



**KEYSIGHT
WORLD 2020**

mmWave material measurements for 5G and Radar

Kenny Liao

Sr. Project Manager / Keysight Technologies



Agenda

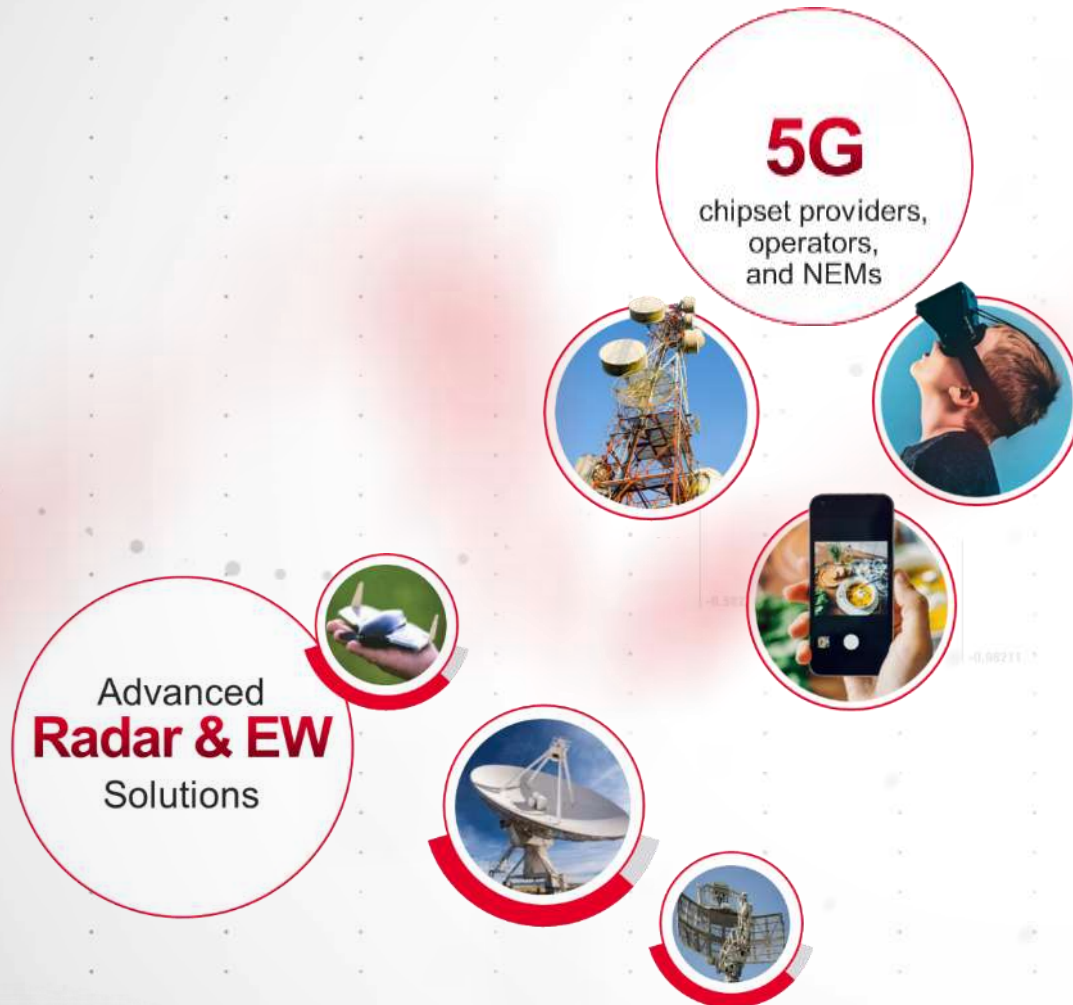
- Market trend of mmWave radar and 5G communication
- Challenges of Dielectric Parameter Measurements
- New mmWave Material Test Solutions
 - Balanced Circular Disk Resonator (BCDR)
 - Split Cylinder Cavity Resonator (SCCR)

Market trend of mmWave radar and 5G communication

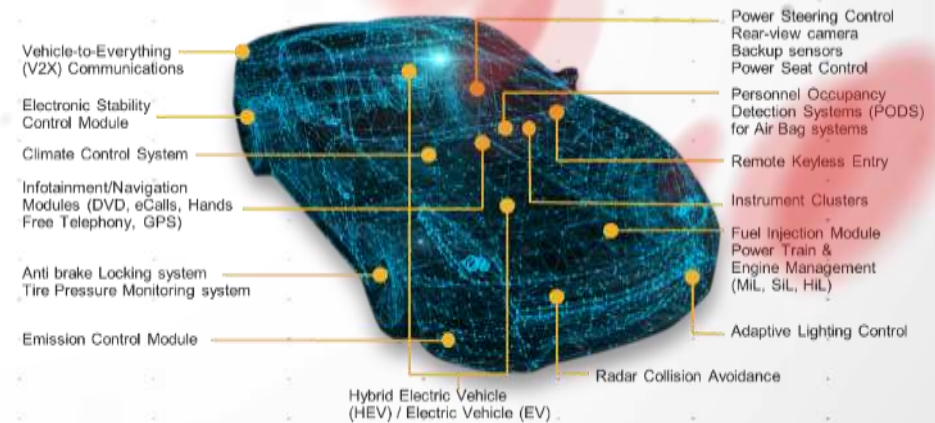


Market trends

EMERGING NEW APPLICATIONS



Automotive and Energy

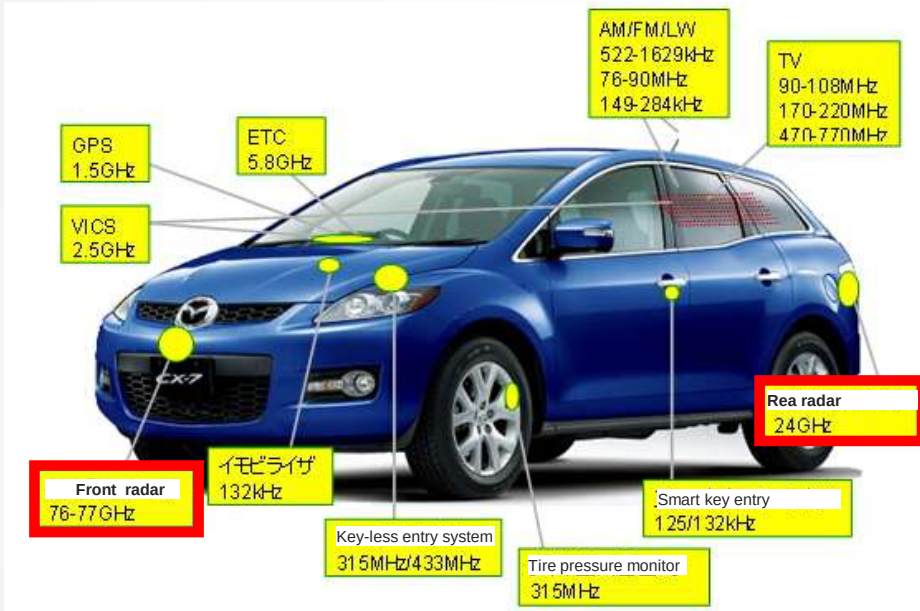


Food

Biomedical

Applications at millimeter frequencies

1. Automotive radars (76-77 GHz, 24 GHz, 77-81GHz)

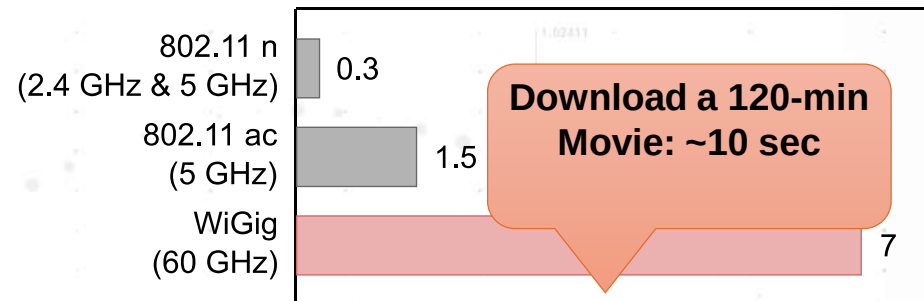


(from ESI Group HP)

- ✓ Front long range radar: 76-77 ,77-81GHz
- ✓ Rear short range radar: 24 GHz

2. Next-generation wireless communications (WiGig, 60 GHz band)

Peak Data Transfer Speeds (Gbps)



Demonstration experiment at Narita Int'l airport
(Feb. 18-26, 2016)

New Operating Bands In 5G NR – up to 40G by FR2

SUB-6GHZ AND MMWAVE



Frequency Range 1: 400 MHz to 6 GHz	Frequency Range 2: 24.25 to 52.6 GHz	Frequencies up to 90 GHz are currently being investigated for future releases.
Adds 1.5 GHz of new spectrum in frequency bands	Adds 8.25 GHz of new spectrum in frequency bands	
n77: 3.3–4.2 GHz n78: 3.3–3.8 GHz n79: 4.4–5 GHz	n257: 26.5-29.5 GHz n258: 24.25-27.5 GHz n260: 37–40 GHz	

Note :

3GPP band n258 refers to the range between 24.25-27.5 GHz and is commonly called 26 GHz. And 3GPP band n257 refers to 26.5-29.5 GHz. It is commonly called 28 GHz.

A lot of 5G commercial trial & initial deployment focus on:

- **3.6 to 3.8GHz band (part of n77 & n78)**
- **26 to 27.5GHz band (part of n257 & n258)**

Downlink 3.4 to 4.2GHz



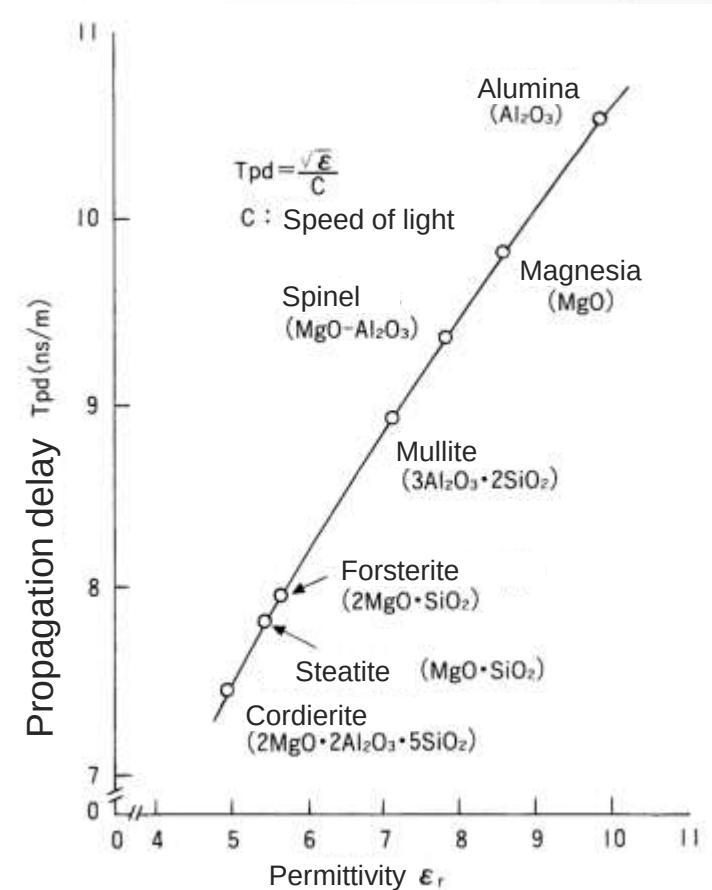
Satellite Ground Station

New bands	Supporting operators
Band n77 (3300-4200 MHz) Band n78 (3300-3800 MHz)	NTT DOCOMO, KDDI, Softbank Mobile, China Mobile, China Unicom, China Telecom, KT, SK Telecom, LG Uplus, Etisalat, Orange, Telecom Italia, British Telecom, Deutsche Telekom, Telstra
Band n257 (26.5-29.5 GHz) Band n258 (24.25-27.5 GHz)	NTT DOCOMO, KDDI, Softbank Mobile, China Mobile, KT, SK Telecom, LG Uplus, Etisalat, Orange, Verizon, T-mobile, Telecom Italia, British Telecom, Deutsche Telekom, Telstra

Material performance requested by 5G and mmW radar

LOW DK AND LOW DF

- Ideal performance is “air”
 - Designers have to use dielectric material to hold or to protect signal line, but they prefer “as same as nothing there”.
- Lower Dk & Low Df
 - Lower Dk (ϵ_r) : To achieve lower latency/delay signal
 - Lower Df ($\tan\delta$): To avoid signal loss at high speed signal
- Users' request
 - Dk and Df at target frequency range = to cover 30GHz and 80GHz

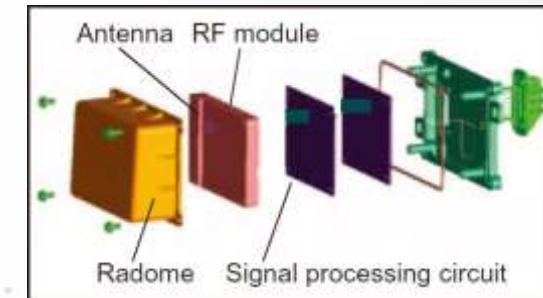


Propagation delay vs. Dk of ceramics

Figure modified based on https://www.jstage.jst.go.jp/article/ieejfms1990/113/7/113_7_495/_pdf/-char/ja

Desired performance for mmWave radar material

Product	mmWave radar		
Material	Bumper Emblem Paint	Radome	Antenna & print circuit board
Requirement	Good transparency for mmWave		Low cost, Small footprint, Avoid performance degrade at mmWave
Desired electric performance	Low refraction and low loss =Low dk, less than 3.0 Low df to avoid loss in mmWave range	Low loss transmission line = low df, High conductivity. Accurate dk value & anisotropy understanding for good design	



Ref. Denso Technical review vol.9 No.2

All application request low dk and low df material

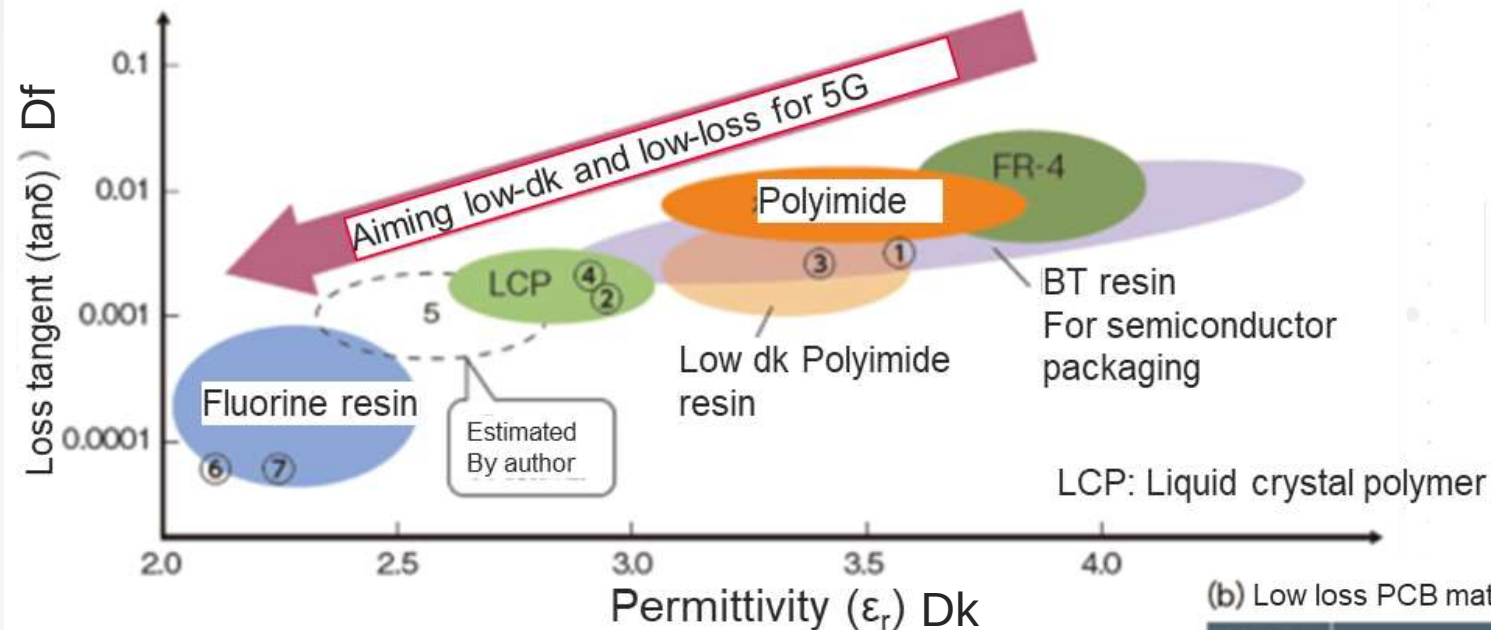
Expected performance for 5G dielectric materials

Product	Rigid / Flexible print circuit board	IC / Semiconductor	Antenna protection, Mobile chassis	Others
Material	Resin Base material Composite Registration Adhesive Coverlay Copper Clad Laminate (CCL) Pre-preg	IC package Sealing material Adhesive Under fill	Resin Paint	Glass Transparent base Optical material Camera lens Anti-reflection film Connector form
Expected performance	Low dk, Low df, Low loss, Low transmission loss(Surface conductivity)	Low dk, Low df, User expects that filling space by resin doesn't change performance vs. air		

All application request low dk and low df material

Typical PCB material Dk and Df

(a) Characteristics of PCB materials



(b) Low loss PCB material examples

(a) での位置	Supplier	Product name	Material	Release schedule
①	Panasonic	R-5575	Thermosetting resin (details are hidden)	Released on June 2017
②	Panasonic	FELIOS LCPとR-BM17	Cpre as LCP	Prod. on Jan. 2017
③	MGC	HL972LF type LD	BT resin	Prod. on May 2017
④	DYCONEX社	Advanced LCP Substrates	LCP	Early production
⑤	Murata	MetroCirc	LCP and Fluorine resin (estimation by nikkeibp)	Production. Released on Nov. 2016
⑥	Rogers社	CuClad	Fluorine resin (PTFE)	Production
⑦	Sumitomo Elec	未定	Fluorine resin	Under development

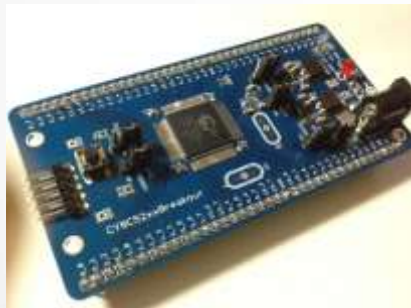
Ref; NikkeiBP 2017July
<https://tech.nikkeibp.co.jp/dm/atcl/mag/15/398081/071100093/>

Challenges of Dielectric Parameter Measurements



Result often differs from simulation...

