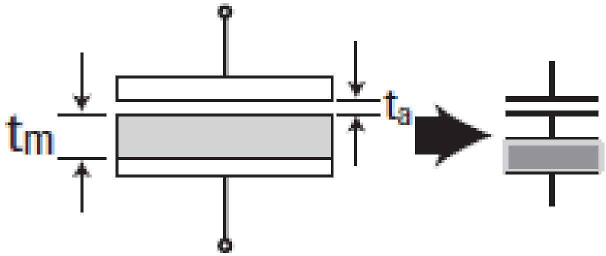


Air gap effects



$C_o = \varepsilon_o \frac{A}{t_a}$ Capacitance of airgap

$C_x = \varepsilon_x \varepsilon_o \frac{A}{t_m}$ Capacitance of dielectric material

Measured capacitance

$$C_{err} = \frac{1}{\frac{1}{C_o} + \frac{1}{C_x}} = \varepsilon_{err} \varepsilon_o \frac{A}{t_m + t_a}$$

Measured error due to airgap

$$1 - \frac{\varepsilon_{err}}{\varepsilon_x} = \frac{\varepsilon_x - 1}{\varepsilon_x + \frac{t_m}{t_a}}$$

Non-contacting electrode method

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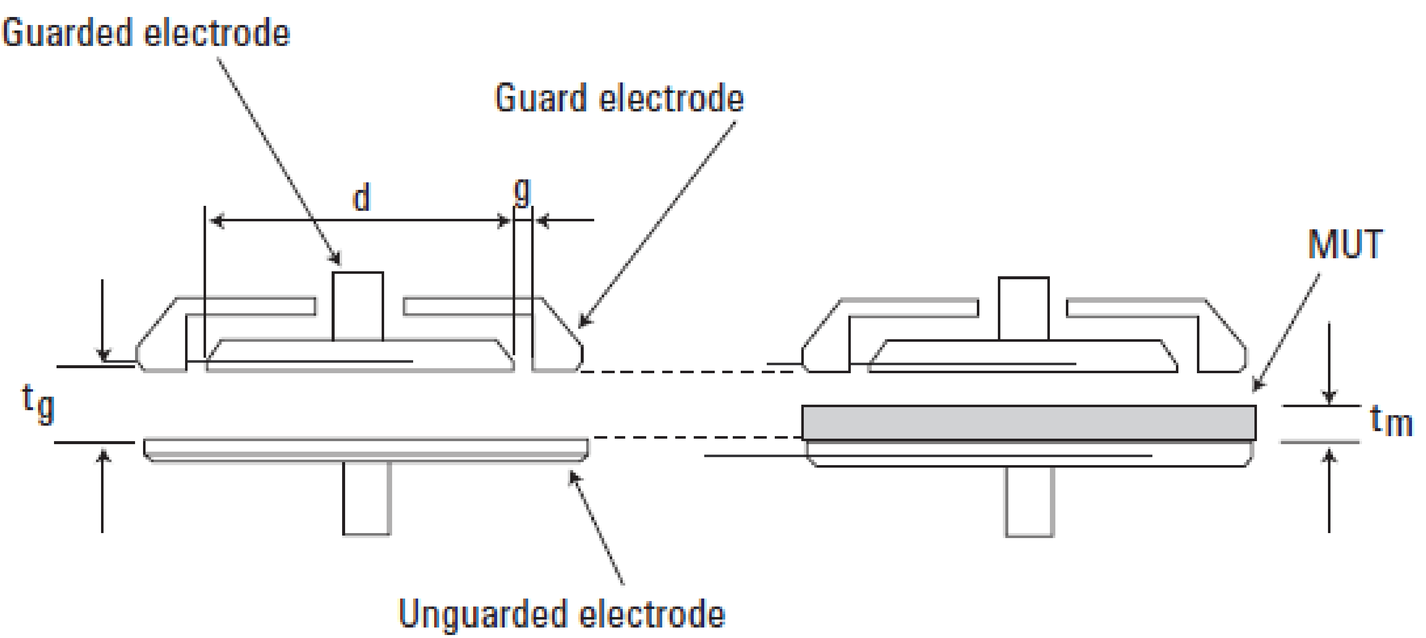

Parallel plate measurement methods comparison

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Method	Accuracy	Application MUT	Operation
Contacting electrode	LOW	Solid material with a flat and smooth surface	1 measurement
Non-Contacting electrode	MEDIUM	Solid material with a flat and smooth surface	2 measurements
Thin film electrode	HIGH	Thin film electrode must be applied onto surfaces	1 measurement

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Coaxial probe system

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Dielectric measurement setup for liquid using the coaxial probe method

Coaxial probe

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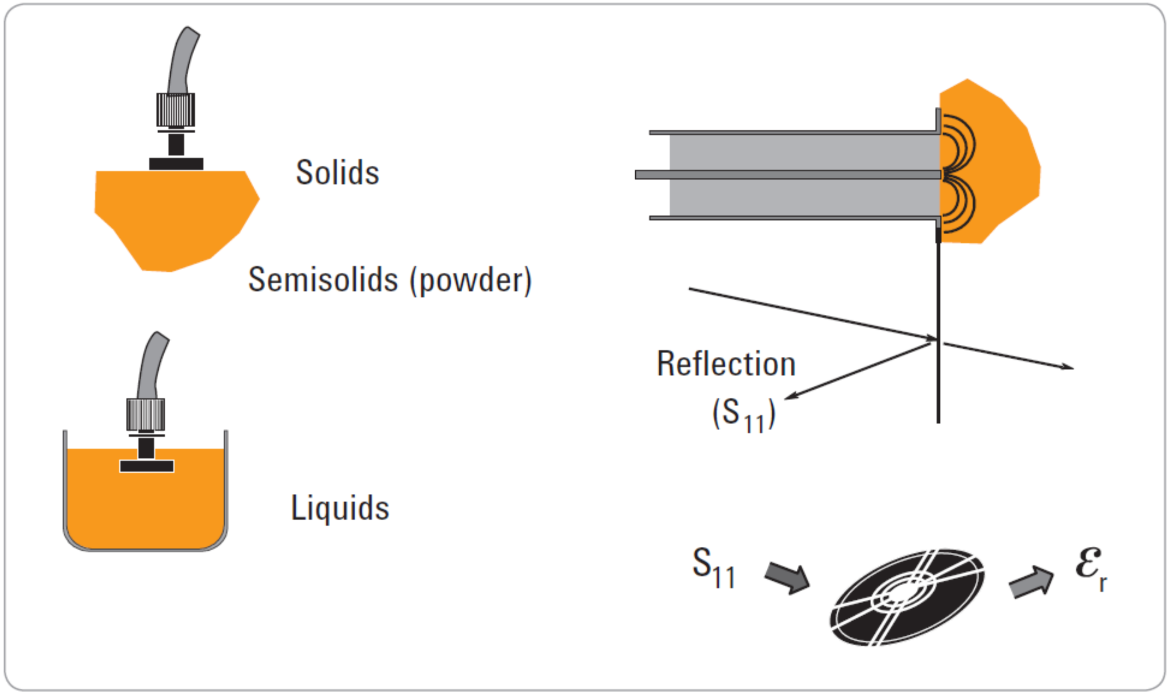

Technique features:

- Broadband
- Simple and convenient (non destructive)
- Limited ε_r accuracy
- Limited tan δ low loss resolution
- Best for liquids of semi-solids

Assumptions:

- Semi-infinite thickness
- Non-magnetic material
- Isotropic and homogeneous
- Flat surface
- No air gaps or bubbles

Three probe designs
1. High temperature probe

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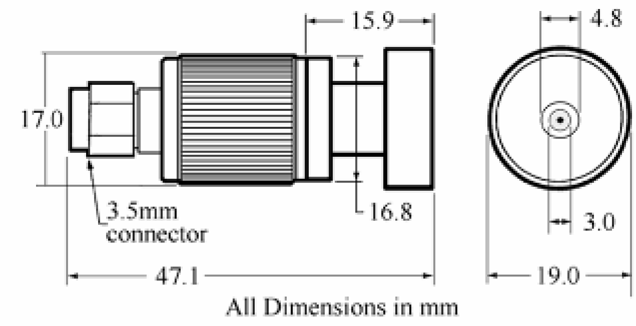

High Temperature Probe

- 0.200 – 20GHz (low end 0.01GHz with impedance analyzer)
- Withstands -40 to 200 degrees C
- Survives corrosive chemicals
- Flanged design allows measuring flat surfaced solids.

Three probe designs
2. Slim form probe

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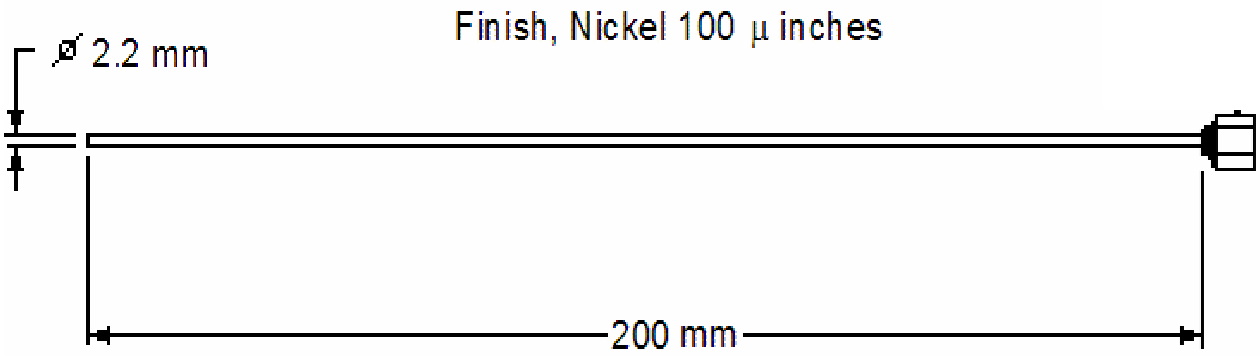

Slim Form Probe

- 0.500 – 50GHz
- Low cost consumable design
- Fits in tight spaces, smaller sample sizes
- For liquids and soft semi-solids only

Three probe designs
3. Performance probe

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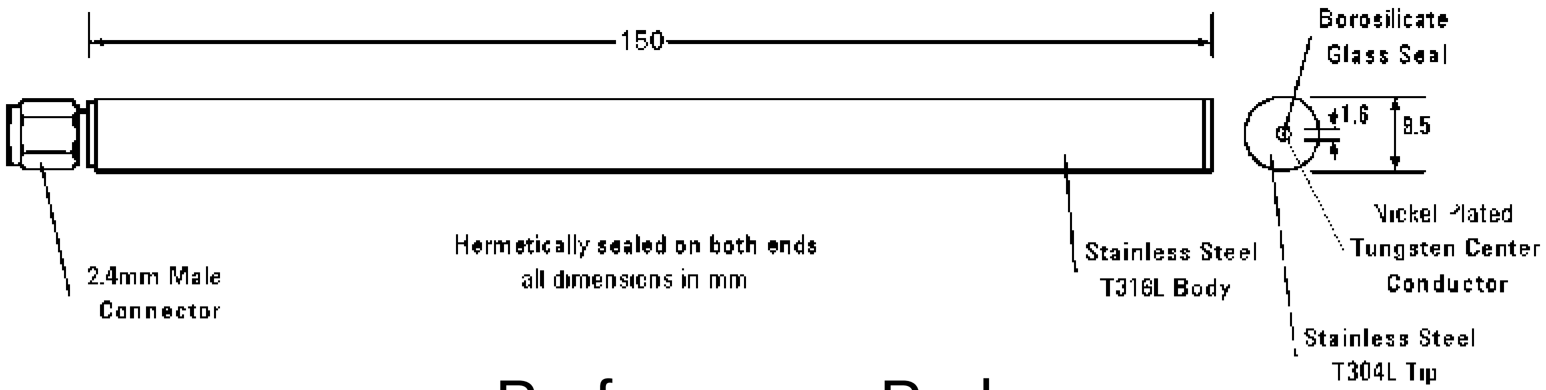

Performance Probe

Combines rugged high temperature performance with high frequency performance, all in one slim design.

•0.500 – 50GHz
•Withstands -40 to 200 degrees C
•Hermetically sealed on both ends, OK for autoclave
•Food grade stainless steel

Coaxial probe system

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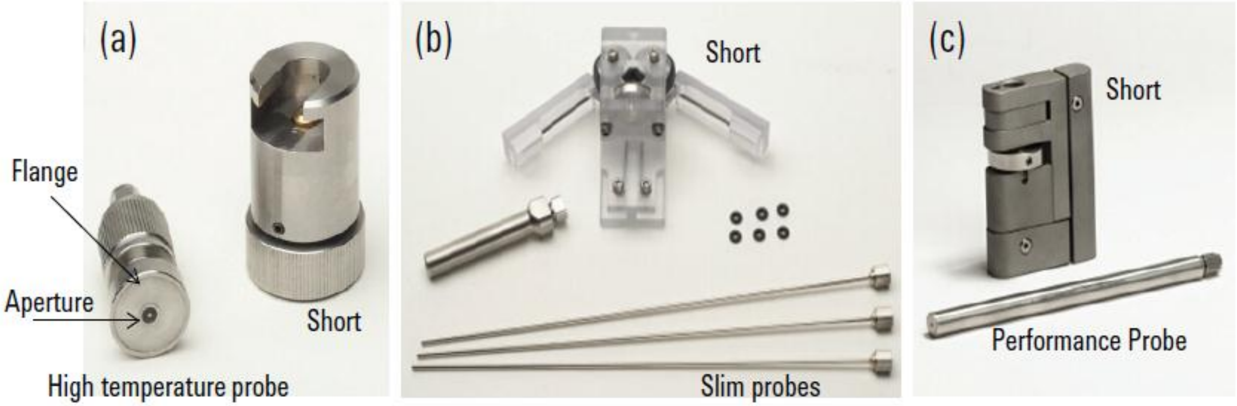
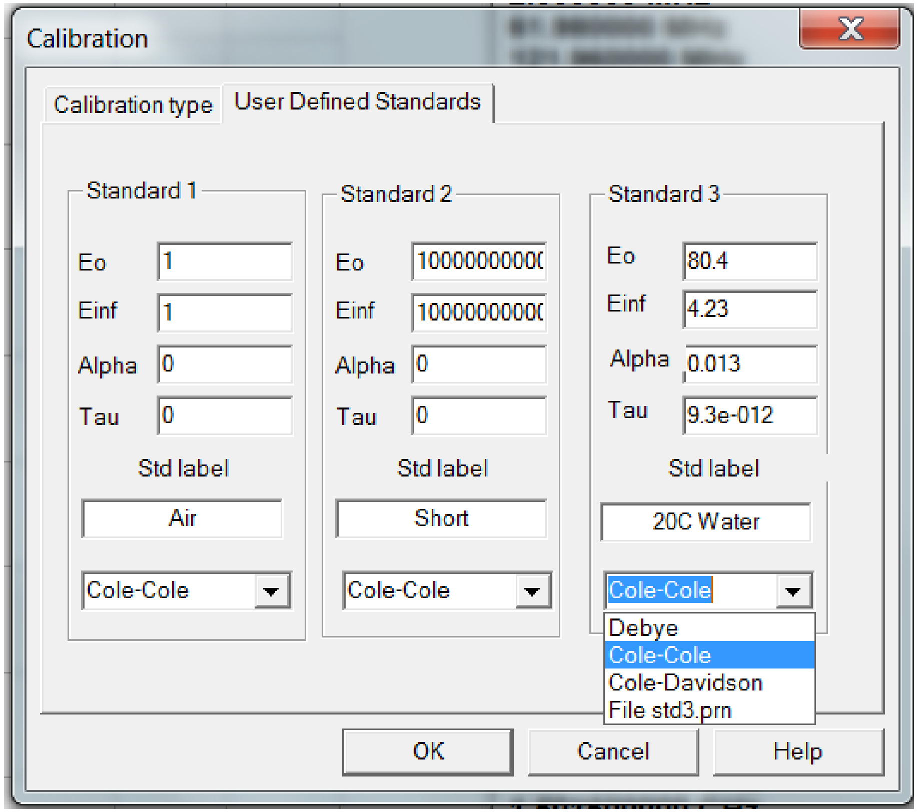
Calibration is required!!!



Coaxial probe system calibration



Three standards:
Air, Short, Water

Air, Short, Load

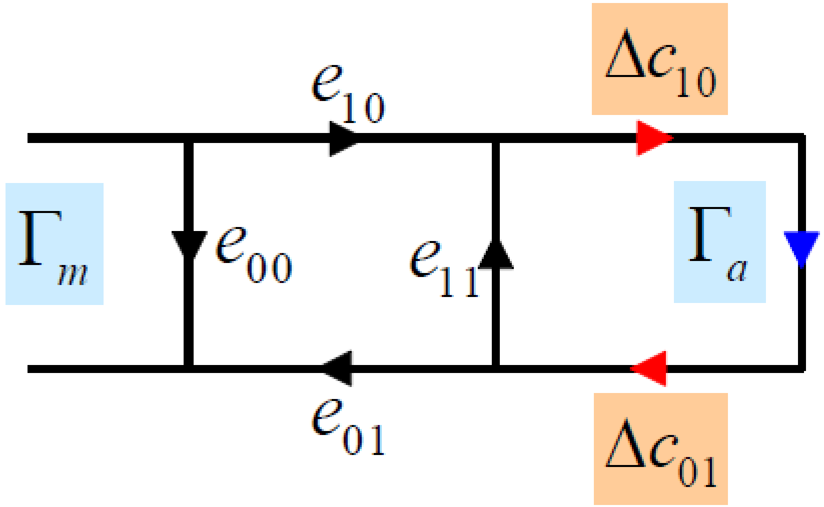
User Defined Debye Cole

Cole Cole-Davidson

Permittivity Data

Refresh calibration

If the perturbation is small, the change can be characterized by the measuring of a single calibration standard.



Γ_m = Measured S_{11}

Γ_a = Actual S_{11}

e_{00} = Directivity error

e_{11} = Source match error

$e_{10}\ e_{01}$ = Reflection tracking error

$\Delta c_{10}\ \Delta c_{01}$ = Perturbation term

Coaxial probe example data
The perfect martini

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Coaxial probe example data

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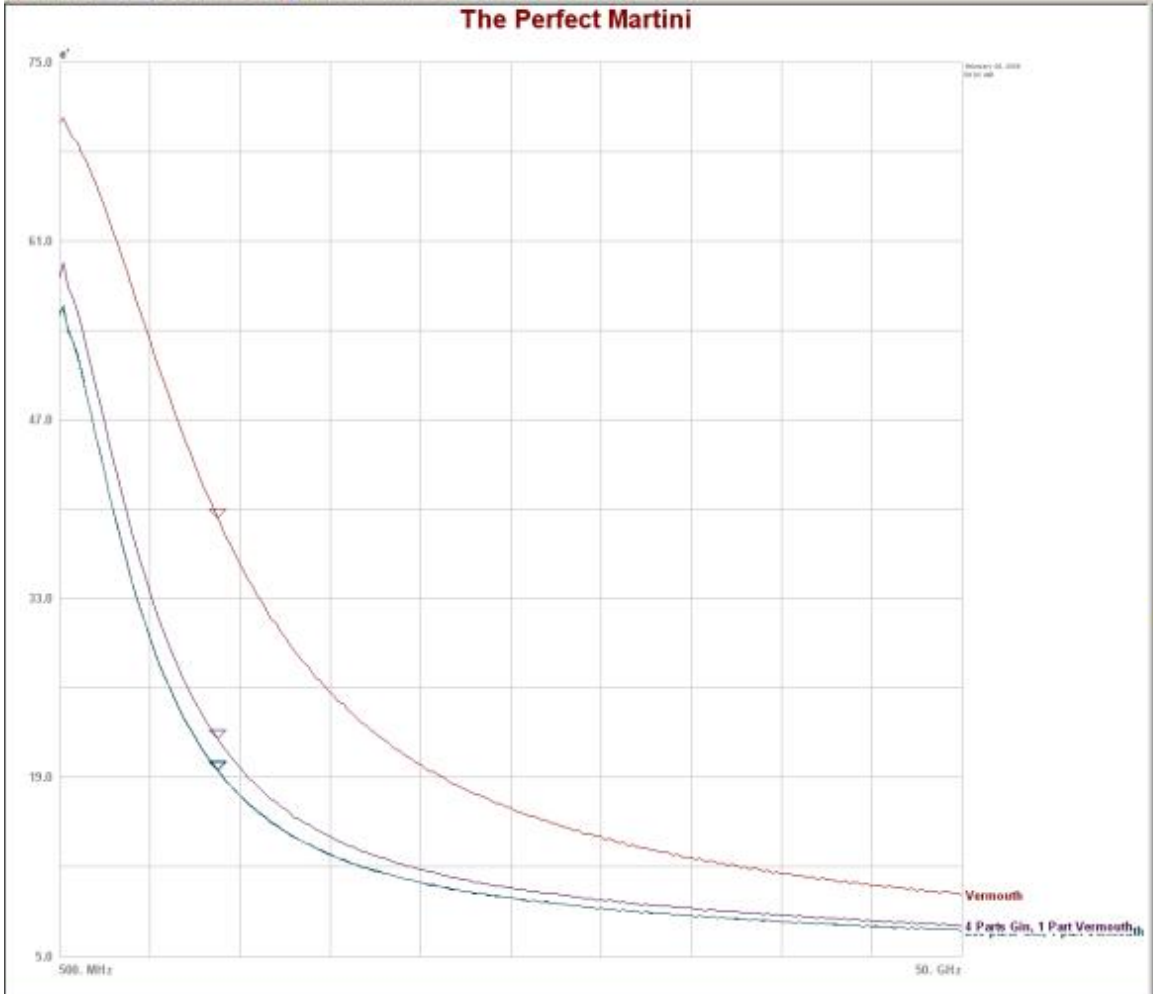
perfectMartini.tst - 85070