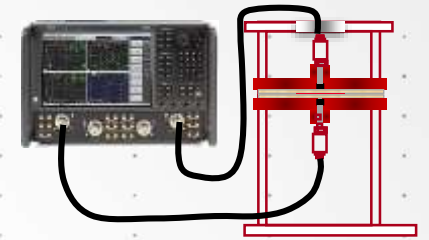
- Another 8 to 12 weeks to run the 2nd round
- Cost thousands\$



1. Design a circuit

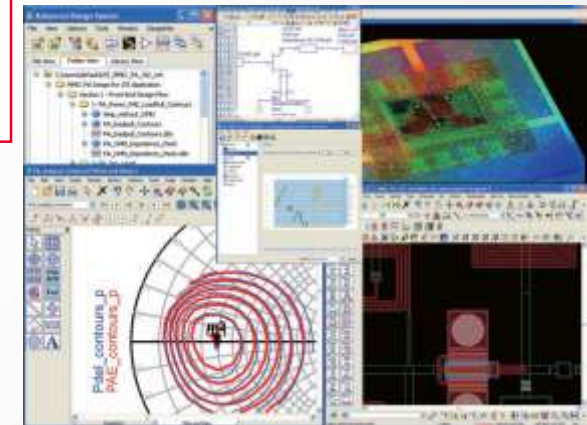


2. getting ϵ_r
 $\tan\delta$ from the
data sheet



2+. Material Test

3. Circuit
simulation



4. Design the
final circuit

5. Make an
actual circuit

6. Evaluate the
circuit and find
difference!

4~ weeks

4-6 weeks

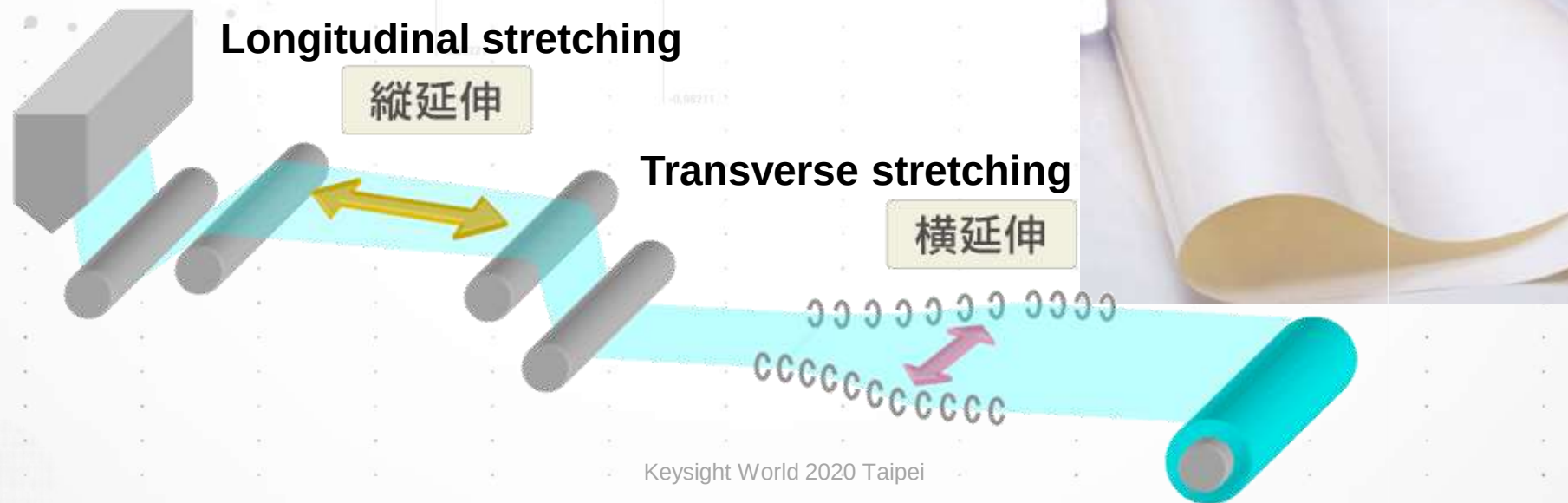
Dielectric constants in the in-plane X and Y directions may be different

Liquid crystal polymer (LCP film)

1. Low water absorption
2. Excellent high-frequency electrical characteristics (low permittivity, low dielectric loss)
3. High dimensional stability

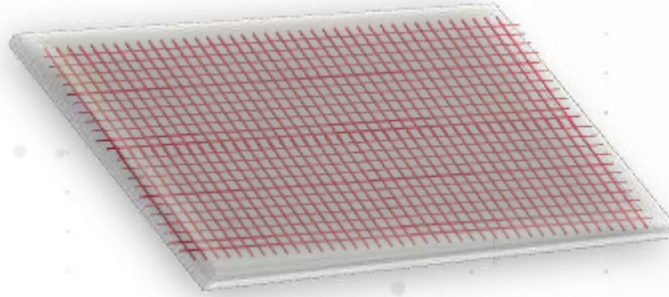
But, strong **anisotropy**

...In recent years, a method for controlling anisotropy has been developed



Case 2 glass epoxy substrate / FR-4

FR-4 is impregnated glass cloth ($D_k = 6.3$) with organic resin ($D_f = 2 - 4$), and then stacked many layers



Supplier A; Nominal value of $D_k = 4.4$

Supplier B ; Nominal value of $D_k = 4.2$

Results are different depending on what measurement method is used

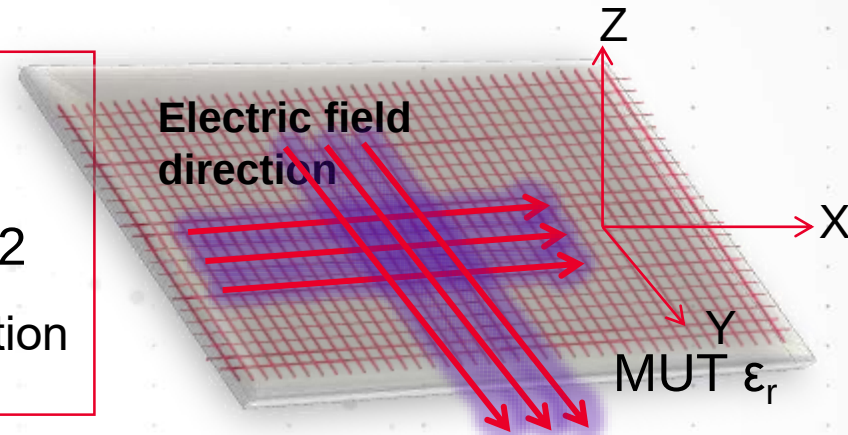
The glass epoxy substrate has its **anisotropy** due to its structure.

Actual meas. value of supplier A

permittivity in plane direction = 4.43

permittivity in thickness direction = 4.02

→ “Nominal value” means in plane direction

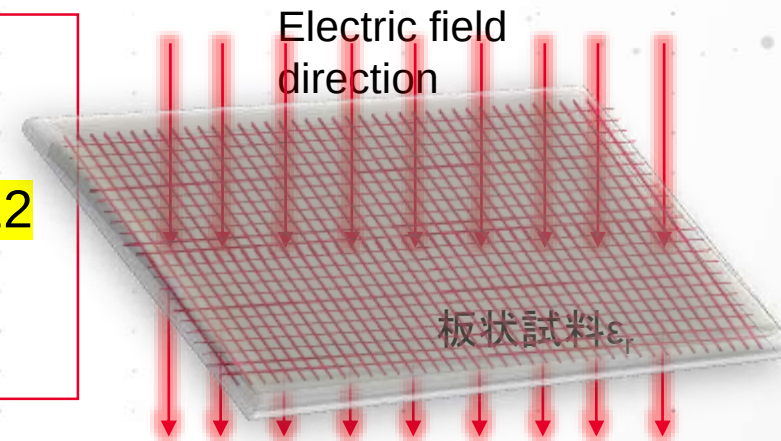


Actual meas. value of supplier B

permittivity in plane direction = 4.55

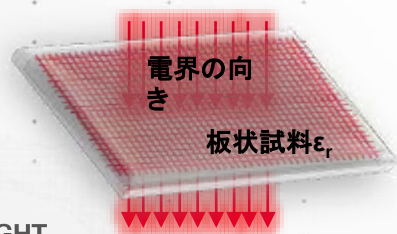
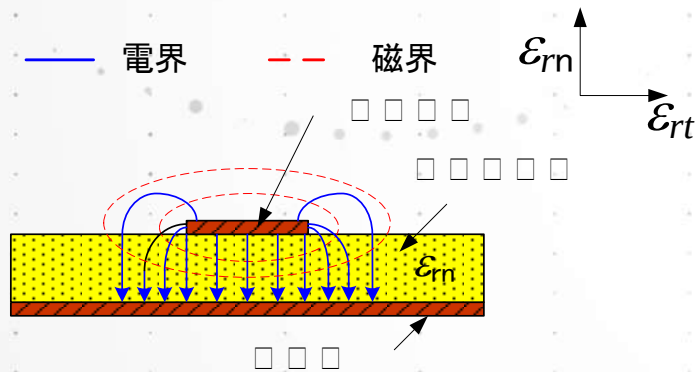
permittivity in thickness direction = 4.22

→ “Nominal value” means in thickness direction

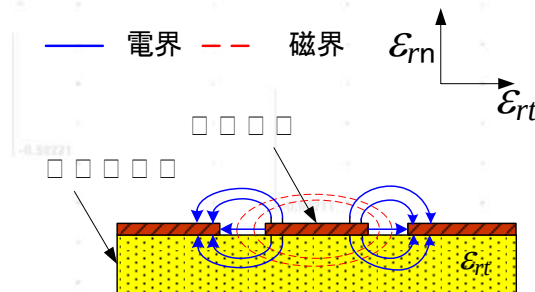


The electric field in the vertical (thickness) and horizontal (surface) direction

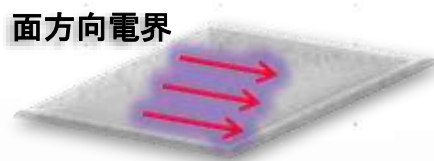
Strip line / Micro strip line



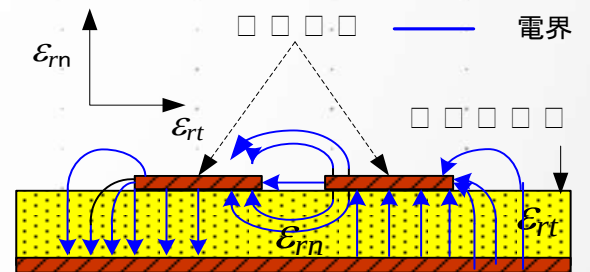
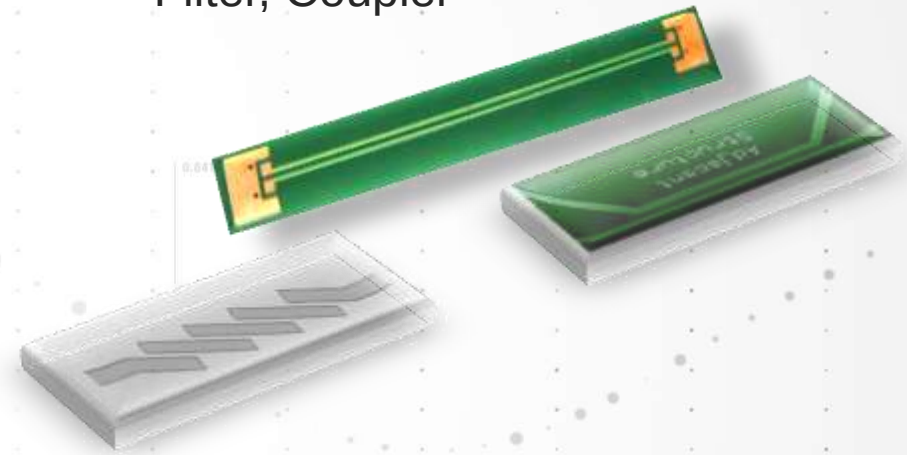
Coplanar line



面方向電界



Differential transmission line, Filter, Coupler

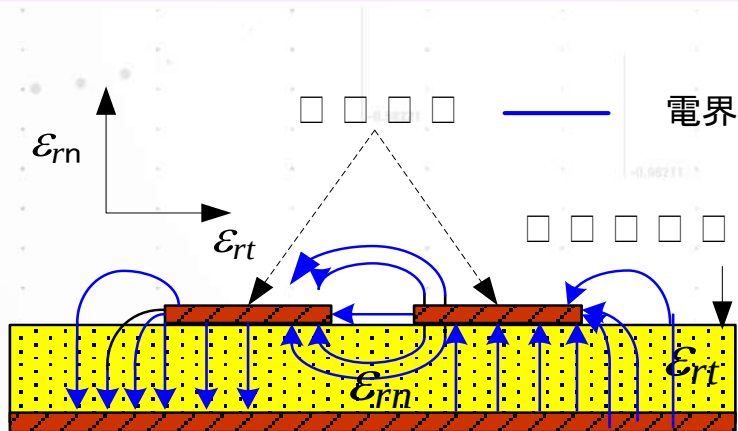


Not only surface direction, but also thickness direction measurement

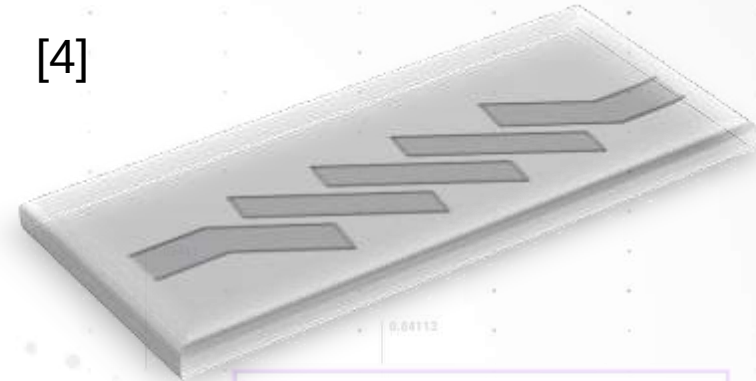
[3]



Differential strip transmission line

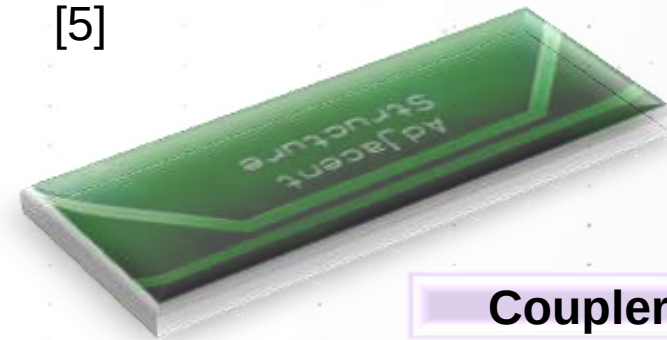


[4]



Band pass filter

[5]