File Edit View Calibration Measure Chart Table Display Preferences Help



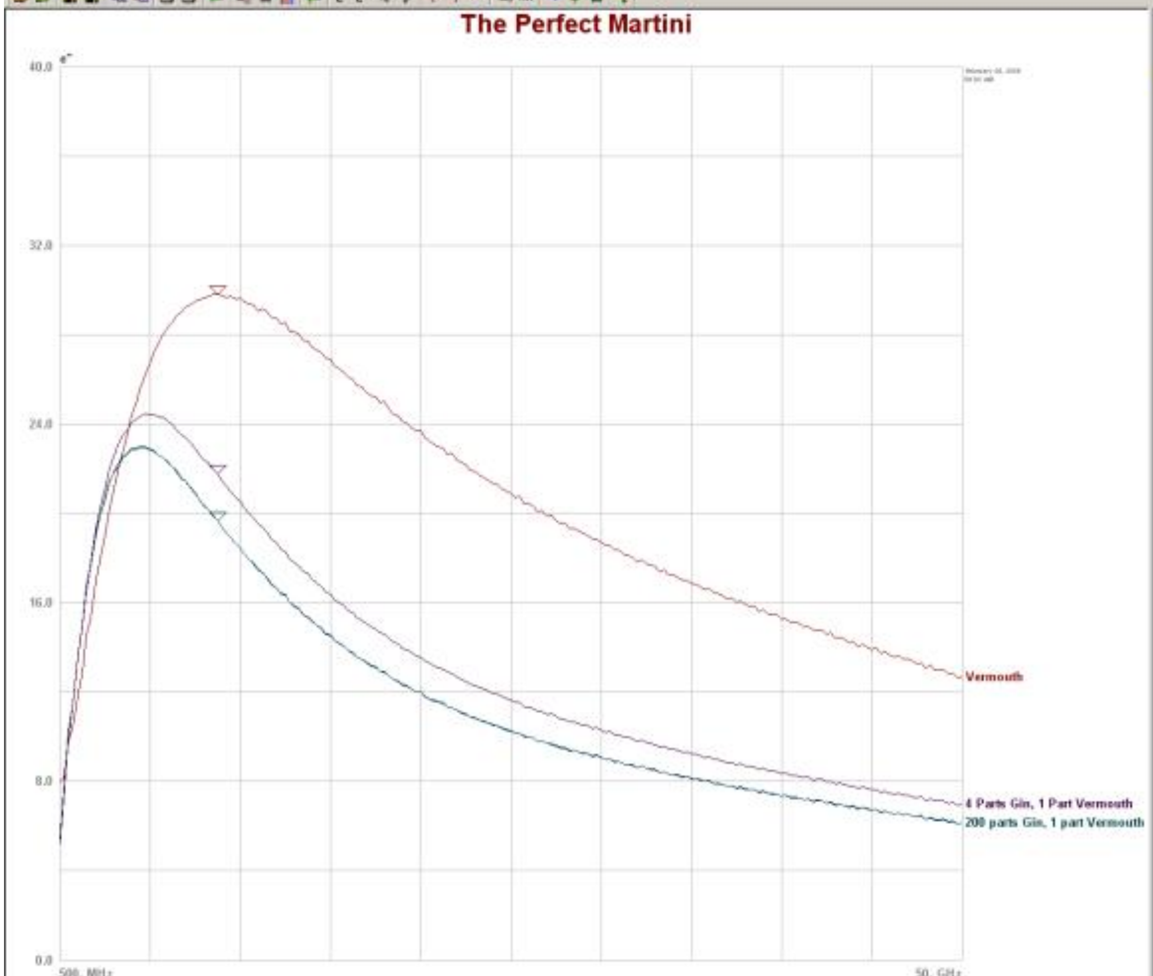
The Perfect Martini

Frequency	e'	e''	e'	e''	e'	e''	e'	e''
500.000000 MHz	70.2625	7.9535	55.4461	5.3026	55.1262	5.1993	58.1765	5.2748
747.500000 MHz	70.6440	8.1545	55.5959	7.4059	55.9984	7.1781	59.2798	7.5567
995.000000 MHz	69.7128	9.7825	54.1323	10.2504	53.8839	10.1065	57.3565	9.9222
1.242500000 GHz	69.0730	10.4801	53.0715	11.4939	53.1891	11.5318	56.5375	11.5445
1.490000000 GHz	68.7236	11.7887	51.9394	13.5422	52.1520	13.5674	55.4844	13.5304
1.737500000 GHz	67.7794	12.9394	50.6738	15.0026	50.4731	15.0472	54.1249	15.0354
1.985000000 GHz	67.2771	14.4813	49.1195	16.5243	49.1009	16.7140	52.8337	16.6668
2.232500000 GHz	66.4586	15.3584	47.6403	17.7193	47.6442	17.7107	51.3300	17.8283
2.480000000 GHz	65.5622	16.8902	45.8083	18.9444	45.8119	19.0834	49.6798	19.2268
2.727500000 GHz	64.5635	18.0080	44.4032	19.9393	44.4895	19.9771	48.2831	20.2942
2.975000000 GHz	63.6480	19.0058	42.9024	20.5837	42.8853	20.6930	46.8047	21.0906
3.222500000 GHz	62.7227	20.0444	41.4030	21.3052	41.3795	21.3571	45.3582	21.9086
3.470000000 GHz	61.6160	20.9968	39.9205	21.7962	39.8763	21.8158	43.8199	22.5409
3.717500000 GHz	60.7857	21.9303	38.5999	22.0780	38.4826	22.2250	42.4696	23.0532
3.965000000 GHz	59.5479	22.7916	37.1202	22.4926	37.0703	22.5790	40.9603	23.4967
4.212500000 GHz	58.5534	23.5546	35.7688	22.6378	35.7322	22.7195	39.6429	23.7590
4.460000000 GHz	57.5948	24.3628	34.5723	22.8392	34.5664	22.8928	38.4032	24.0574
4.707500000 GHz	56.4039	24.9346	33.3380	22.8724	33.2600	22.8975	37.1045	24.2165
4.955000000 GHz	55.4064	25.6637	32.2032	22.9638	32.1274	23.0265	35.8929	24.3849
5.202500000 GHz	54.3696	26.2187	31.1227	22.9425	31.0619	22.9991	34.7460	24.4446
5.450000000 GHz	53.2227	26.7337	30.0021	22.8347	29.9352	22.8810	33.5593	24.4213
5.697500000 GHz	52.2434	27.2330	29.0921	22.7666	29.0234	22.8252	32.5677	24.4309
5.945000000 GHz	51.1333	27.6085	28.0976	22.5868	28.0259	22.6254	31.4815	24.3157
6.192500000 GHz	50.1428	28.0185	27.2082	22.4963	27.1503	22.4980	30.5387	24.2888
6.440000000 GHz	49.1774	28.3124	26.4169	22.2793	26.3613	22.3044	29.5901	24.1101
6.687500000 GHz	48.1062	28.5957	25.5461	22.0461	25.4759	22.0745	28.6993	23.9340
6.935000000 GHz	47.2406	28.8364	24.9046	21.8461	24.8299	21.9164	27.9847	23.7493
7.182500000 GHz	46.2269	29.0119	24.1202	21.5697	24.0389	21.5955	27.1056	23.5390
7.430000000 GHz	45.3065	29.2602	23.4246	21.4132	23.3587	21.4156	26.3715	23.3750
7.677500000 GHz	44.4150	29.3336	22.8403	21.1565	22.7751	21.1834	25.6673	23.1496
7.925000000 GHz	43.4638	29.5115	22.1516	20.8962	22.0970	20.9125	24.9344	22.9205
8.172500000 GHz	42.6804	29.5646	21.6900	20.6254	21.6195	20.6412	24.3901	22.6406
8.420000000 GHz	41.7877	29.6350	21.0875	20.3527	21.0426	20.3602	23.7291	22.4004
8.667500000 GHz	40.9949	29.7229	20.5915	20.1853	20.5251	20.1832	23.1668	22.2514
8.915000000 GHz	40.1983	29.7827	20.1300	19.9055	20.0624	19.9070	22.6116	21.9737
9.162500000 GHz	39.3290	29.8185	19.5765	19.6698	19.5162	19.6699	22.0202	21.7571
9.410000000 GHz	38.6647	29.7482	19.2322	19.4025	19.1815	19.3993	21.5926	21.4666
9.657500000 GHz	37.8149	29.6714	18.7611	19.1195	18.6896	19.1185	21.0517	21.2141
9.905000000 GHz	37.1675	29.6955	18.3837	18.9096	18.3262	18.9110	20.6455	20.9824
10.152500000 GHz	36.4761	29.6007	18.0221	18.6532	17.9488	18.6419	20.1948	20.7060
10.400000000 GHz	35.7253	29.6130	17.5842	18.4571	17.5310	18.4491	19.7231	20.5291
10.647500000 GHz	35.1769	29.4673	17.3444	18.2078	17.2796	18.1983	19.4195	20.2572
10.895000000 GHz	34.4389	29.3899	16.9259	17.9444	16.8605	17.9494	18.9588	20.0095
11.142500000 GHz	33.9083	29.3275	16.7024	17.7548	16.6282	17.7309	18.6641	19.7812
11.390000000 GHz	33.1374	29.0424	16.3712	17.5084	16.2612	17.4409	18.2567	19.5227
11.637500000 GHz	32.6366	29.1523	16.0502	17.3157	15.9697	17.3493	17.9861	19.3548
11.885000000 GHz	32.1232	29.0464	15.8308	17.1236	15.7694	17.1045	17.6576	19.1468
12.132500000 GHz	31.4186	28.8108	15.4644	16.8357	15.4131	16.8152	17.2862	18.8583
12.380000000 GHz	31.0875	28.7339	15.3267	16.6930	15.2844	16.6730	17.1183	18.6842
12.627500000 GHz	30.4535	28.5042	15.0308	16.4258	14.9918	16.4032	16.7555	18.4165
12.875000000 GHz	29.9976	28.5258	14.7538	16.3704	14.7348	16.3335	16.5068	18.2960
13.122500000 GHz	29.4999	28.1731	14.6267	16.0356	14.5659	16.0546	16.2756	17.9981
13.370000000 GHz	28.9320	28.0994	14.3965	15.8785	14.2981	15.8452	15.8855	17.8278
13.617500000 GHz	28.5140	28.0372	14.1966	15.7346	14.1821	15.7244	15.7588	17.6533
13.865000000 GHz	28.0644	27.7593	13.9153	15.4541	13.9130	15.4700	15.5112	17.4039
14.112500000 GHz	27.6800	27.6946	13.8042	15.3817	13.7681	15.3391	15.3485	17.2871
14.360000000 GHz	27.2714	27.4449	13.7182	15.1962	13.6348	15.1571	15.1705	17.0657
14.607500000 GHz	26.7046	27.3240	13.4243	14.9990	13.3914	14.9800	14.8715	16.8825
14.855000000 GHz	26.5333	27.1860	13.3506	14.8564	13.3056	14.8357	14.7718	16.7146
15.102500000 GHz	26.0036	26.9213	13.1220	14.6176	13.0853	14.5950	14.5133	16.4763
15.350000000 GHz	25.6572	26.8883	12.9619	14.5641	12.9270	14.5320	14.3502	16.3954
15.597500000 GHz	25.3586	26.6144	12.8567	14.3338	12.8241	14.3177	14.2003	16.1398