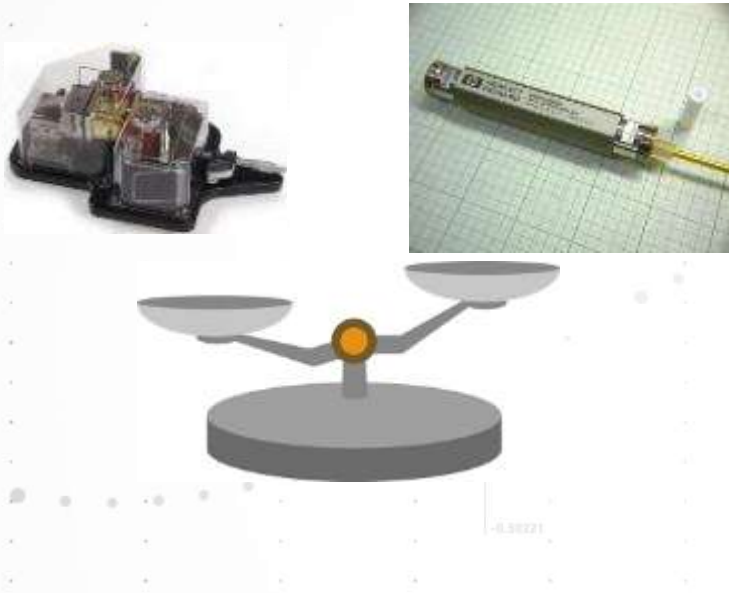


Coupler

**Dominant direction is vertical and horizontal, both.

Materials Characterization Challenges

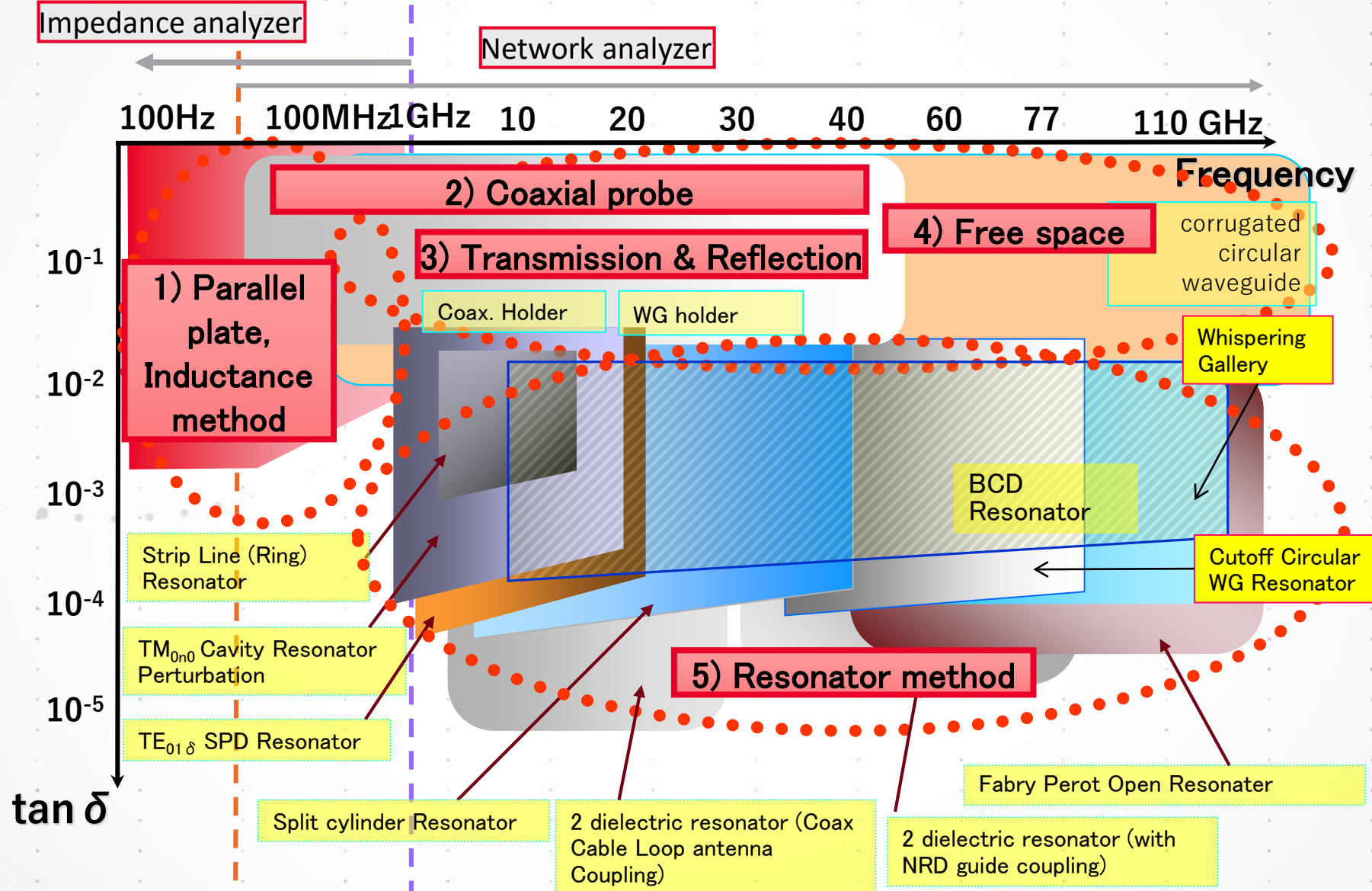
ACCURATE?



Which method should I use?

Improper fixture selection
causes failure results

Solution Mapping: 5 major methods



Select the most suitable method for your MUT

COMPROMISE IS NO LONGER REQUIRED

Parallel Plate & Inductance

ϵ_r and μ_r



Low Frequency below 1GHz

Best for thin flat sheets

Coaxial Probe

ϵ_r



Broadband

Best for liquids, semi-solids

Transmission Line

ϵ_r and μ_r

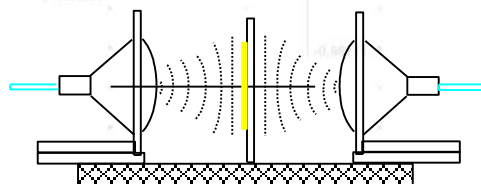


Broadband

Best for machine-able solids

Transmission Free Space

ϵ_r and μ_r



Broadband, mm-wave

Non-contacting

Resonant Cavity

ϵ_r



Single frequency

High accuracy, Best for low loss, or very thin samples

+



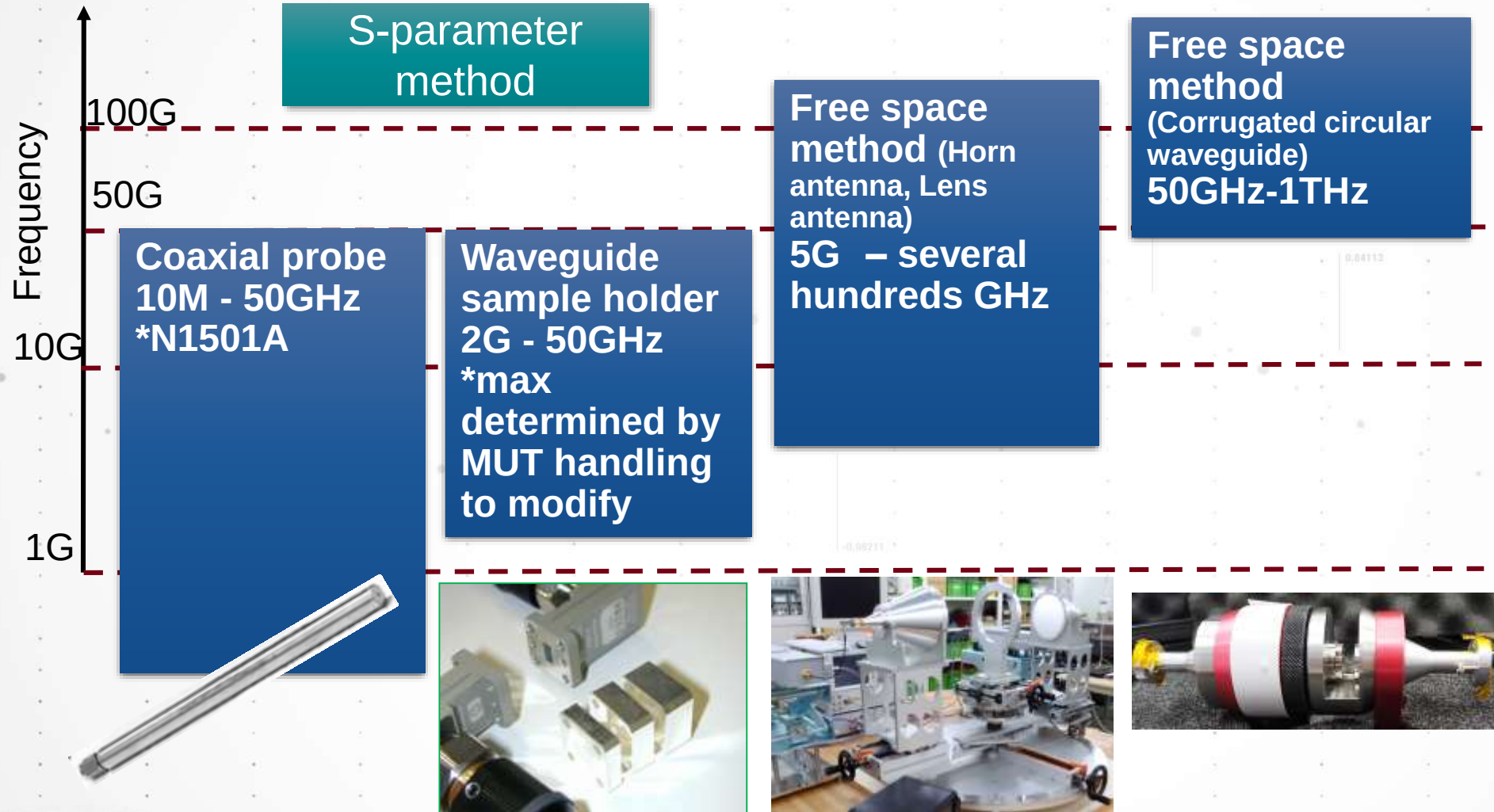
New mmWave Material Test Solutions

- **Balanced Circular Disk Resonator (BCDR)**
- **Split Cylinder Resonator (SCCR)**



Material measurement method for mmWave type 1

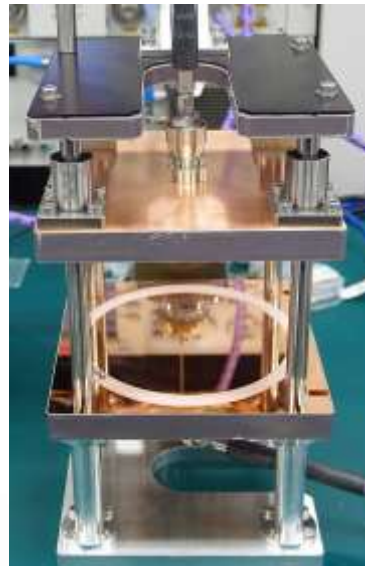
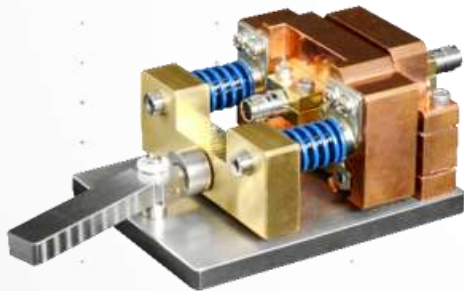
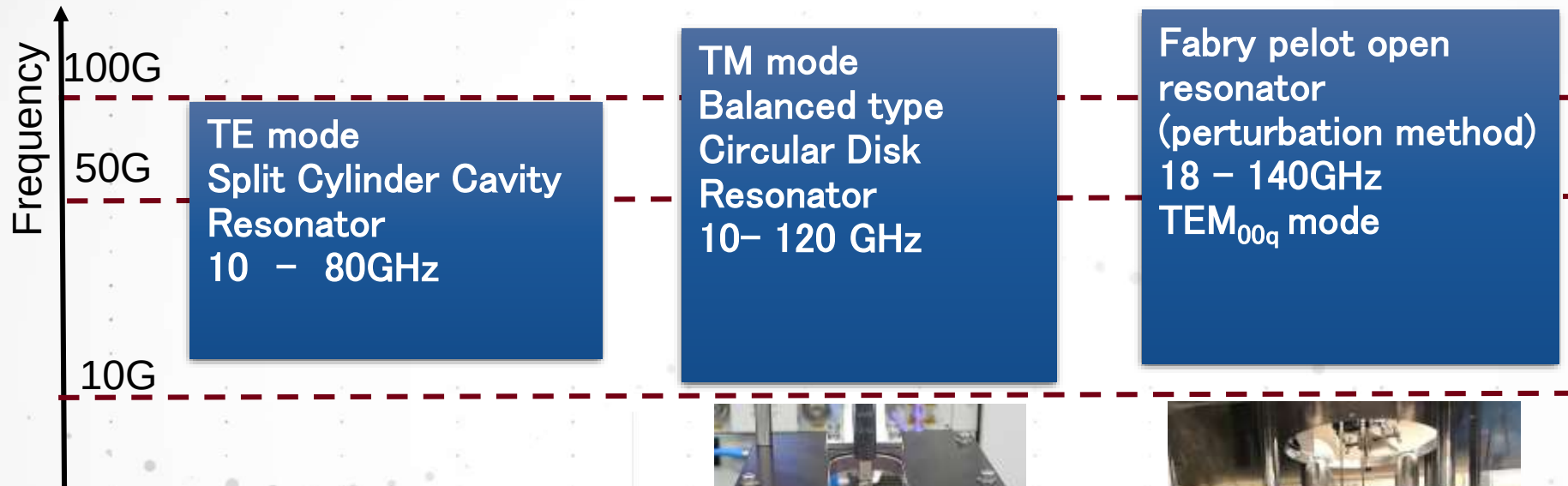
- Continuous frequency point measurements (For Dk or high loss)



Material measurement method for mmWave type 2

- Best for low loss, plate or film type MUT

Resonator method



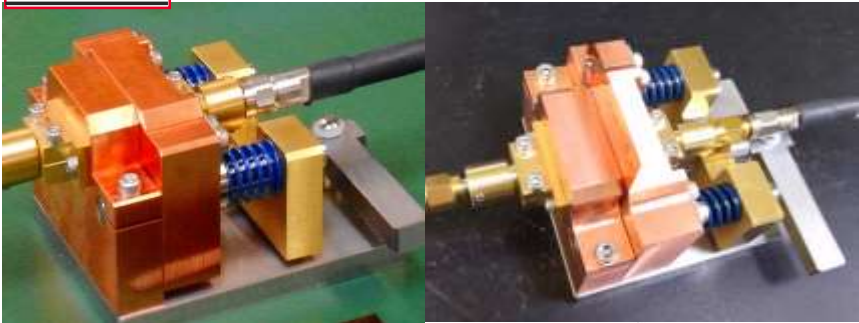
Resonant Cavity Fixtures available thru Keysight

SPDR



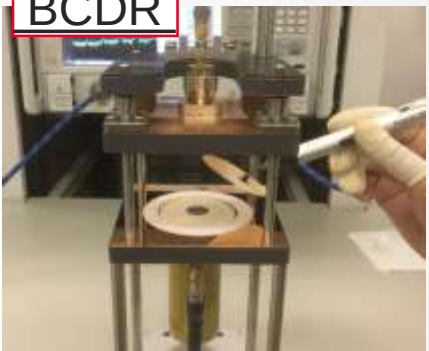
Model #	Description
N1501AE19	1.1 GHz, 3.5 mm (m) Split Post Dielectric Resonator
N1501AE03	2.5 GHz, 3.5 mm (m) Split Post Dielectric Resonator
N1501AE04	5.0 GHz, 3.5 mm (m) Split Post Dielectric Resonator
N1501AE10	10.0 GHz, 3.5 mm (m) Split Post Dielectric Resonator
N1501AE15	15 GHz, 3.5 mm (m) Split Post Dielectric Resonator

SCCR

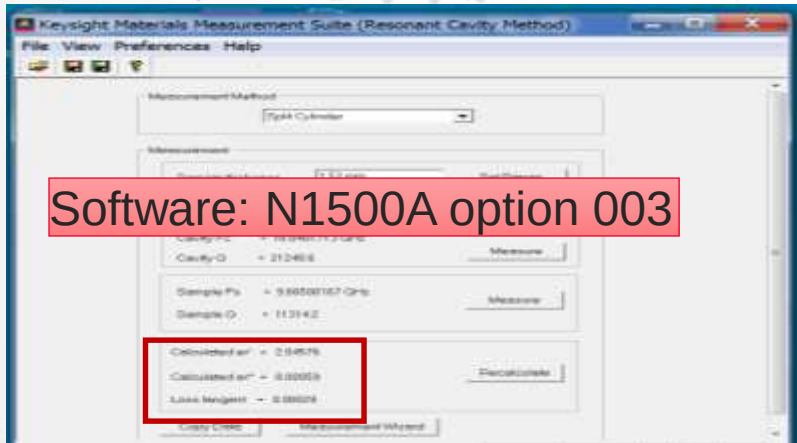


Model #	Description
N1501AKEAD-710	10 GHz, SMA (f) Split Cylinder Resonator
N1501AKEAD-720	20 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-724	24 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-728	28 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-735	35 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-740	40 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-750	50 GHz, 2.4 mm (f) Split Cylinder Resonator
N1501AKEAD-760	60 GHz, 1.85 mm (f) Split Cylinder Resonator
N1501AKEAD-780	80 GHz, 1 mm (f) Split Cylinder Resonator
N1501AKEAD-ST1	Software Split Cylinder Resonator Starter Kit