For Help, press F1

Coaxial probe example data

perfectMartini.tst - 85070



8.172500000 GHz	42.6804	29.5646	21.6900	20.6254	21.6195	20.6412	24.3901	22.6406
8.420000000 GHz	41.7877	29.6350	21.0875	20.3527	21.0426	20.3602	23.7291	22.4004
8.667500000 GHz	40.9949	29.7229	20.5915	20.1853	20.5251	20.1832	23.1668	22.2514
8.915000000 GHz	40.1983	29.7827	20.1300	19.9055	20.0624	19.9070	22.6116	21.9737
9.162500000 GHz	39.3290	29.8185	19.5765	19.6698	19.5162	19.6699	22.0202	21.7571
9.410000000 GHz	38.6647	29.7482	19.2322	19.4025	19.1815	19.3993	21.5926	21.4666
9.657500000 GHz	37.8149	29.6714	18.7611	19.1195	18.6896	19.1185	21.0517	21.2141
9.905000000 GHz	37.1675	29.6955	18.3837	18.9096	18.3262	18.9110	20.6455	20.9824
10.152500000 GHz	36.4761	29.6007	18.0221	18.6532	17.9488	18.6419	20.1948	20.7060
10.400000000 GHz	35.7253	29.6130	17.5842	18.4571	17.5310	18.4491	19.7231	20.5291
10.647500000 GHz	35.1769	29.4673	17.3444	18.2078	17.2796	18.1983	19.4195	20.2572
10.895000000 GHz	34.4389	29.3899	16.9259	17.9444	16.8605	17.9494	18.9588	20.0095
11.142500000 GHz	33.9083	29.3275	16.7024	17.7548	16.6282	17.7309	18.6641	19.7812
11.390000000 GHz	33.1374	29.0424	16.3712	17.5084	16.2612	17.4409	18.2567	19.5227
11.637500000 GHz	32.6366	29.1523	16.0502	17.3157	15.9697	17.3493	17.9461	19.3548
11.885000000 GHz	32.1232	29.0464	15.8308	17.1236	15.7694	17.1045	17.6576	19.1468
12.132500000 GHz	31.4106	28.8108	15.4644	16.8357	15.4131	16.8152	17.2862	18.8583
12.380000000 GHz	31.0875	28.7339	15.3267	16.6930	15.2844	16.6730	17.1183	18.6842
12.627500000 GHz	30.4535	28.5042	15.0308	16.4258	14.9918	16.4032	16.7555	18.4165
12.875000000 GHz	29.9976	28.5258	14.7538	16.3704	14.7348	16.3335	16.5068	18.2960
13.122500000 GHz	29.4999	28.1731	14.6267	16.0356	14.5659	16.0546	16.2756	17.9981
13.370000000 GHz	28.9320	28.0994	14.3965	15.8785	14.2981	15.8452	15.8855	17.8278
13.617500000 GHz	28.5140	28.0372	14.1966	15.7346	14.1821	15.7244	15.7588	17.6533
13.865000000 GHz	28.0644	27.7593	13.9153	15.4541	13.9130	15.4700	15.5112	17.4039
14.112500000 GHz	27.6880	27.6946	13.8042	15.3817	13.7681	15.3391	15.3485	17.2871
14.360000000 GHz	27.2714	27.4449	13.7182	15.1962	13.6348	15.1571	15.1705	17.0657
14.607500000 GHz	26.7846	27.3240	13.4243	14.9990	13.3914	14.9800	14.8715	16.8825
14.855000000 GHz	26.5333	27.1860	13.3506	14.8564	13.3056	14.8357	14.7718	16.7146
15.102500000 GHz	26.0036	26.9213	13.1220	14.6176	13.0853	14.5950	14.5133	16.4763
15.350000000 GHz	25.6572	26.8883	12.9619	14.5641	12.9270	14.5320	14.3502	16.3954
15.597500000 GHz	25.3586	26.6144	12.8567	14.3338	12.8241	14.3177	14.2003	16.1398
15.845000000 GHz	24.9116	26.4947	12.6288	14.1980	12.6280	14.1711	14.0196	16.0008
16.092500000 GHz	24.7273	26.3295	12.6054	14.0752	12.5706	14.0498	13.9022	15.8602
16.340000000 GHz	24.2243	26.0974	12.4181	13.8741	12.3316	13.8485	13.6491	15.6429
16.587500000 GHz	23.9405	25.9908	12.2758	13.7609	12.2258	13.7109	13.5764	15.5421
16.835000000 GHz	23.6640	25.7293	12.1978	13.5824	12.1577	13.5514	13.4362	15.3276
17.082500000 GHz	23.2607	25.6674	12.0180	13.4740	11.9830	13.4700	13.2248	15.2049
17.330000000 GHz	23.0801	25.4318	11.9637	13.3458	11.9368	13.3042	13.1617	15.0713
17.577500000 GHz	22.6760	25.2667	11.7902	13.1772	11.7674	13.1563	12.9721	14.8928
17.825000000 GHz	22.4611	25.2069	11.7176	13.1267	11.6911	13.0999	12.8538	14.8238
18.072500000 GHz	22.2126	24.9422	11.6376	12.9423	11.6113	12.9267	12.7766	14.6429
18.320000000 GHz	21.9689	25.0076	11.5252	12.9280	11.4869	12.8863	12.6562	14.6018
18.567500000 GHz	21.6977	24.6825	11.4533	12.7302	11.4305	12.7038	12.5502	14.3866
18.815000000 GHz	21.3335	24.4359	11.2822	12.5671	11.2605	12.5419	12.3800	14.2262
19.062500000 GHz	21.1573	24.3881	11.2101	12.5126	11.1904	12.4868	12.2735	14.1403
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20.052500000 GHz	20.1464	23.7087	10.8623	12.0286	10.8407	11.9979	11.8610	13.6032
20.300000000 GHz	20.0322	23.7115	10.7976	11.9946	10.7951	11.9970	11.8248	13.5699
20.547500000 GHz	19.7765	23.4005	10.7110	11.8308	10.7065	11.8045	11.7203	13.3939
20.795000000 GHz	19.4886	23.2262	10.5945	11.6919	10.5700	11.6695	11.5672	13.3226
21.042500000 GHz	19.4663	23.0910	10.5842	11.6542	10.6100	11.6069	11.5848	13.1341
21.290000000 GHz	19.1977	22.9833	10.5083	11.5575	10.4850	11.5392	11.4532	13.0882
21.537500000 GHz	18.9997	22.9190	10.4409	11.5304	10.3926	11.4821	11.3572	13.0309
21.785000000 GHz	18.7969	22.6450	10.3740	11.3354	10.3424	11.3324	11.2964	12.8746
22.032500000 GHz	18.5155	22.6876	10.2486	11.3048	10.2251	11.2968	11.1392	12.8355
22.280000000 GHz	18.4684	22.4171	10.2639	11.2251	10.2509	11.1980	11.1605	12.6898
22.527500000 GHz	18.1866	22.2511	10.1380	11.0699	10.1327	11.0482	11.0341	12.5453
22.775000000 GHz	18.0958	22.1722	10.1205	11.0209	10.0792	10.9843	10.9846	12.4621
23.022500000 GHz	17.9007	21.9535	10.0384	10.8865	10.0278	10.8681	10.9229	12.3408
23.270000000 GHz	17.6875	21.8832	9.9618	10.8600	9.9282	10.8202	10.8082	12.2971
23.517500000 GHz	17.6545	21.7267	9.9657	10.7470	9.9618	10.7503	10.8145	12.2126
23.765000000 GHz	17.4475	21.5944	9.8875	10.6917	9.8742	10.6609	10.7405	12.1198
24.012500000 GHz	17.3288	21.4708	9.8340	10.6348	9.7772	10.6370	10.6608	12.0541
24.260000000 GHz	17.1176	21.3399	9.7684	10.5353	9.7672	10.5075	10.5920	11.9326

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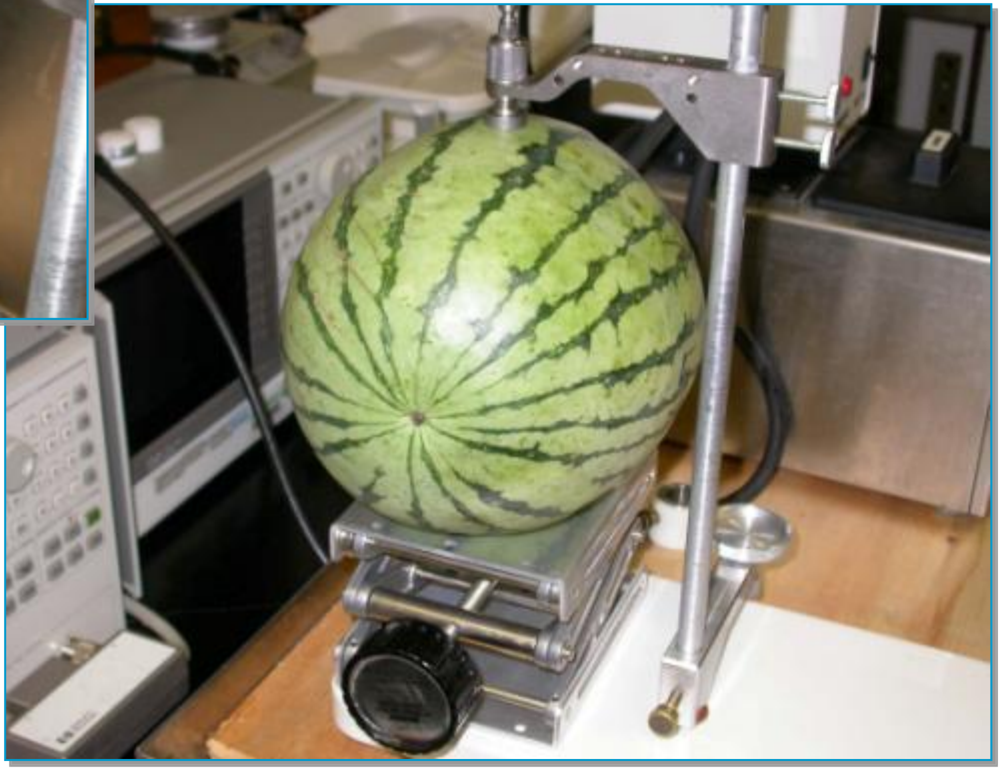
USDA Fruit ripeness research

KEYSIGHT TECHNOLOGIES

Unlocking Measurement Insights for 75 Years



CPAC Carbon nanotube research

KEYSIGHT TECHNOLOGIES

Unlocking Measurement Insights for 75 Years

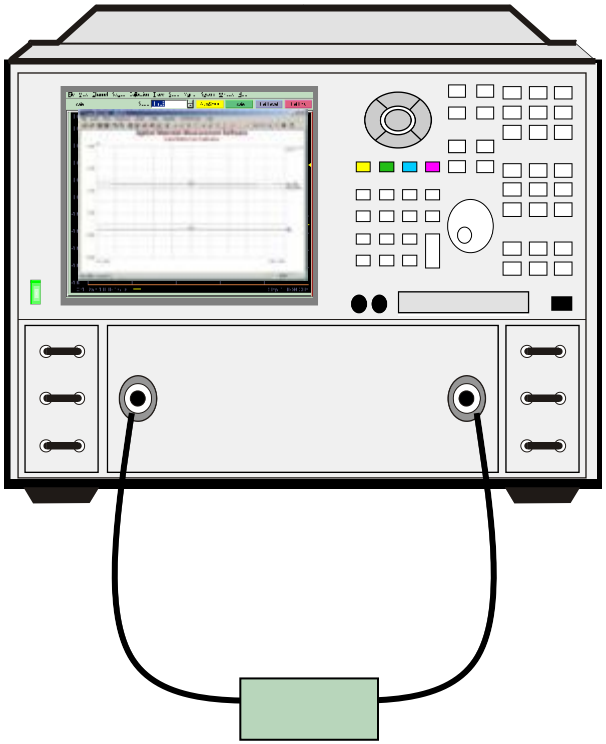
Agenda

Unlocking Measurement Insights for 75 Years

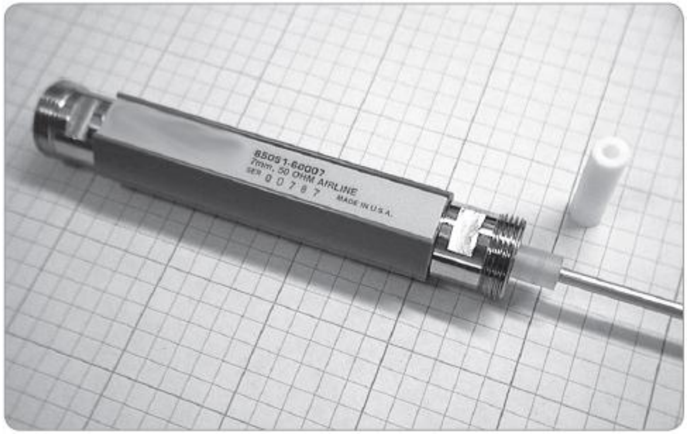
- Introduction
- Permittivity and permeability
- Measurement techniques and systems
- Parallel plate
- Coaxial probe
- **Transmission line**
- Free space
- Resonant cavity

Transmission line system

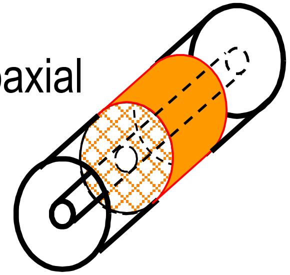
Network Analyzer

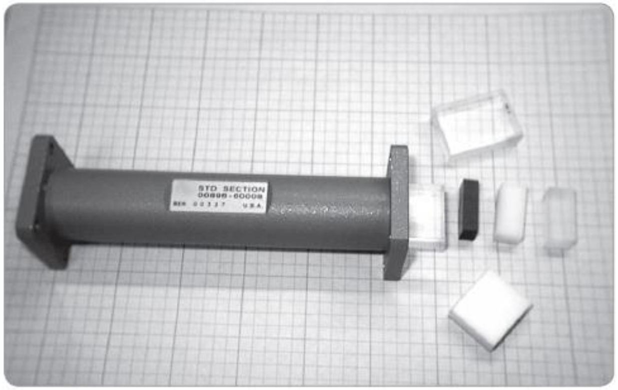


Sample holder
connected between coax cables

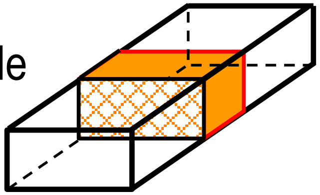


Coaxial



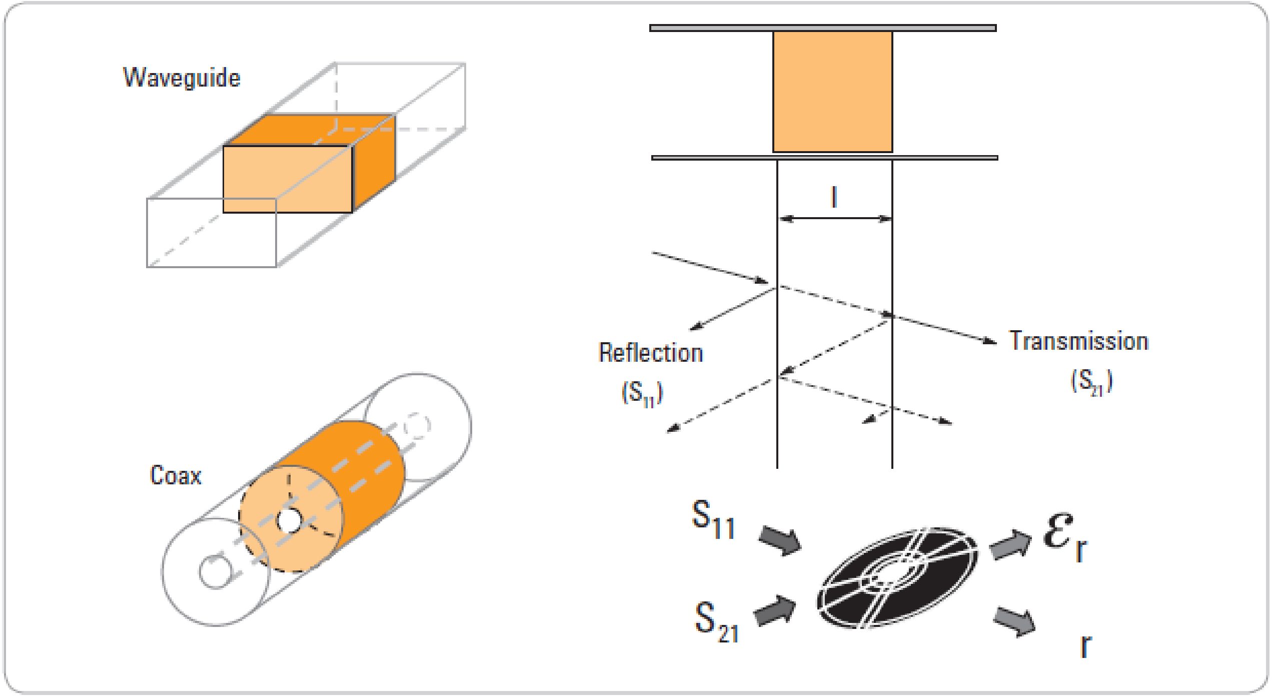


Waveguide



Calibration is required

Transmission line



Technique features:
- Broadband (low freq. limited by practical sample length)
- Limited low loss resolution (depends on sample length)
- Measures magnetic materials
- Anisotropic materials can be measured in waveguide

Assumptions:
- Sample fill fixture across section
- No air gaps at fixture walls
- Smooth, flat faces, perpendicular to long axis
- Homogeneous

Transmission algorithms

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Algorithm	Measured S-parameters	Output
Nicolson-Ross	S11,S21,S12,S22	ε_r and μ_r
Precision (NIST)	S11,S21,S12,S22	ε_r
Fast	S21,S12	ε_r

(85071E also has three reflection algorithms)

Agenda

KEYSIGHT TECHNOLOGIES

Unlocking Measurement Insights for 75 Years

- Introduction
- Permittivity and permeability
- Measurement techniques and systems
- Parallel plate
- Coaxial probe
- Transmission line
- **Free space**
- Resonant cavity