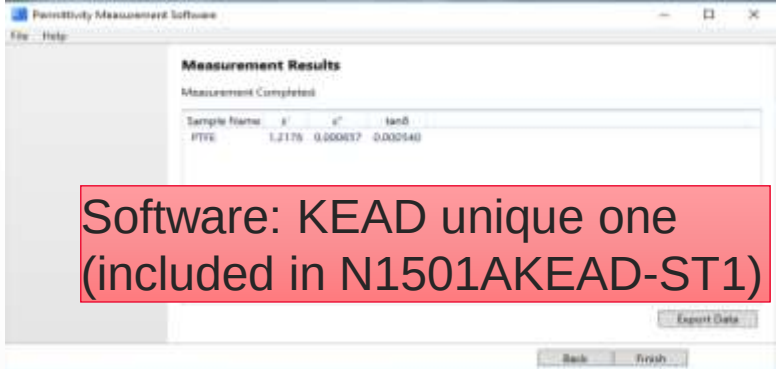
BCDR



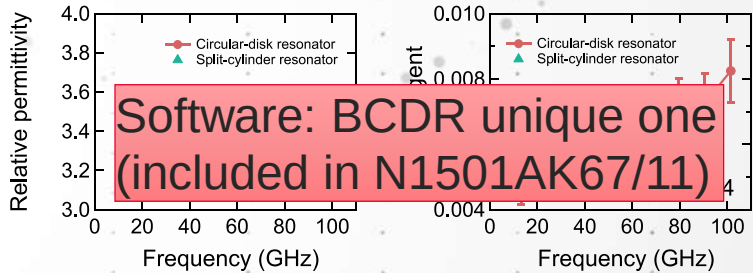
Model #	Description
N1501AE67	67 GHz Balanced Circular Disk Resonator
N1501AE11	110 GHz Balanced Circular Disk Resonator



Software: N1500A option 003



Software: KEAD unique one
(included in N1501AKEAD-ST1)



SCCR

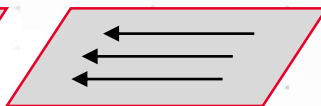


85072A 10 GHz Split Cylinder Resonator

Software: N1500A option 003

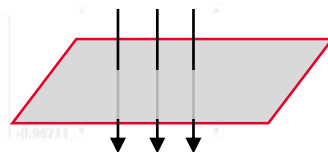
Low loss ($<10^{-2}$) solution mapping

E-Field direction Horizontal (X-Y)



Method	Original Supplier	Frequency	Standard	MUT thickness, size (Vary depends on ϵ_r' & freq.)
TM0x0 perturbation cavity	KEAD, Keycom, etc.	1G to 10 GHz	JIS C2565, ASTM D2520	
TE01x Split Post Dielectric Resonator (SPDR)	QWED (N1501AExx)	1.1G to 15 GHz		0.7 mm, 15mm x 15mm @15G
TE011 Split Cylinder Cavity Resonator (SCCR)	Keysight (85072A), KEAD (N1501AKEAD)	Up to 80 GHz	IPC TM-650 2.5.5.13	20 μm ~ 300 μm (best for 100 μm), 34mmx45mm > 20G
TEM00x Fabry-Perot Open Resonator	Keycom	Up to 140 GHz	JIS R 1660-2	10~20 μm , max 100 μm . 65mm x 65mm

E-Field direction Vertical (Z)



Method	Original Supplier	Frequency	Standard	MUT thickness, size (Vary depends on ϵ_r' & freq.)
Parallel plate capacitor method	Keysight 16451B/453A	30M / 1 GHz	ASTM D150 / n/a	
Line/Ring resonator	Keycom, self-made, etc.	Up to 15 GHz	IPC TM-650 2.5.5.5.1	
TM0x0 Balanced Circular-Disk Resonator (BCDR)	Oshima (N1501AE67/11)	Up to 67/110 GHz	Plan to publish IEC IC in 2020 May	0.1 mm ~ 1mm, Best for 0.2~0.5mm, 50mm Φ x 2 ea.

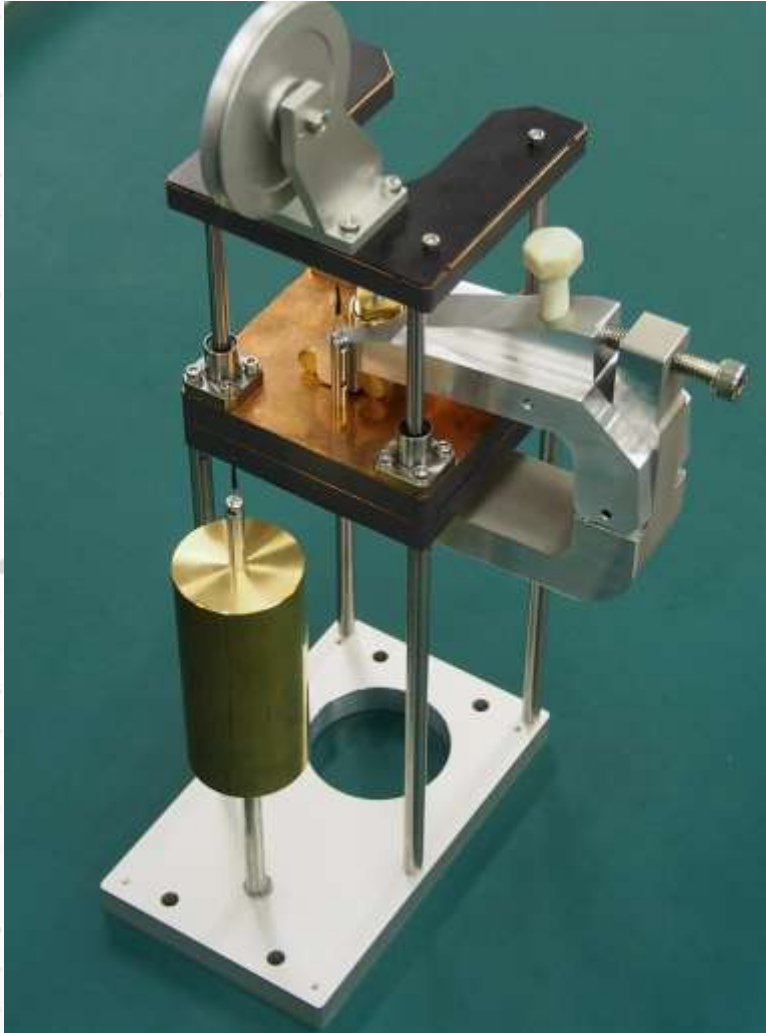
New mmWave Material Test Solutions

- ✓ Balanced Circular Disk Resonator (BCDR)
- Split Cylinder Resonator (SCCR)



Exterior Photo of BCD Resonator

BALANCED TYPE CIRCULAR DISK RESONATOR



BCD Resonator and PNA (Coax. and WG Banded)

Configuration

Only PNA supported



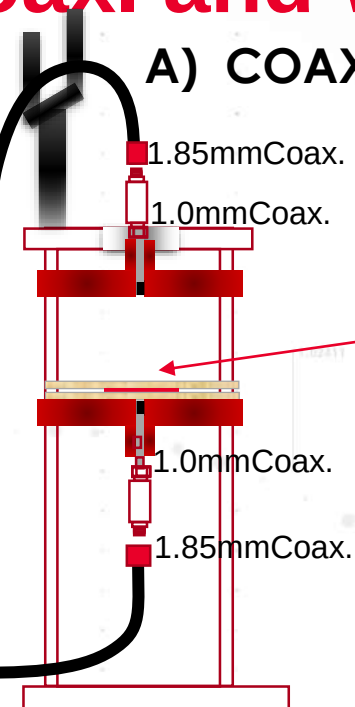
L > 900mm



BCDR
Software

Windows PC 64bit

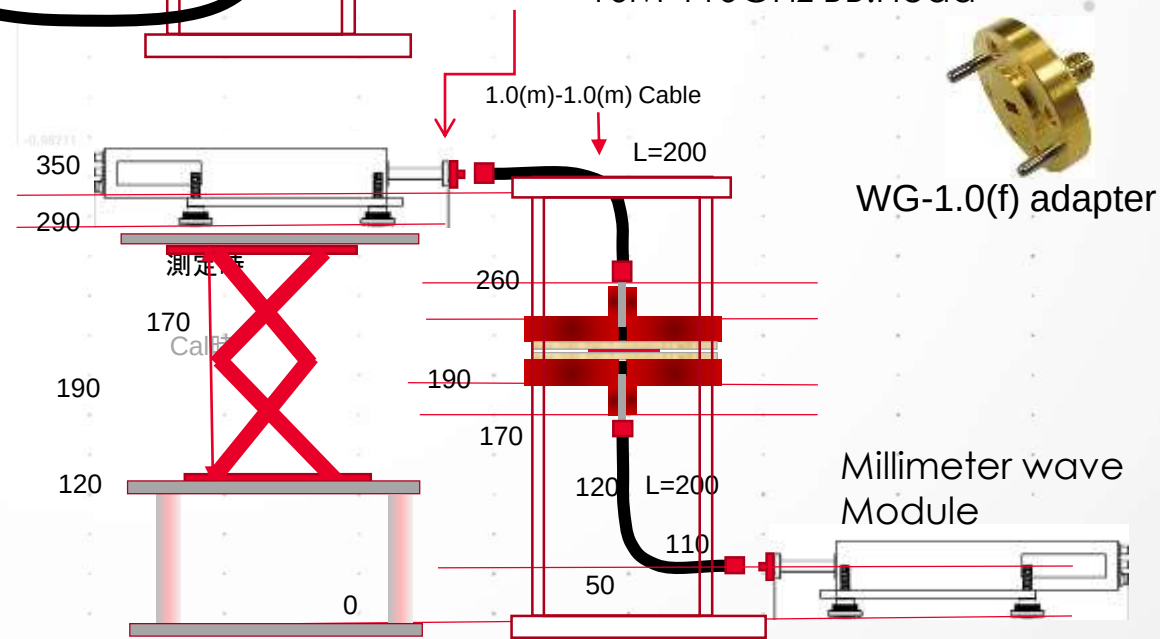
A) COAX. BAND < 70GHz



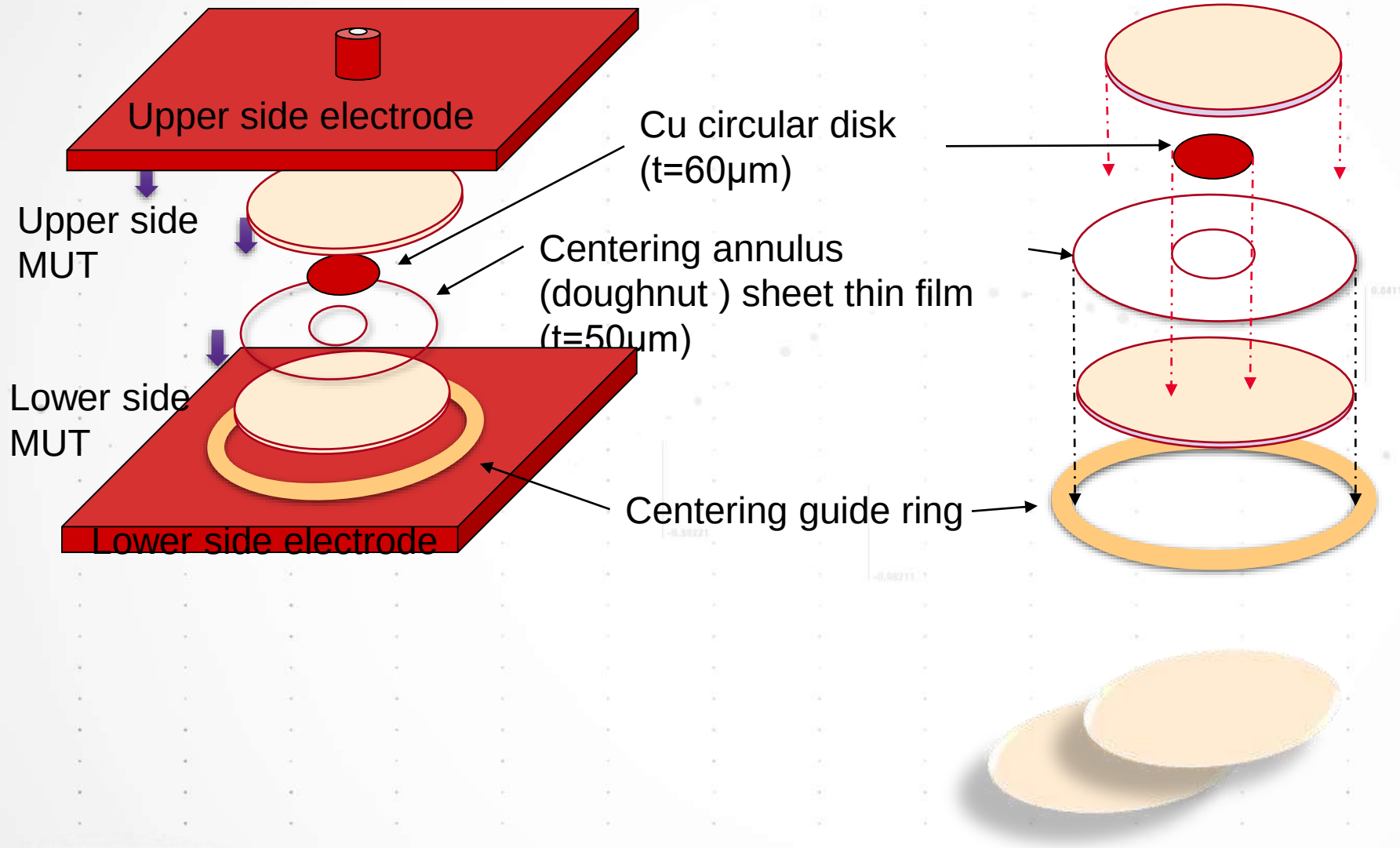
DISK electrode and
2MUT

B) Waveguide BAND

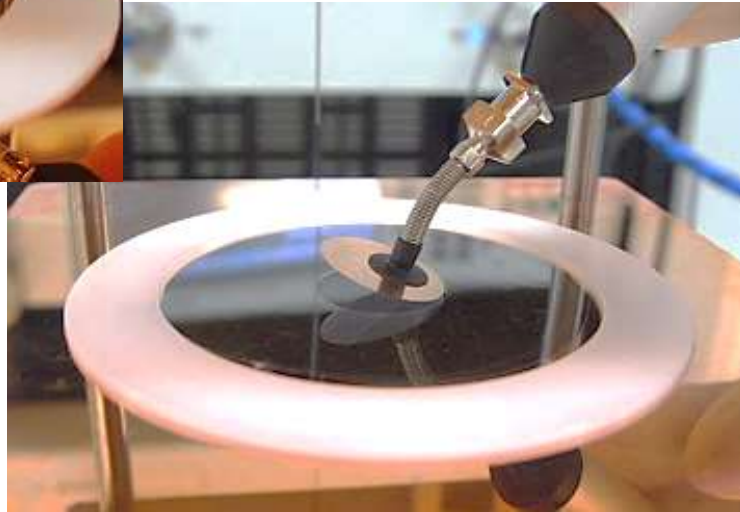
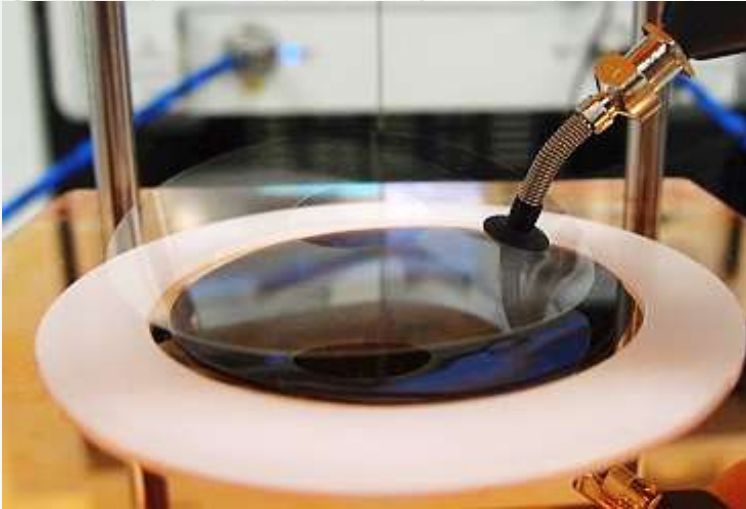
BANDED Module or
10M-110GHz BB.Head



Setting electrode and MUT inside Cavity

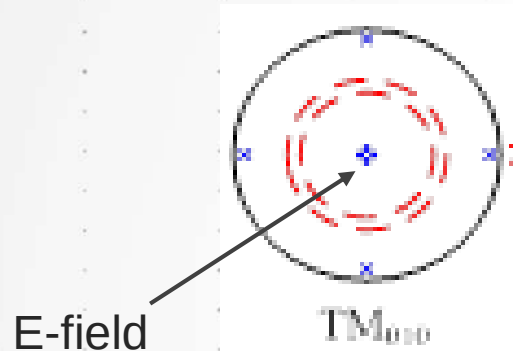


Set up the MUT and electrode



Resonant Frequency (Approximation formula)

TM_{0m0} RESONANT FREQUENCY APPROXIMATE EXPRESSION



$$f_{0m0} = \frac{c}{2\pi R \sqrt{\epsilon_{rn}}} x'_{0m0}$$

$$f'_{010} = 3.8317$$

$$f'_{020} = 7.0155$$

$$f'_{030} = \dots$$

....

R= radius of center electrode

ϵ_{rn} = permittivity (Dk) of thickness direction

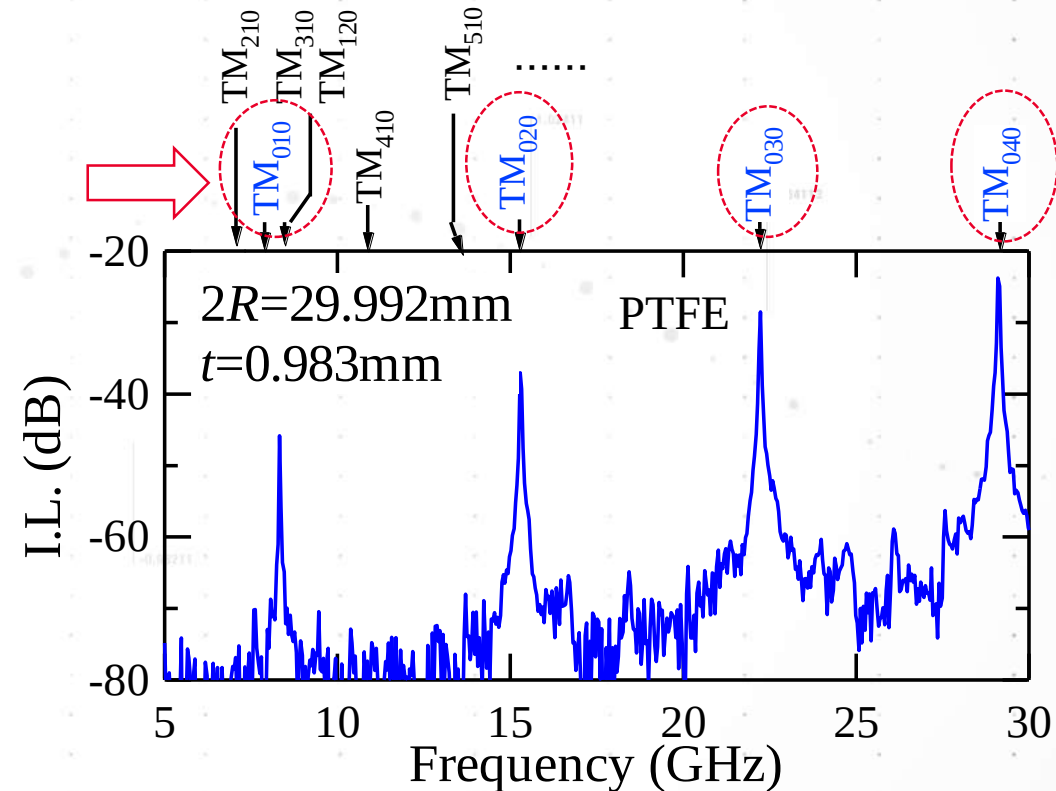
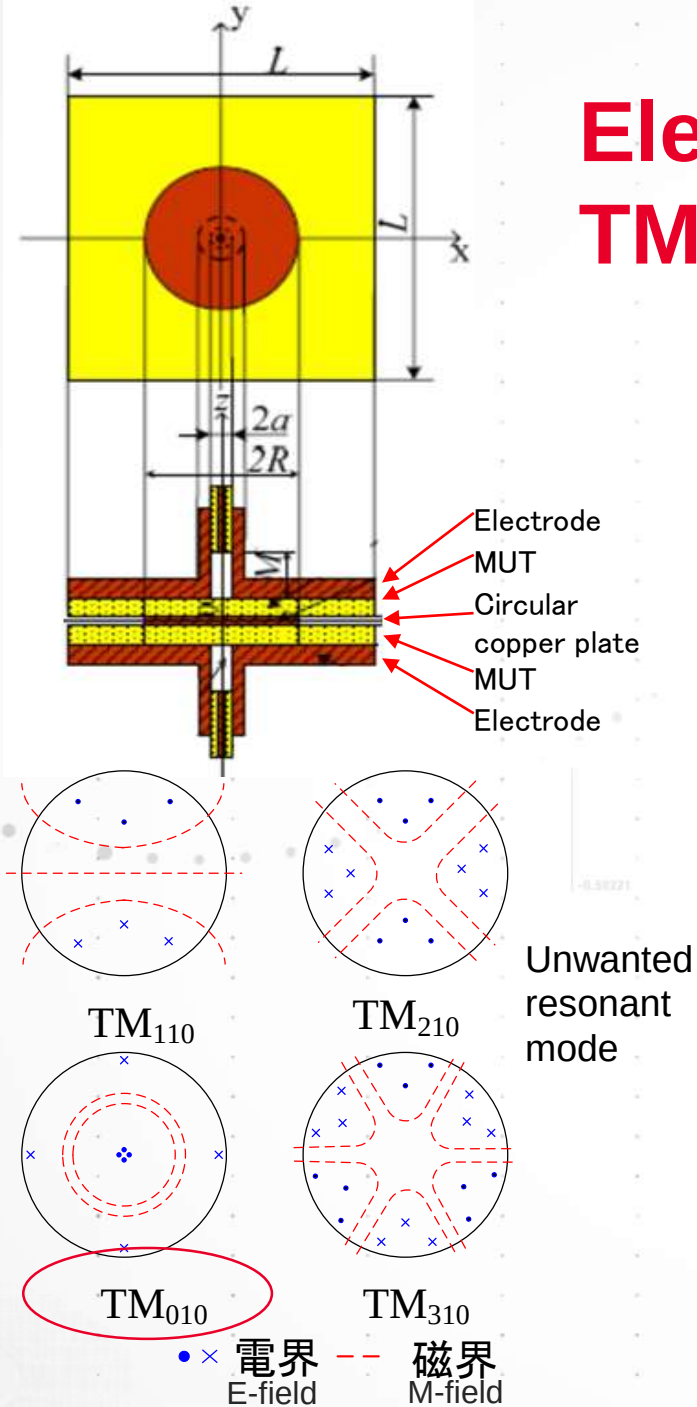
PTFE($\epsilon_r=2.04$) disc $\Phi 15\text{mm}$ $f_{010} \cong 17.07\text{GHz}$

FR4 ($\epsilon_r=4$) disk $\Phi 15\text{mm}$ $f_{010} \cong 11.89\text{GHz}$

PTFE($\epsilon_r=2.04$), disk $\Phi 18\text{mm}$ $f_{010} \cong 14.22\text{GHz}$

FR4($\epsilon_r=4$) , disk $\Phi 18\text{mm}$ $f_{010} \cong 9.9\text{GHz}$

Electromagnetic field distribution in TM_{0m0} resonance mode



Dielectric measurement in microwave –
 IEICE, vol. J89-C, no.12, pp.1039-1046, Dec.
 2006,
 Hasuike, Kawabata, Kobayashi

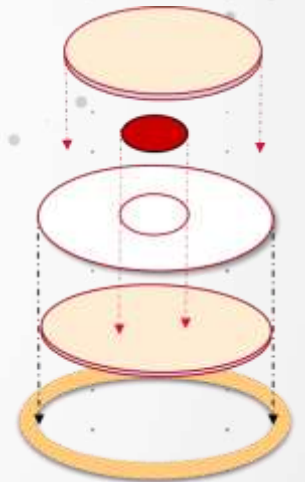
TM_{0m0} Resonant Frequency (Approximation)

CALCULATED FROM RESONATOR DIAMETER AND DIELECTRIC CONSTANT

TM0m0 BCDR, Electrode diameter vs. Permittivity vs. Resonant frequency (GHz)												
		Electrode diameter (mm)			Electrode diameter (mm)			Electrode diameter (mm)				
		12	6.00E-03		15	7.50E-03		18	9.00E-03			
		Permittivity			Permittivity			Permittivity				
X'0m0 value	Mode	2.04	4.2	6.5	Mode	2.04	4.2	6.5	Mode	2.04	4.2	6.5
3.8317	TM010	21.33	14.87	11.95	TM010	17.07	11.89	9.55	TM010	13.45	9.45	7.71
7.0155	TM020	39.06	27.22	21.88	TM020	31.14	21.89	17.55	TM020	24.45	17.45	14.21
10.1743	TM030	56.65	39.48	31.14	TM030	45.17	31.89	25.55	TM030	35.45	25.45	20.21
13.3237	TM040	73.33	51.32	40.10	TM040	58.89	41.89	32.55	TM040	45.45	32.45	25.21
16.4730	TM050	89.06	61.72	48.88	TM050	71.38	50.74	39.55	TM050	55.45	39.45	30.21
19.6223	TM060	104.79	72.12	57.76	TM060	87.37	60.89	48.95	TM060	72.81	50.74	40.79
22.7716	TM070	120.52	88.32	70.99	TM070	101.38	70.65	56.79	TM070	84.48	58.88	47.33
25.9037	TM080	144.22	100.51	80.80	TM080	115.38	80.41	64.64	TM080	96.15	67.01	53.86
29.0468	TM090	161.72	112.71	90.60	TM090	129.38	90.17	72.48	TM090	107.82	75.14	60.40
32.1897	TM0100	179.22	124.91	100.40	TM0100	143.38	99.92	80.32	TM0100	119.48	83.27	66.94

Resonant frequency in each mode (TM0m0 (m=1~n) is determined by sample's Dk and circular disk electrode diameter

Resonant frequency in each mode (TM_{0m0} (m=1~n)) is determined by sample's Dk and circular disk electrode diameter



※Maximum measure-able frequency is determined by thickness and permittivity. See next page.

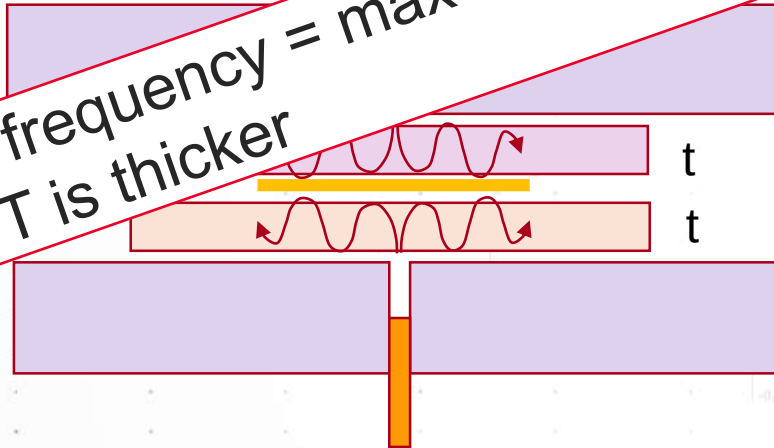
Factors that determine the Max. Frequency

Approximate expression for calculating the cutoff frequency of radial radiation

$$f_c = \frac{c}{2\pi R \sqrt{\epsilon_{rn}}} X_{0m0}(S_c) = \frac{c}{\pi \sqrt{\epsilon_{rn}}}$$

T=MUT thickness
C=Speed of light

Fc (cut off frequency = max frequency) becomes lower when MUT is thicker



Example of maximum frequency calculation

- a) T=1mm $\epsilon_r=2 \Rightarrow 52.85\text{GHz}$
- b) T=1mm $\epsilon_r=4 \Rightarrow 37.37\text{GHz}$
- c) T=1mm $\epsilon_r=9 \Rightarrow 24.91\text{GHz}$

When the thickness of the specimen is increased, the unloaded Q increases. But at the same time, the cutoff frequency regarded as a waveguide consists of center electrode and upper/lower electrode is decreases , and the electromagnetic energy has a radius propagating in the direction toward the outside of the resonator. This radiation causes a limit of measurement frequency.

Max. Frequency(Max. GHz) determined by thickness and permittivity ϵ_r

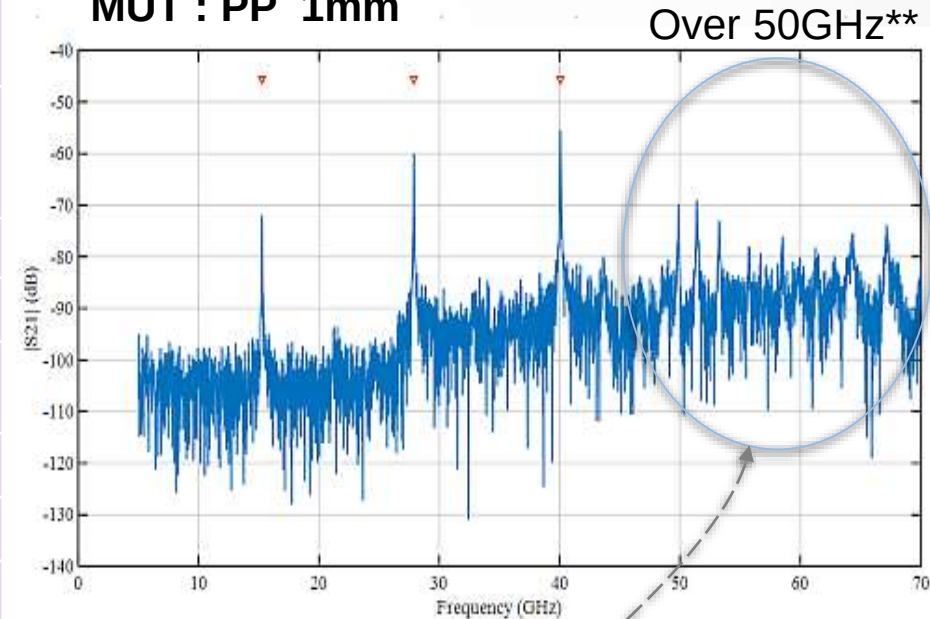
Max frequency becomes lower when MUT is thicker

TM_{0m0} permittivity VS. Max. frequency(GHz)

※can measure at TM_{0m0} under Max. freq.

Permittivity	2.04	4.2	6.5
Thickness mm	Max.GHz	Max.GHz	Max.GHz
1.0	52.5	36.6	29.4
0.9	58.3	40.6	32.7
0.8	65.6	45.7	36.7
0.7	75.0	52.2	42.0
0.6	87.5	61.0	49.0
0.5	104.9	73.1	58.8
0.4	131.2	91.4	73.5
0.3	174.9	121.9	98.0
0.2	262.4	182.9	147.0
0.1	524.7	365.7	294.0