Free space system

KEYSIGHT TECHNOLOGIES

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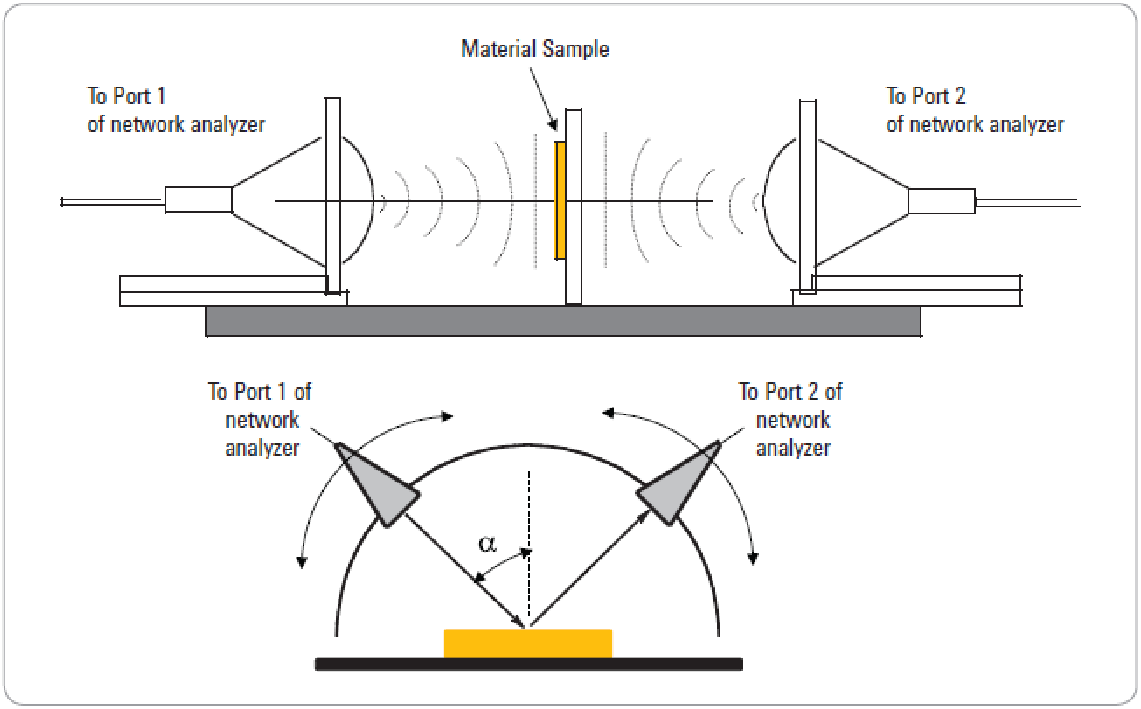
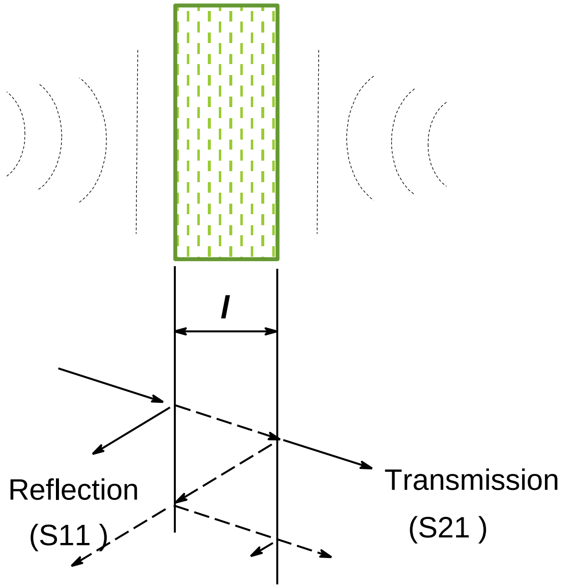
Dielectric measurement setup for free space measurement

Free space system





Technique features:

- Non-contacting, non-destructive
- High frequency (low freq. Limited by practical sample size)
- Useful for high temperature
- Antenna polarization may be varied for anisotropic materials
- Measures magnetic materials

Assumptions:

- Flat parallel faced samples
- Sample in non-reactive region
- Beam spot is contained in sample
- Known thickness > 20/360 λ

Free space system requires calibration

KEYSIGHT TECHNOLOGIES

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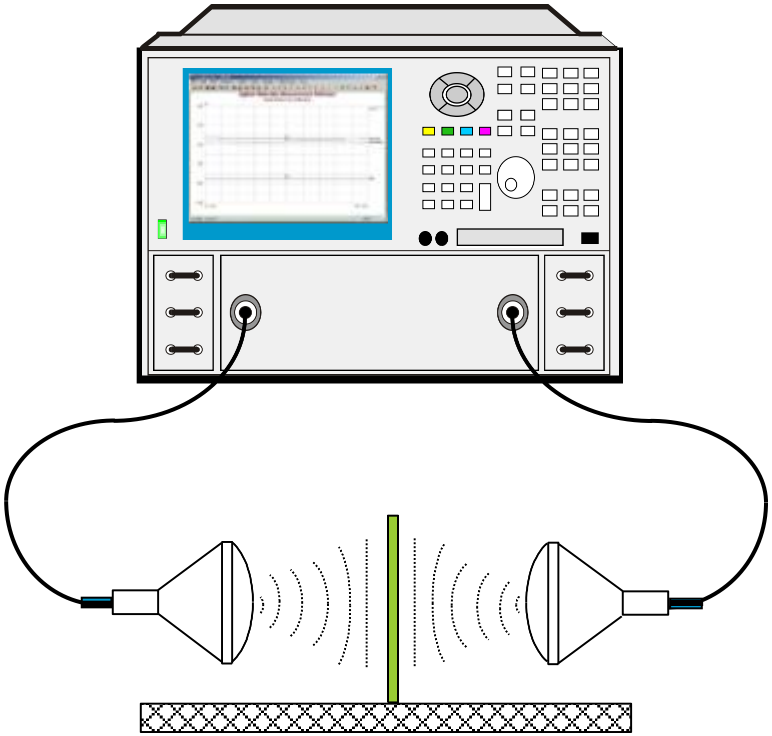

Before a measurement can be made, a calibration must be performed to remove systematic errors.

TRL calibration

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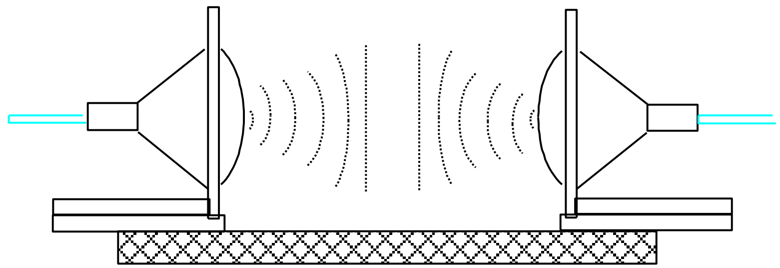
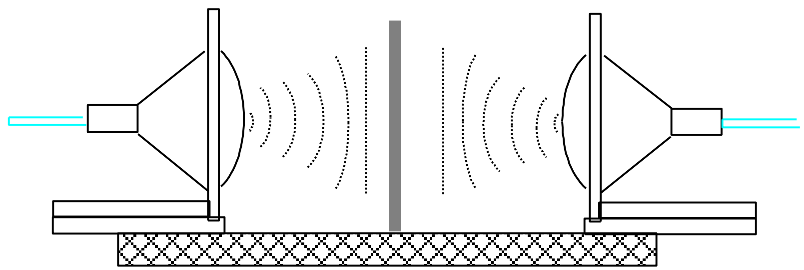
Thru

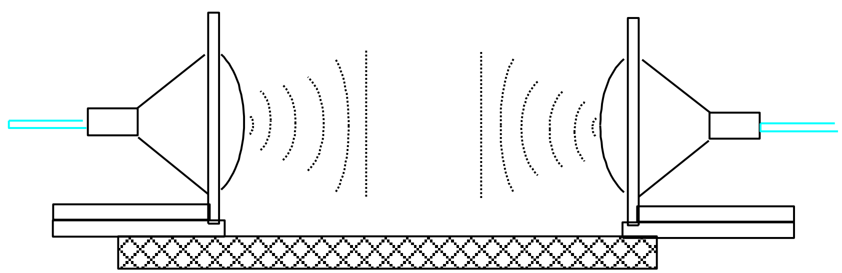


Reflect



Move the antenna away to compensate for the thickness of the short. Move it back for the next step.

Line



Move the antenna away on a quarter-wavelength and then back in the original position.

Agilent Technologies

Gated, reflect, line (GRL) calibration

KEYSIGHT TECHNOLOGIES

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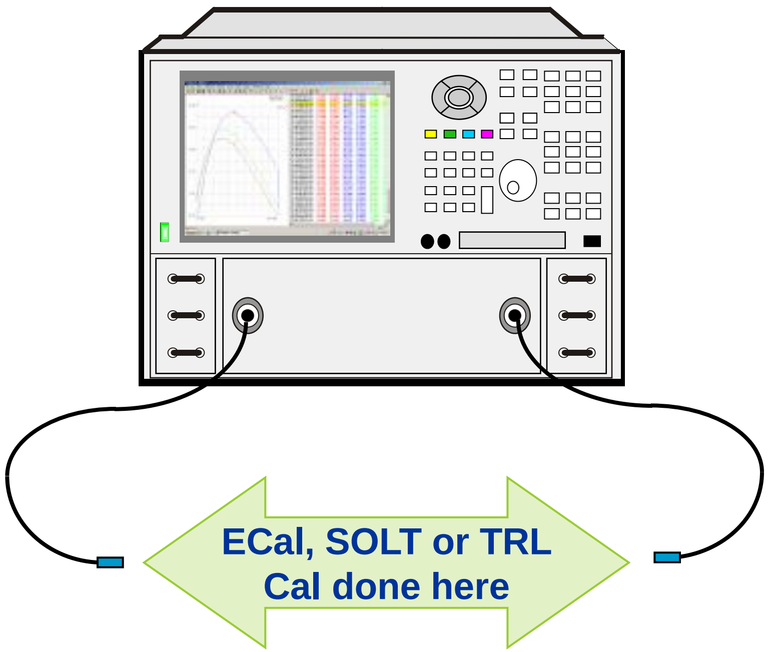
Two Tiered Calibration

1. Two port calibration at waveguide or coax input into antennas removes errors associated with network analyzer and cables.



Gated, reflect, line (GRL) calibration

KEYSIGHT TECHNOLOGIES

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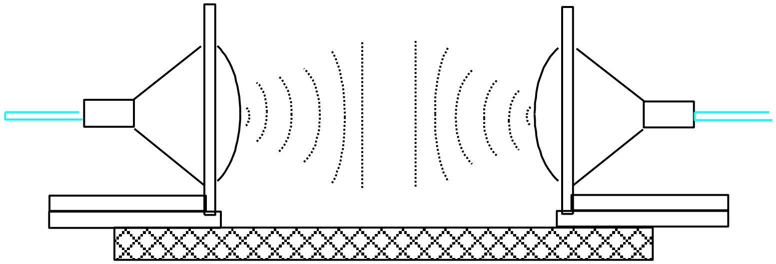
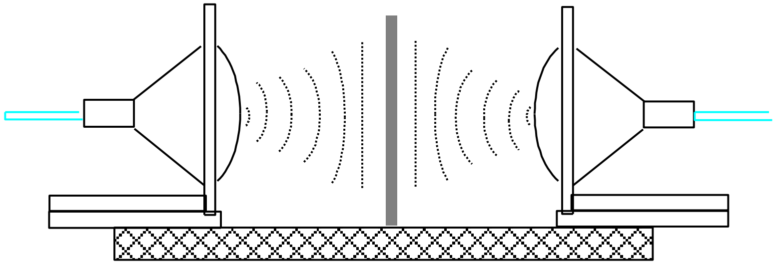
Two Tiered Calibration

2. Two additional free space calibration standards remove errors from antennas and fixture.

Line
(empty fixture)



Reflect
(metal plate of known thickness)