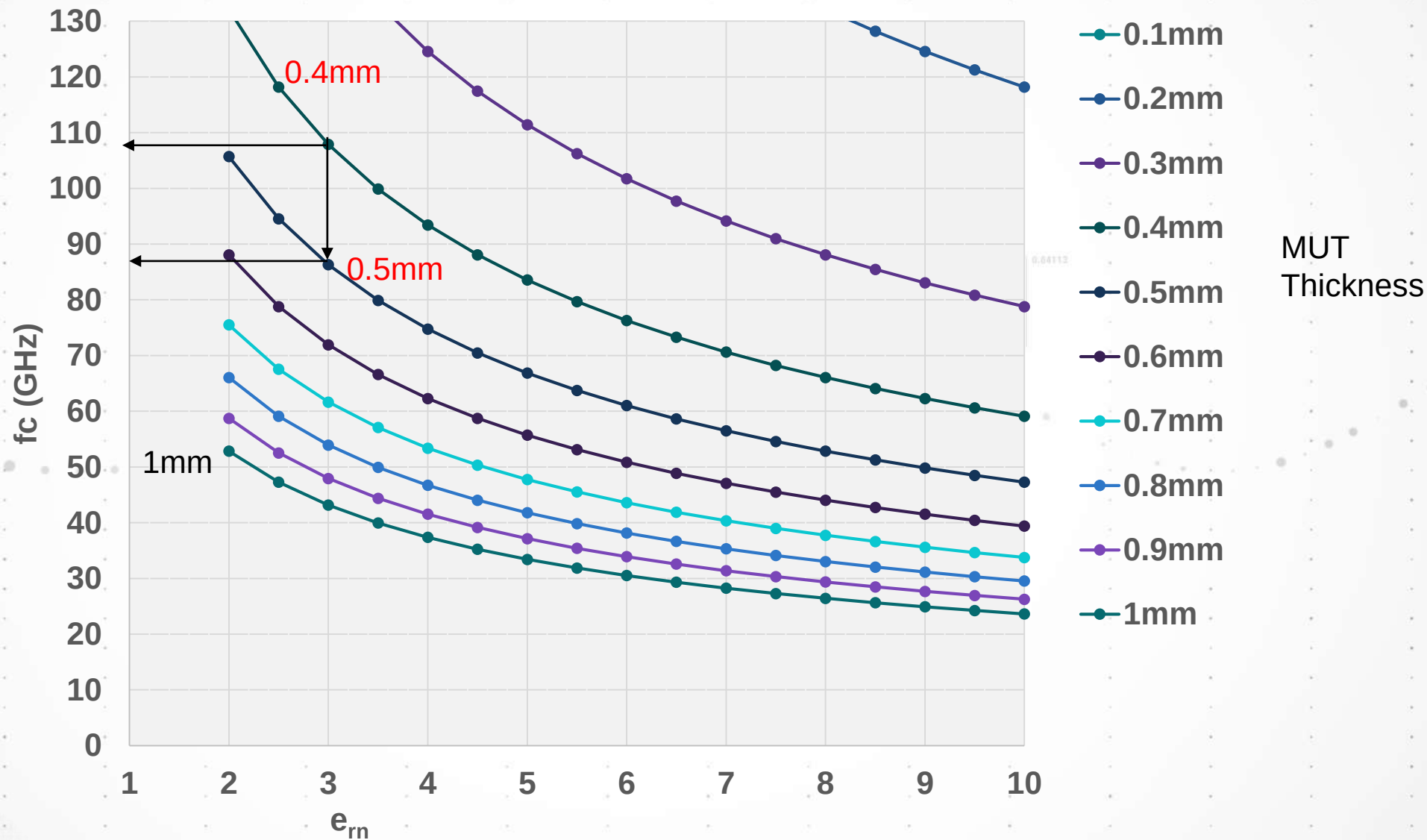
MUT : PP 1mm



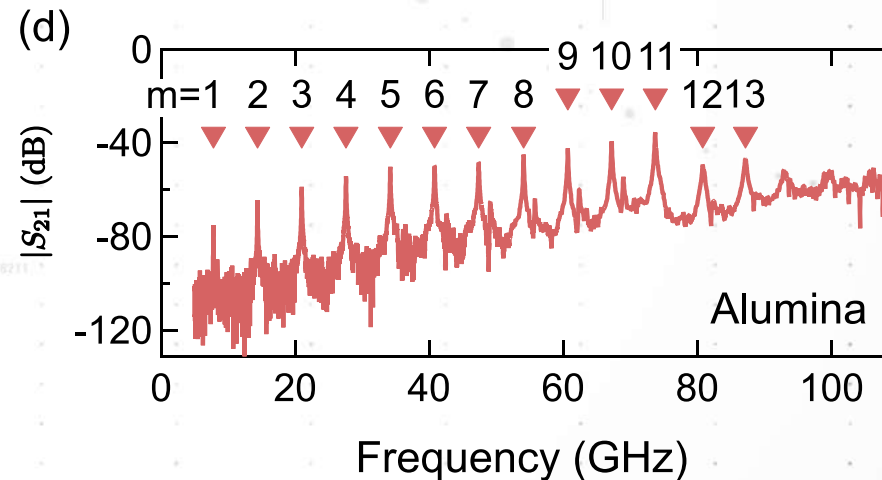
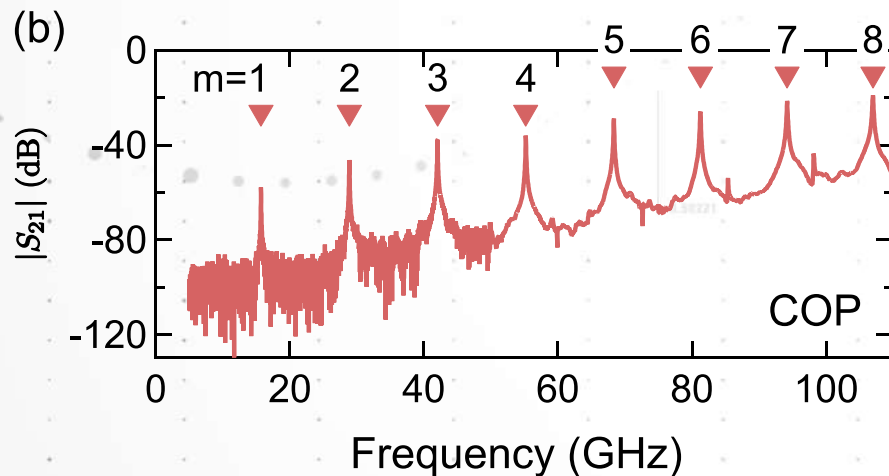
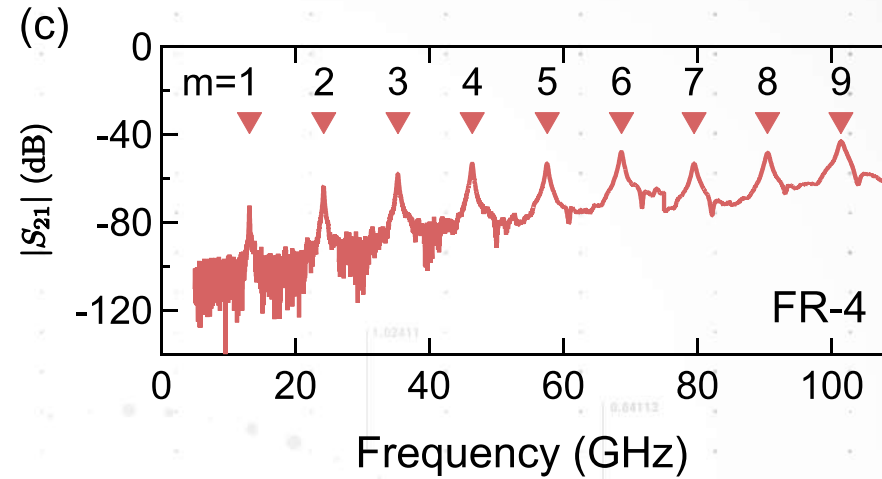
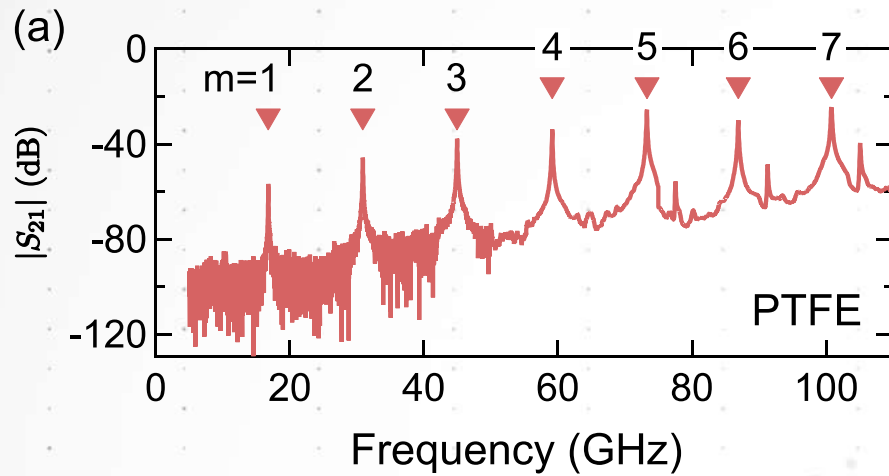
**The resonance peak waveform disappeared due to the influence of energy leakage, making measurement impossible

Max available frequency vs. thickness & Dk

Max. Frequency vs. thickness , permittivity



BCD RESONATOR Resonant traces

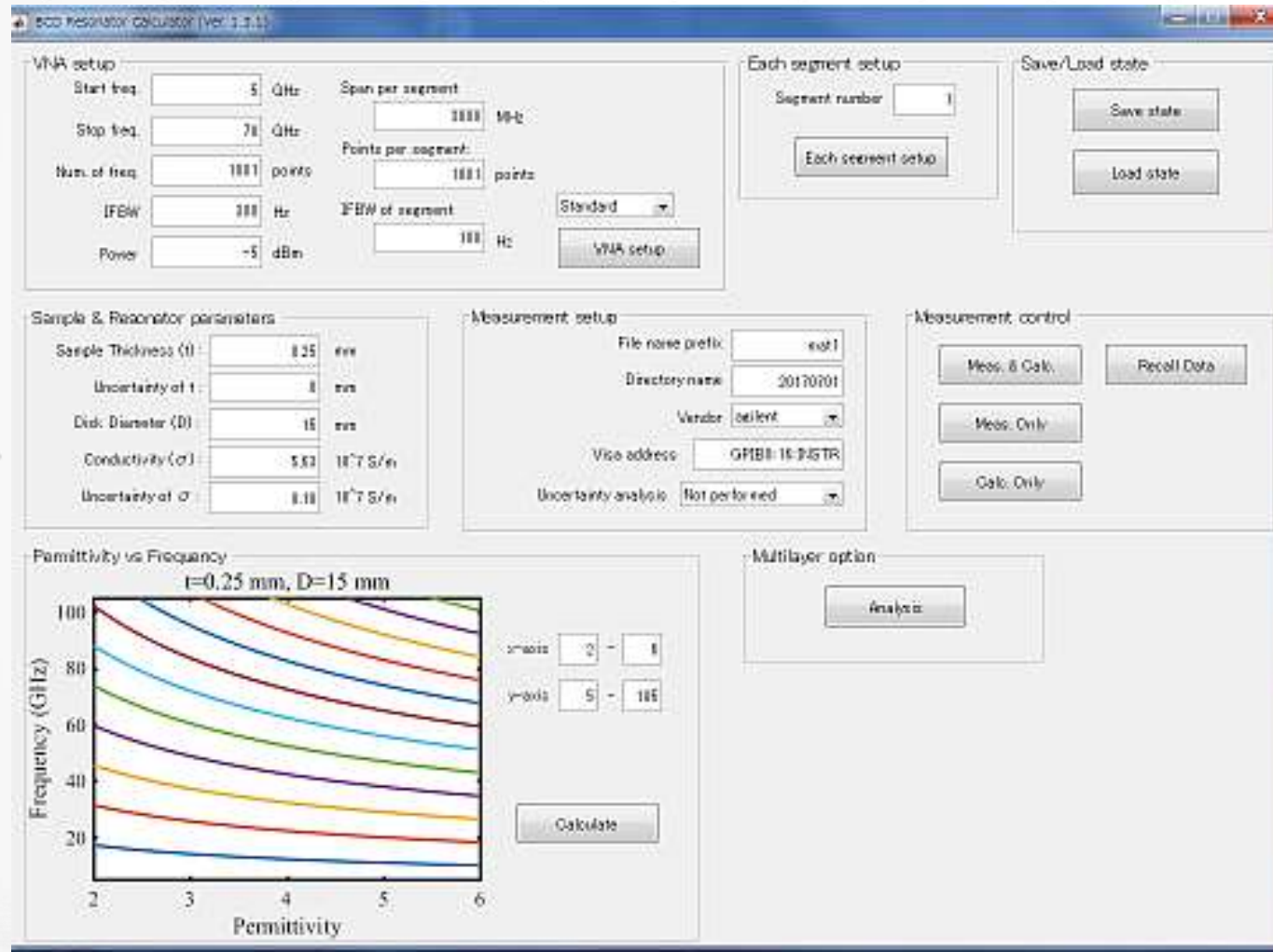


Only TM_{0m0} modes are observed up to **110 GHz** except alumina (radiation error)

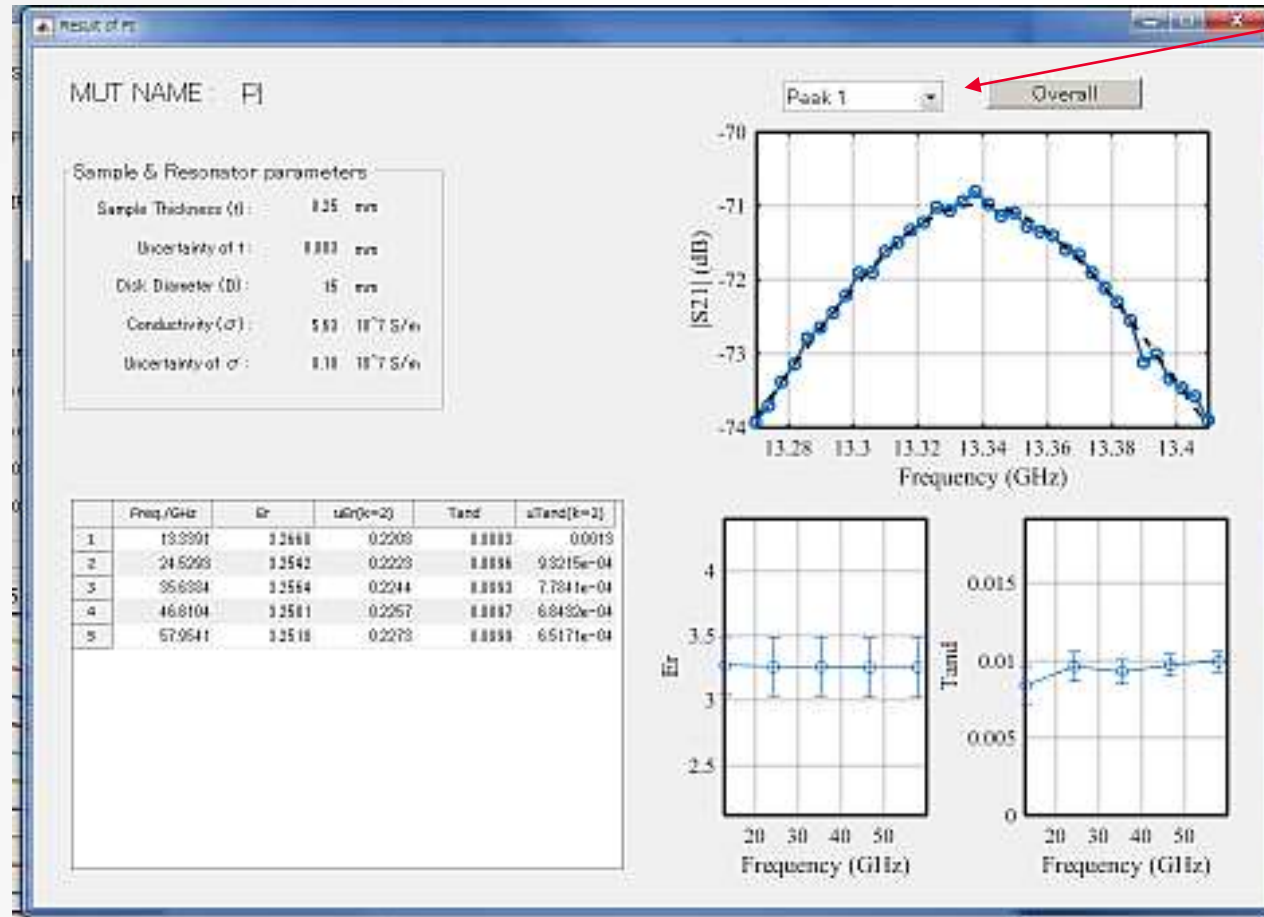
(PTFE: polytetrafluoroethylene, COP: cyclic olefin polymer, FR-4: flame-retardant type 4)

BCD Resonator Software

MATLAB base Software on Windows (64bit) PC

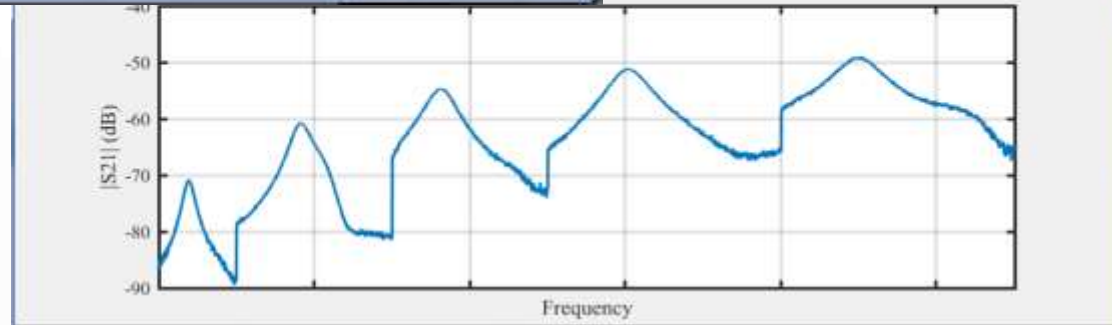


Measurement result

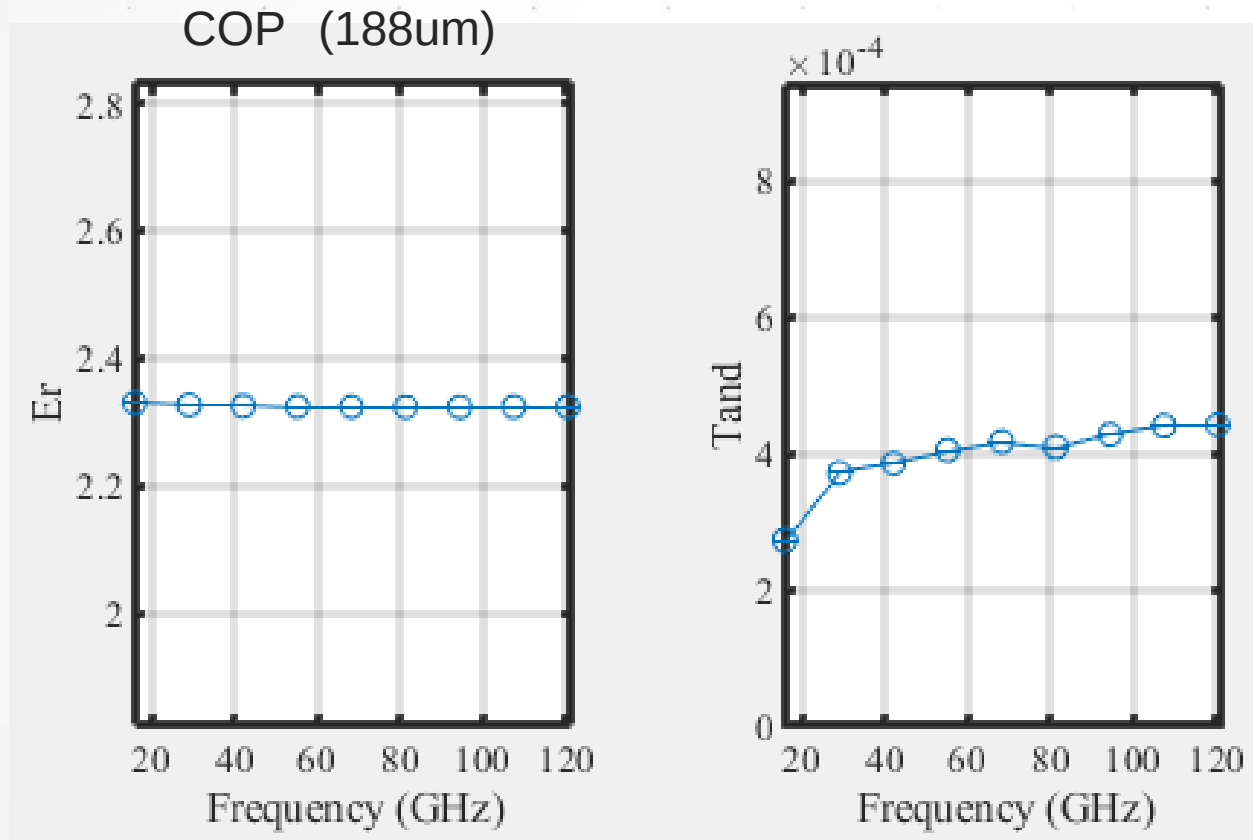


Pull down menu

Peak 1
Peak 2
Peak 3
Peak 4
Peak 5



Measurement result example (COP 188 um)