Quasi-optical VNA measurements

KEYSIGHT TECHNOLOGIES

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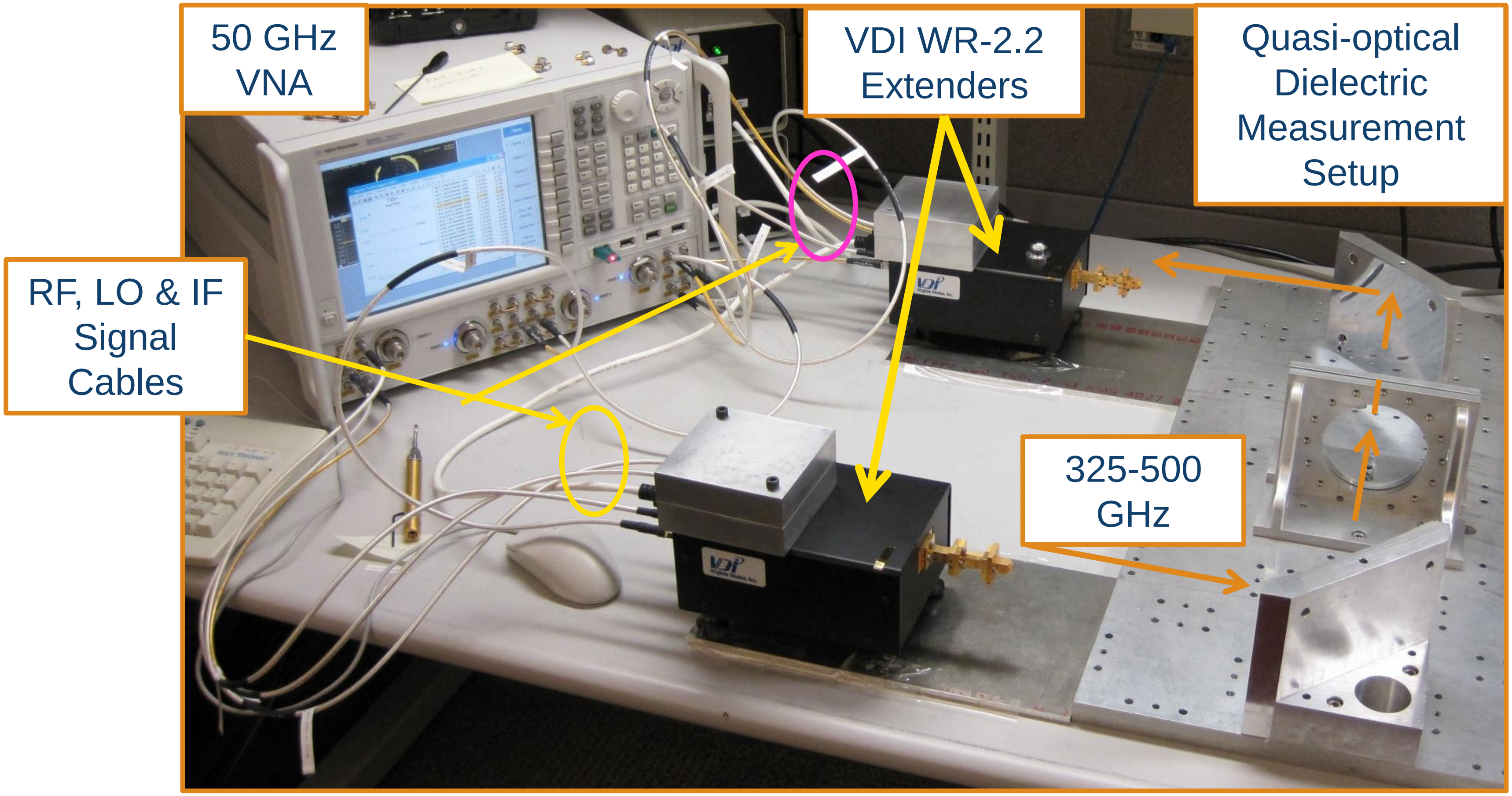
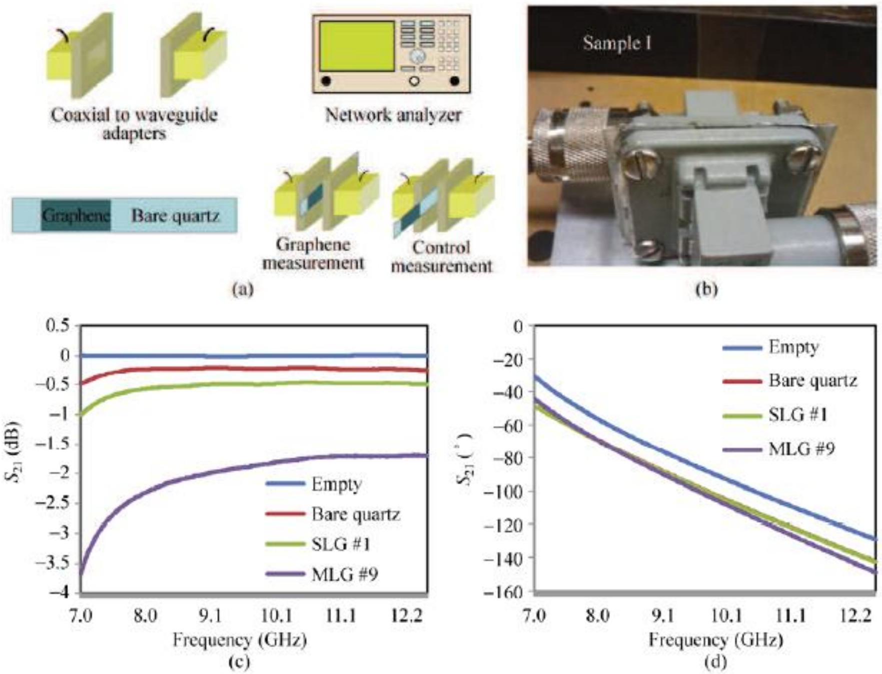


- **Quasi-optical dielectric measurements performed at Agilent**

THz graphene characterization



Frequency extenders allow measurements to 1.1 THz

Measurement details

Frequency domain measurements of the absolute value of multilayer graphene (MLG) and single-layer graphene (SLG) sheet conductivity and transparency from DC to 1 THz

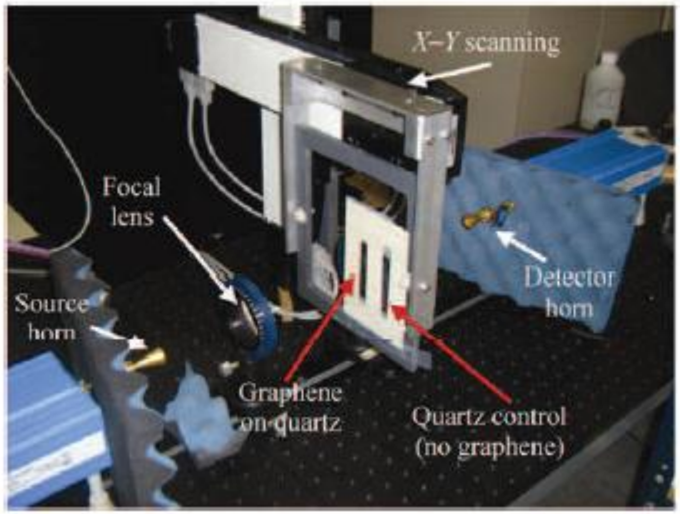


Figure 7 Picture of X-band imaging and quasi-optic transmission apparatus

Paper details

Terahertz Graphene Optics

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Agenda

KEYSIGHT TECHNOLOGIES

Unlocking Measurement Insights for 75 Years

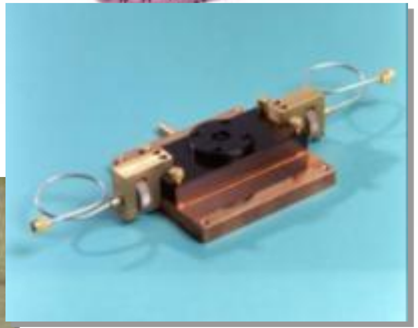
- Introduction
- Permittivity and permeability
- Measurement techniques and systems
- Parallel plate
- Coaxial probe
- Transmission line
- Free space
- **Resonant cavity**

Resonant cavity system

Agilent Split Cylinder Resonator
IPC TM-650-2.5.5.5.13

IPC
ASSOCIATION CONNECTING ELECTRONICS INDUSTRIES

ASTM 2520 Waveguide Resonators



Split Post Dielectric Resonators from QWED

Resonant cavity technique

fc = Resonant Frequency of Empty Cavity

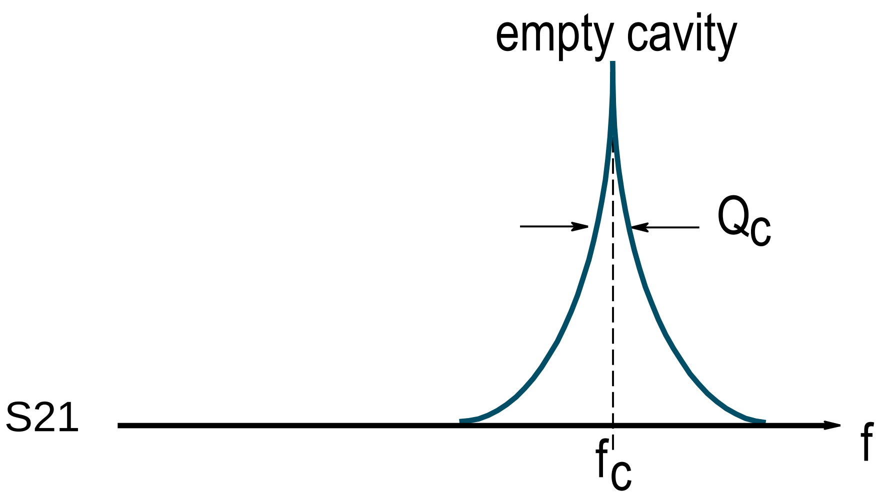
fs = Resonant Frequency of Filled Cavity

Qc = Q of Empty Cavity

Qs = Q of Filled Cavity

Vs = Volume of Empty Cavity

Vc = Volume of Sample



$$\varepsilon_r' = 1 + \frac{V_c(f_c - f_s)}{2V_s f_s}$$

$$\varepsilon_r'' = \frac{V_c}{4V_s}\left(\frac{1}{Q_s} - \frac{1}{Q_c}\right)$$

ASTM 2520

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KEYSIGHT TECHNOLOGIES

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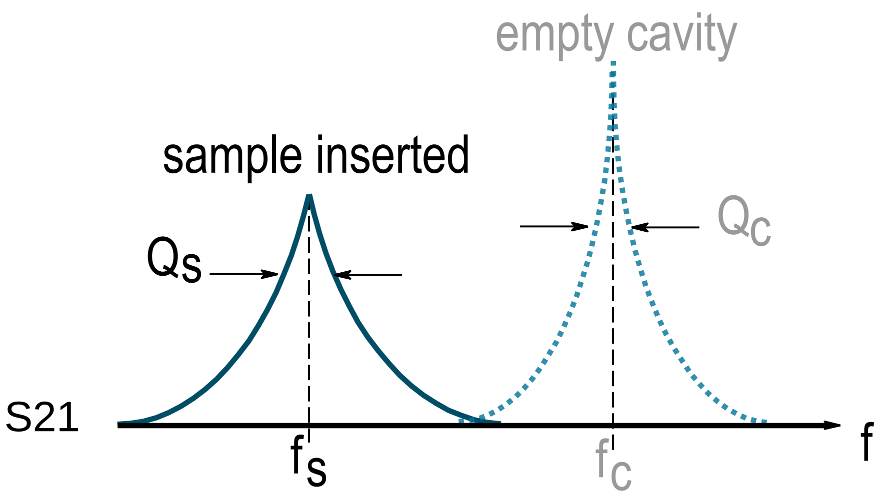