Excellent repeatability

Data from AIST,

MUT: COP (Er' 2.3x, tanD ~4E-4)

Thickness: 0.2509 mm

of meas: 7

Freq ~ 130G

Dk = ~2.3

Df = 4 x 10E-4

Repeatability

Dk: < 0.2%

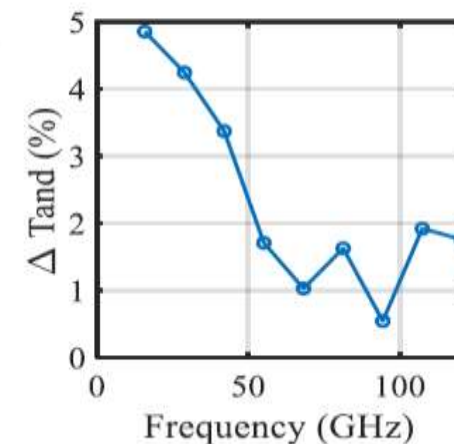
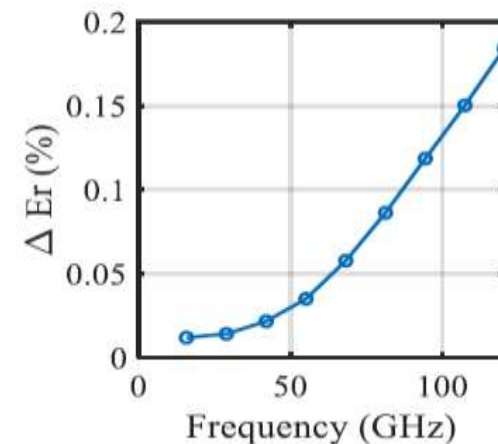
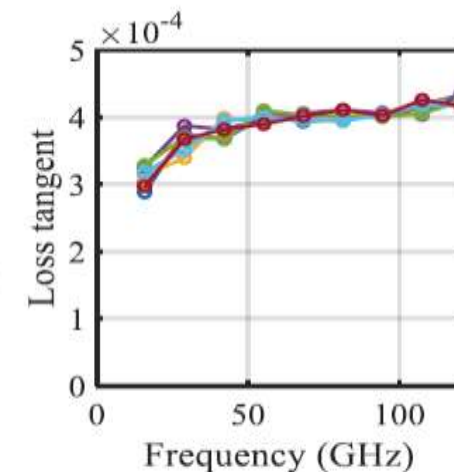
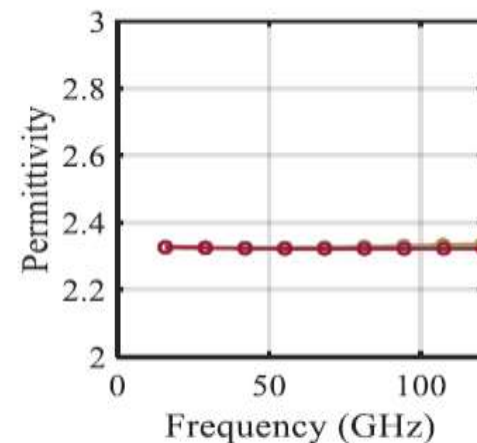
Df: < 5%

- 材料: COP
(cyclic olefin polymer)
- 試料厚: 0. 2509 mm
- 測定回数: 7回
- 周波数: ~130 GHz

$$\text{Repeatability} \equiv \frac{\text{Std.}}{\text{Average}}$$

✓ 誘電率 < 0.2%

✓ 誘電正接 < 5%



BCD Resonator specification

Typical performance

Frequency f : about 10GHz - 110GHz

Circular disk size : $\varnothing 15\text{mm}$, $\varnothing 12\text{mm}$, $\varnothing 18\text{mm}$

Permittivity ϵ_{rn} : 1.1 – 10

Accuracy : $\pm(1-5)\%$

Loss tangent $\tan\delta_n$: 10^{-2} - 10^{-4}

Accuracy : $\pm(10-30)\%$

Size of Dielectric sheet (Sample = Material Under Test)

MUT Thickness(t) : 0.1 - 1mm 0.5mm(better)

MUT SIZE $\varnothing 30\text{mm}$ - $\varnothing 50\text{mm}$ >2 times of circular disk electrode diameter

Fixture Dimension about W104 X D172 X H329.5 mm

Weight about 5kg

Connector type

N1501AE11: 1.0 mm(f) Coax.(Max.110GHz)

N1501AE67: 1.85 mm(f) Coax.(Max.67GHz)

Measurement sample (MUT)

Required number of MUT

1 pair (same permittivity, same thickness)

Suitable sample

Plastic plate-shaped dielectric substrate, sheet dielectric substrate

Not suitable for measurement

Roughness on the surface and having protrusions

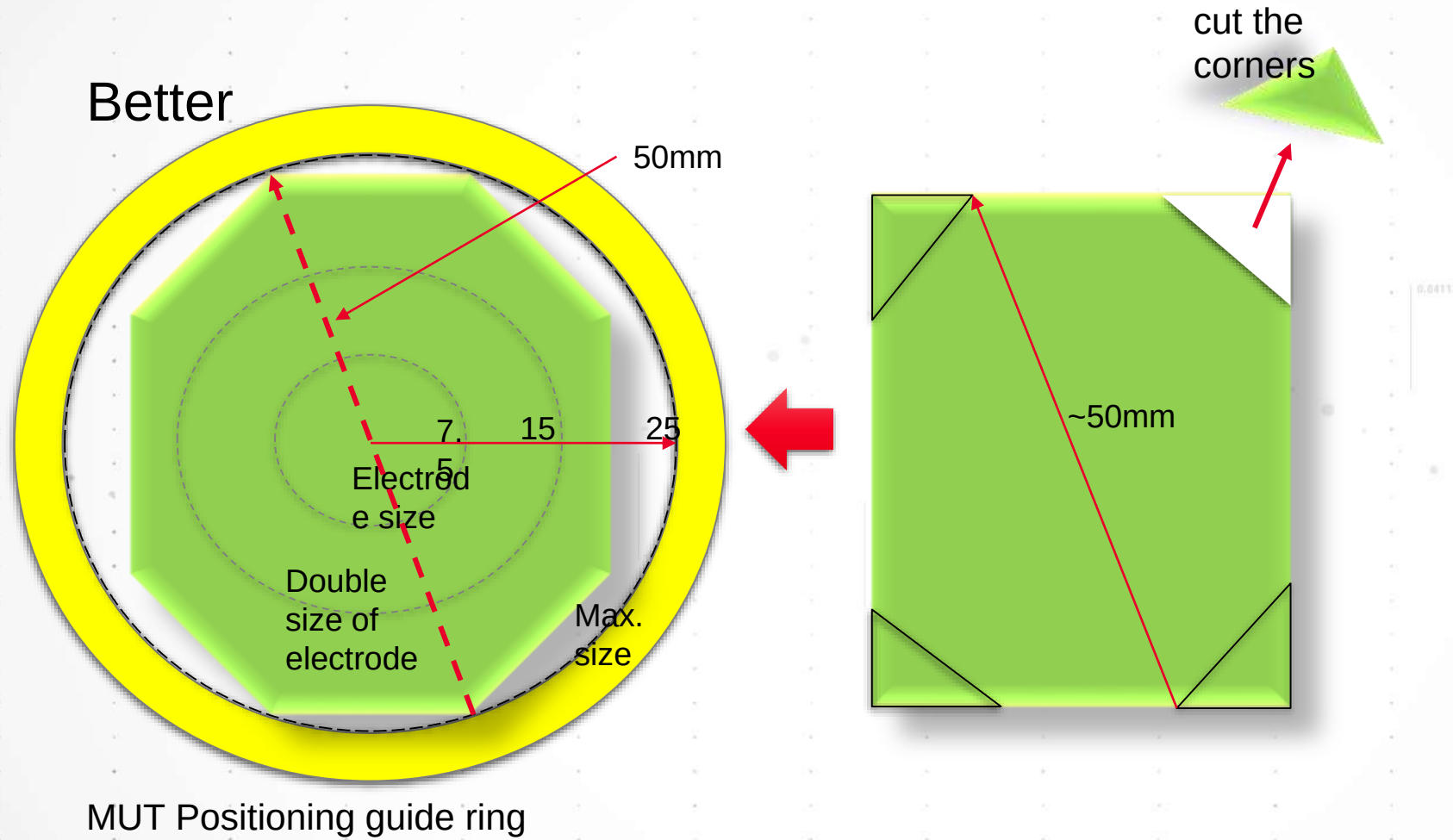
(Surface roughness: preferably 30 μm or less)

hard and easily broken (thin vitreous, thin ceramic substrates, etc.)

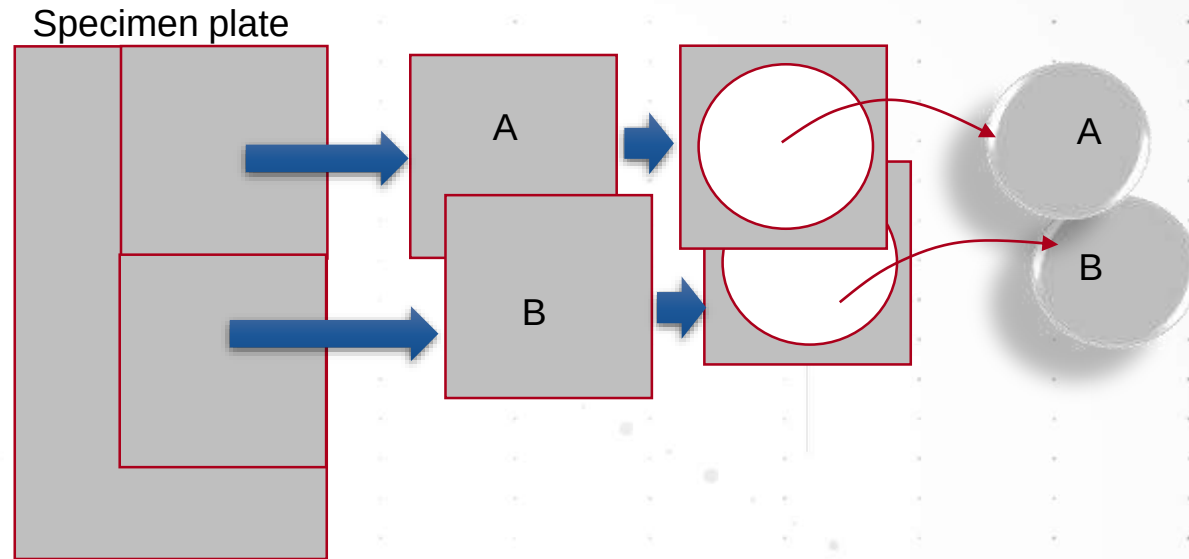
Warping with a hard substrate

Copper-clad board or substrate with copper electrode left

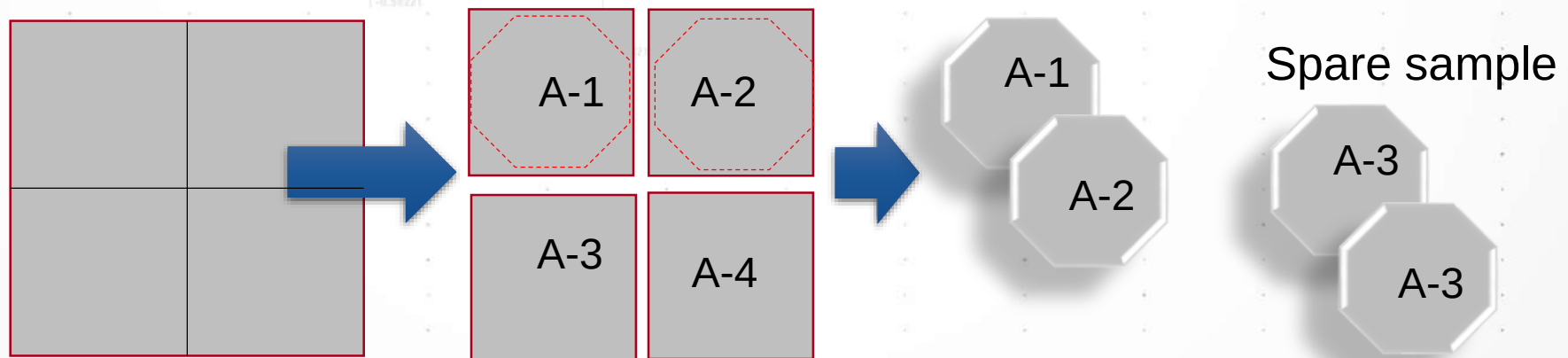
How to set in the cavity for square sheet



Sample preparation



Best way (two samples from the same sheet)



Summary

- I. Wide frequency range, 10 GHz to 67G or 110 GHz
- II. Multi frequency-points measurement by using multiple higher modes, such as $TM_{010,020,0n0}\dots$
- III. Good for low loss material, $\tan\delta$ range from 0.01 to 0.0001.
- IV. Measure permittivity with E-field of thickness direction
- V. Do not need to know MUT thickness accurately. (Disk electrode diameter accuracy and its position is much important.)
- VI. Remote control and calculation software are bundled. Complete measurement package for the lower loss materials
- VII. Thickness: 0.1mm to 1.0mm
- VIII. Not easy to measure the “hard” and “thin” materials . it means the fragile materials like glass, because of using strong clamping fixture. Very sensitive to the roughness of surface.

New mmWave Material Test Solutions

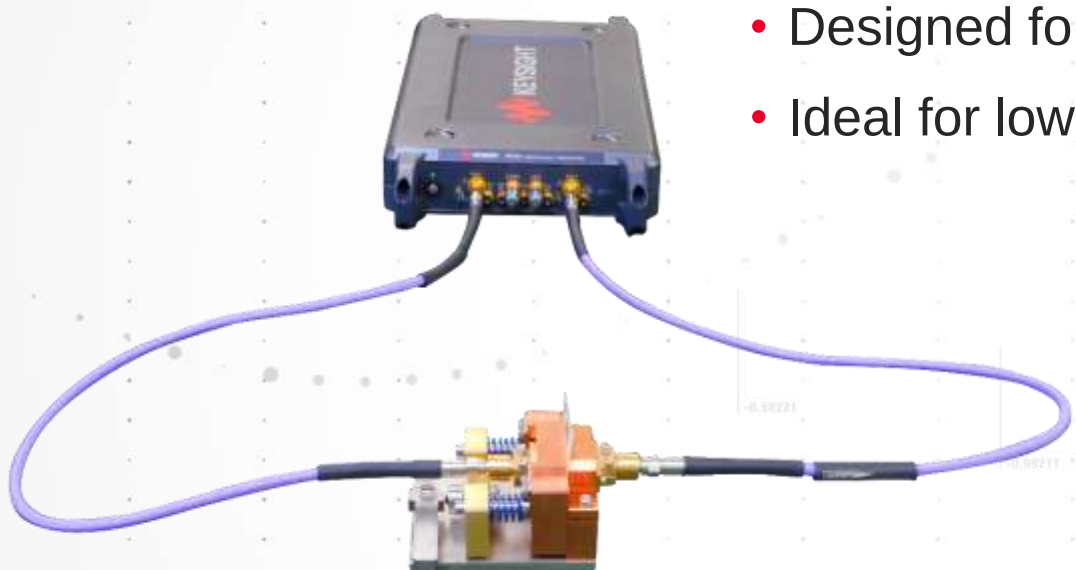
- Balanced Circular Disk Resonator (BCDR)
- ✓ Split Cylinder Resonator (SCCR)



Split Cylinder Cavity Resonator for Dk/Df test

Easy to use low Dk/Df test **up to 80 GHz!**

**5G &
Automotive radar
AD – Satellite**



- Designed for easy operation and high repeatability.
- Ideal for low loss materials ($0.0001 < \tan\delta < 0.01$ typical)