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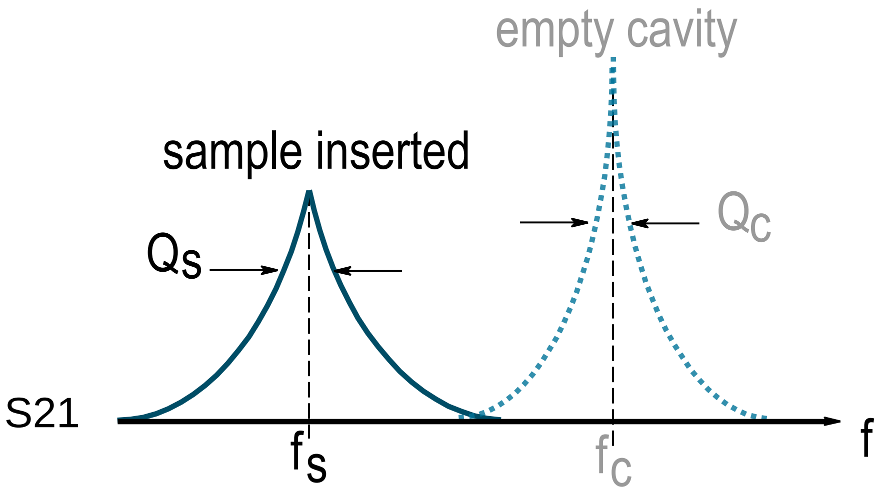

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ASTM 2520

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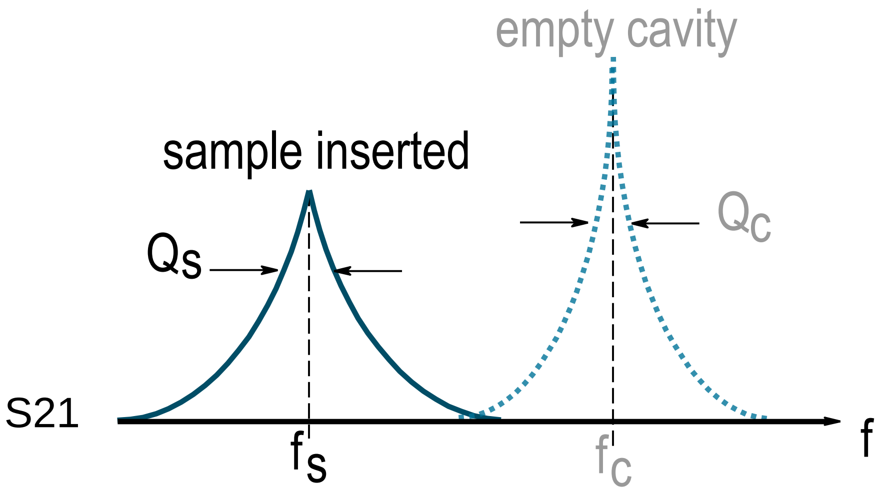

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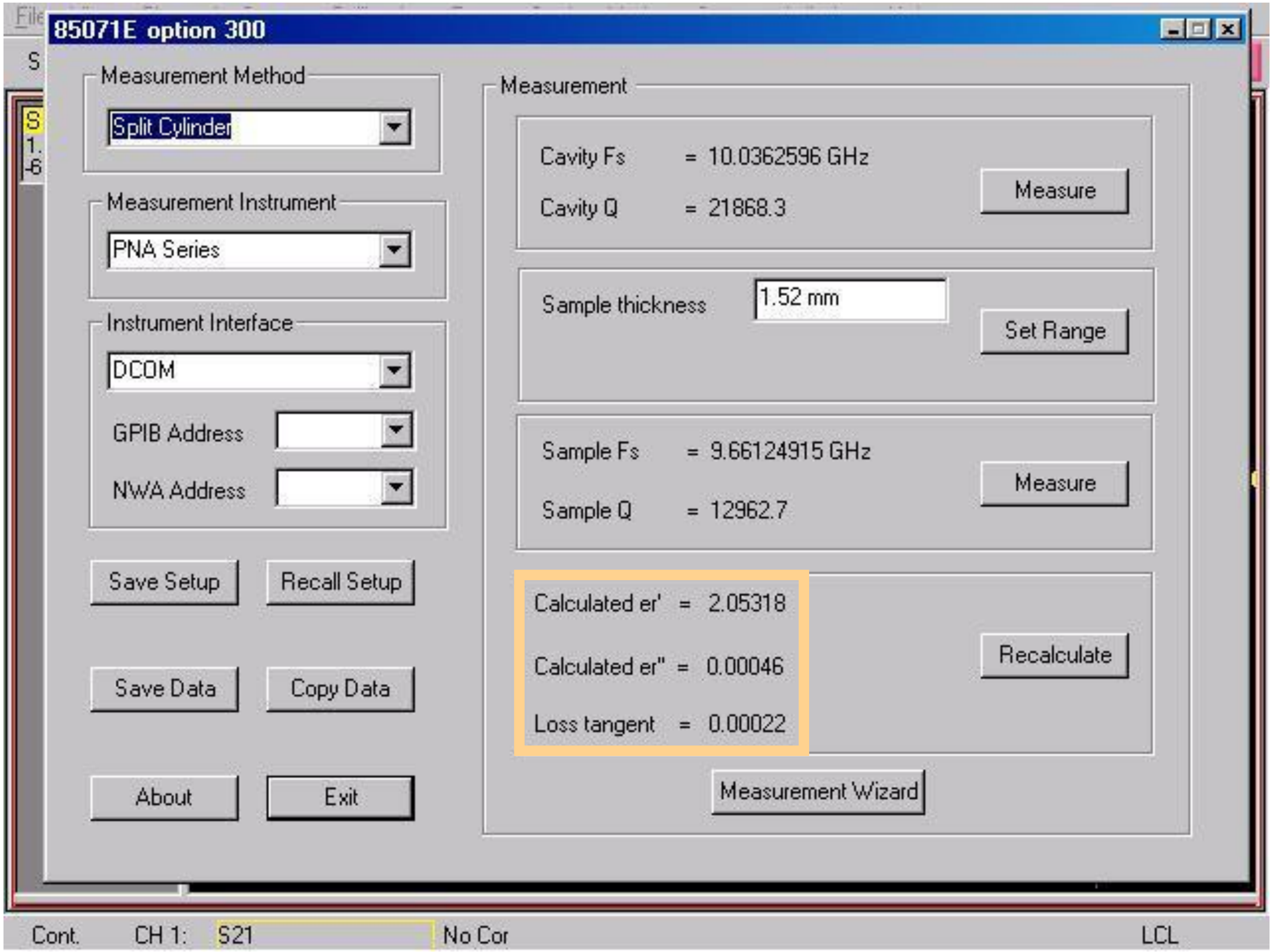
ASTM 2520

Resonant cavity example data



Resonant vs. broadband transmission

KEYSIGHT TECHNOLOGIES

Unlocking Measurement Insights for 75 Years

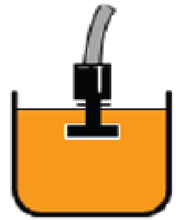
	Resonant	Broadband
Low Loss materials	Yes e_r" resolution $\leq 10^{-4}$	No e_r" resolution $\geq 10^{-2}$-10^{-3}
Thin Films and Sheets	Yes 10GHz sample thickness <1mm	No 10GHz optimum thickness ~ 5-10mm
Calibration Required	No	Yes
Measurement Frequency Coverage	Discrete Frequencies	Broadband or Banded

Summary technique and strengths

KEYSIGHT TECHNOLOGIES

Coaxial Probe

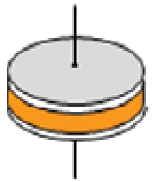
ε_r



Broadband, convenient, non-destructive
Best for lossy MUTs; liquids and semi-solids

Parallel Plate

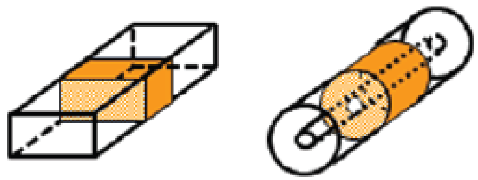
ε_r



Accurate
Best for low frequencies; thin, flat sheets

Transmission Line

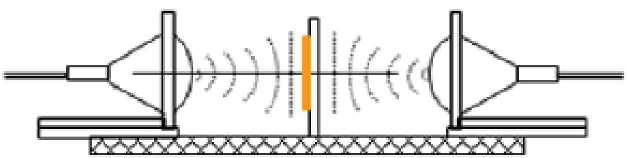
ε_r and μ_r



Broadband
Best for lossy to low loss MUTs; machineable solids

Free Space

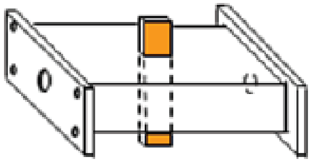
ε_r and μ_r



Broadband; Non-contacting
Best for flats sheets, powders, high temperatures

Resonant Cavity

ε_r



Single frequency; Accurate
Best for low loss MUTs; small samples

References

KEYSIGHT TECHNOLOGIES

Unlocking Measurement Insights for 75 Years

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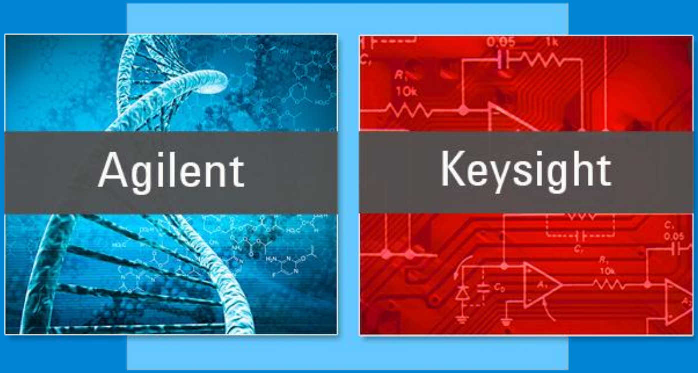
Thank you!



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