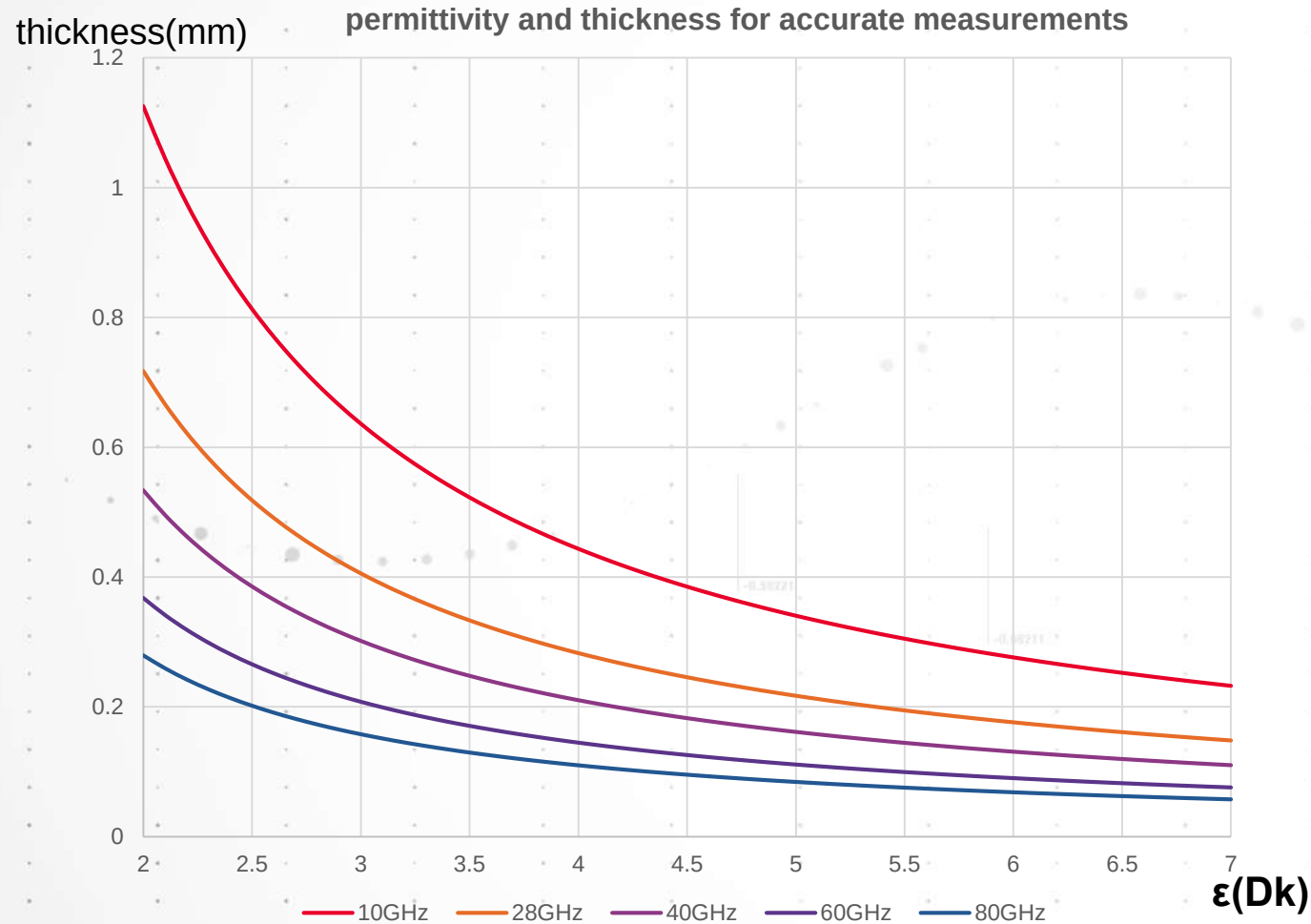
Model #	Description
N1501AKEAD-710	10 GHz, SMA (f) Split Cylinder Resonator
N1501AKEAD-720	20 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-724	24 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-728	28 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-735	35 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-740	40 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-750	50 GHz, 2.4 mm (f) Split Cylinder Resonator
N1501AKEAD-760	60 GHz, 1.85 mm (f) Split Cylinder Resonator
N1501AKEAD-780	80 GHz, 1 mm (f) Split Cylinder Resonator
N1501AKEAD-ST1	Software Split Cylinder Resonator Starter Kit

Excellent Repeatability up to 80 GHz!

Repeat 8 measurements: removing/inserting the sample every time

	ϵ			$\tan\delta$		
	28GHz	40GHz	80GHz	28GHz	40GHz	80GHz
1	3.5513135	3.5461616	3.5316448	0.0014638	0.0014985	0.0026641
2	3.5573029	3.5513652	3.5259343	0.0014652	0.0015015	0.0027728
3	3.5373529	3.5454758	3.5286601	0.0014661	0.0015031	0.0027724
4	3.5475343	3.5451975	3.5406693	0.0014636	0.0015016	0.0026712
5	3.5462314	3.5571790	3.5343098	0.0014635	0.0015048	0.0027275
6	3.5546762	3.5534020	3.5418378	0.0014570	0.0015082	0.0026762
7	3.5535140	3.5450251	3.5301140	0.0014585	0.0015111	0.0027662
8	3.5463382	3.5533046	3.5460484	0.0014584	0.0015120	0.0026603
Avg	3.5492829	3.5496389	3.5349023	0.0014620	0.0015051	0.0027138
S. Dev	0.0063110	0.0047489	0.0071602	0.0000035	0.0000049	0.0000513

Sample size limitation

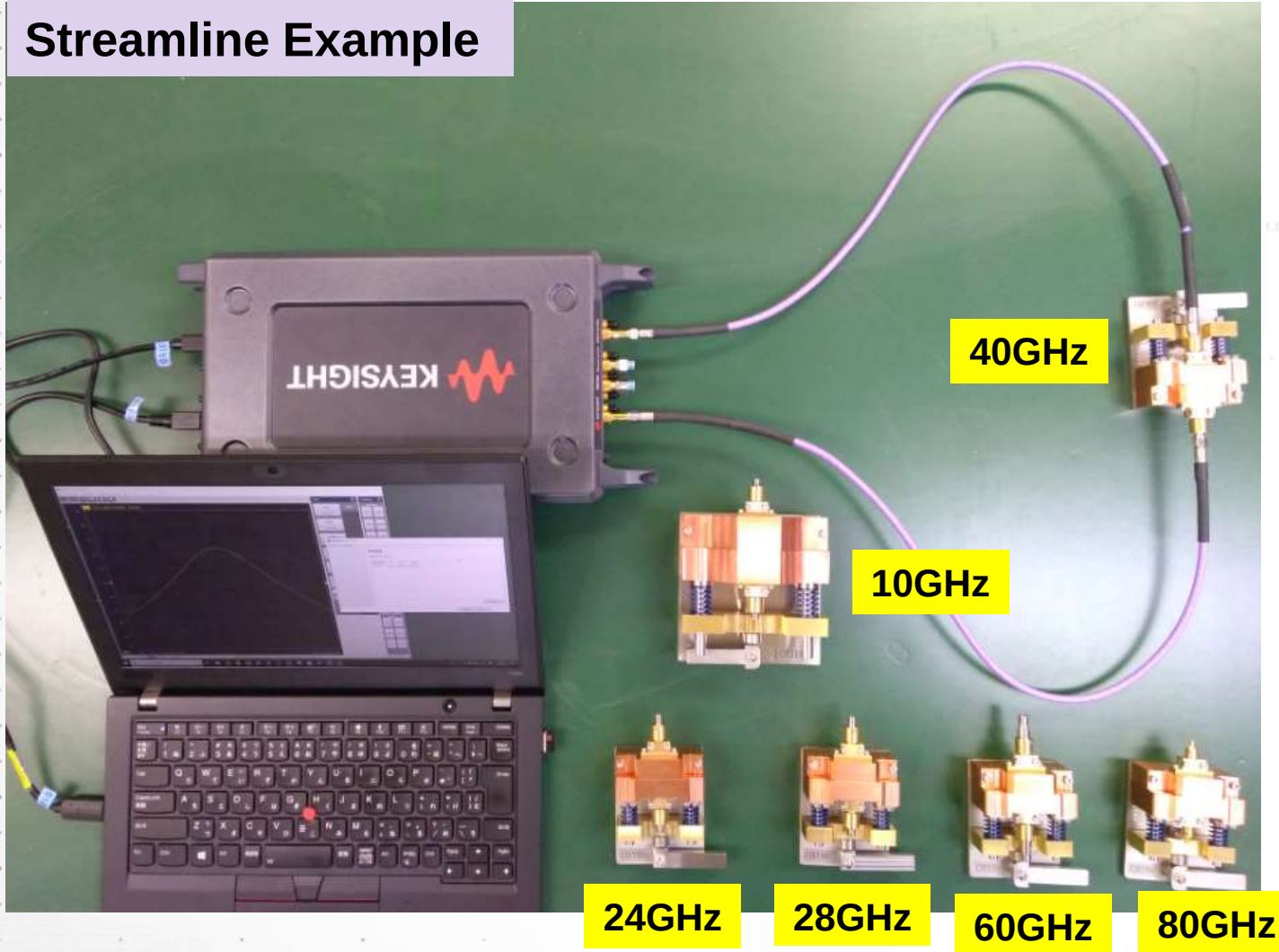


left graph is a guideline for material size and permittivity

$\tan\delta$ guideline is hard to set clearly but $\tan\delta < 0.01$ is a rough guideline

Split Cylinder Configuration: PNA/ENA/Streamline supported

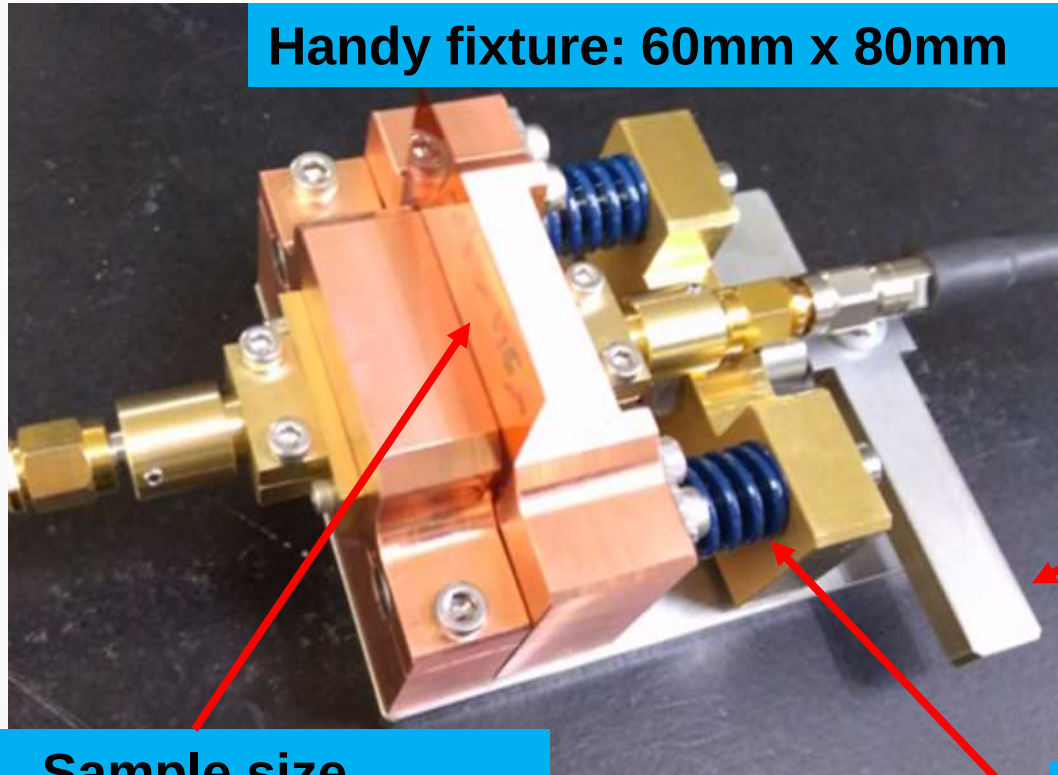
Streamline Example



The same design concept for all frequencies:
10/20/24/28/35/40/50/60/80GHz

Split Cylinder Key Design Features

Designed for easy operation and high repeatability



Handy fixture: 60mm x 80mm

Test software with step by step instruction ensures right measurements from the beginning.

Lever for easy operation

**Sample size
35mm x 50mm
Thickness 20um ~ 300um**

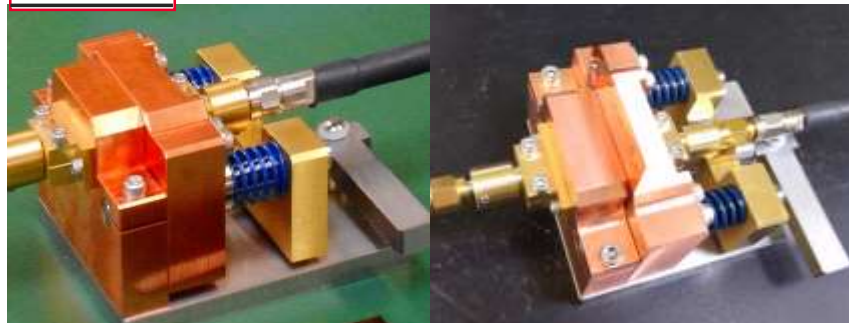
**Two springs fix a sample properly:
A key to repeatable measurements**

Resonant Cavity Fixtures available thru Keysight

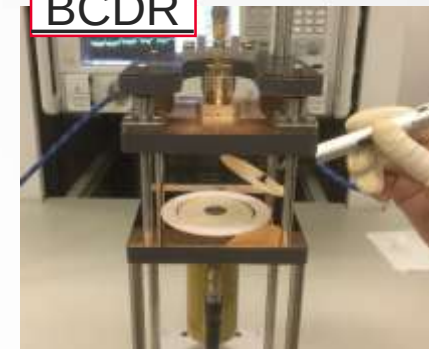
SPDR



SCCR



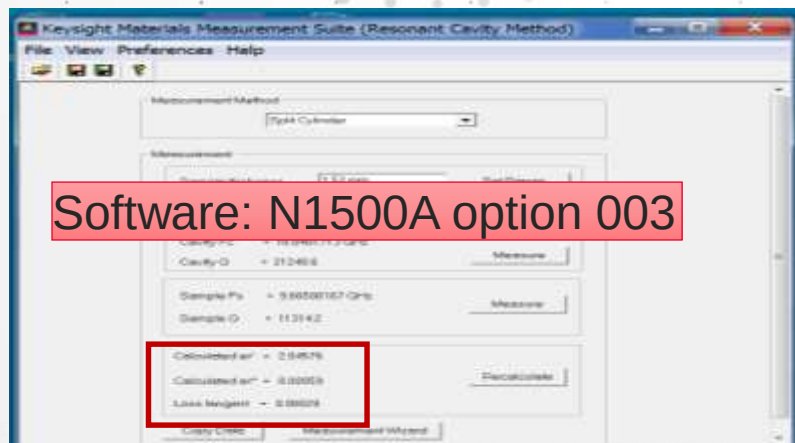
BCDR



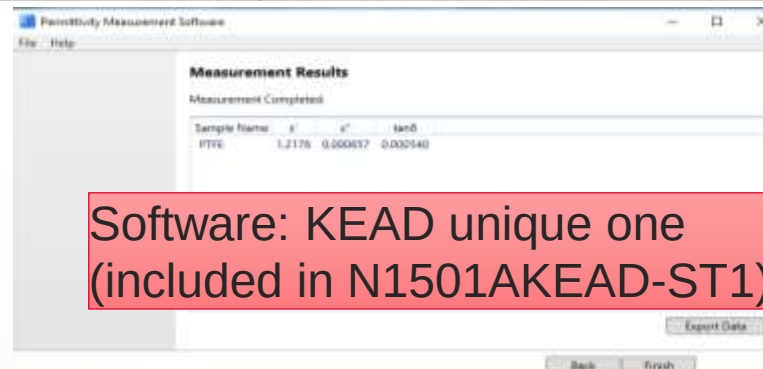
Model #	Description
N1501AE19	1.1 GHz, 3.5 mm (m) Split Post Dielectric Resonator
N1501AE03	2.5 GHz, 3.5 mm (m) Split Post Dielectric Resonator
N1501AE04	5.0 GHz, 3.5 mm (m) Split Post Dielectric Resonator
N1501AE10	10.0 GHz, 3.5 mm (m) Split Post Dielectric Resonator
N1501AE15	15 GHz, 3.5 mm (m) Split Post Dielectric Resonator

Model #	Description
N1501AKEAD-710	10 GHz, SMA (f) Split Cylinder Resonator
N1501AKEAD-720	20 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-724	24 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-728	28 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-735	35 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-740	40 GHz, 2.92 mm (f) Split Cylinder Resonator
N1501AKEAD-750	50 GHz, 2.4 mm (f) Split Cylinder Resonator
N1501AKEAD-760	60 GHz, 1.85 mm (f) Split Cylinder Resonator
N1501AKEAD-780	80 GHz, 1 mm (f) Split Cylinder Resonator
N1501AKEAD-ST1	Software Split Cylinder Resonator Starter Kit

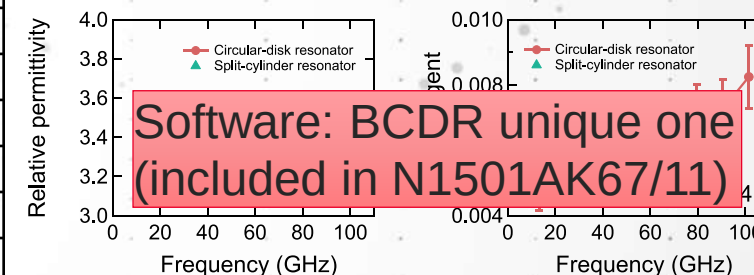
Model #	Description
N1501AE67	67 GHz Balanced Circular Disk Resonator
N1501AE11	110 GHz Balanced Circular Disk Resonator



Software: N1500A option 003



Software: KEAD unique one
(included in N1501AKEAD-ST1)



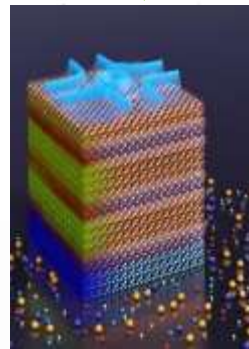
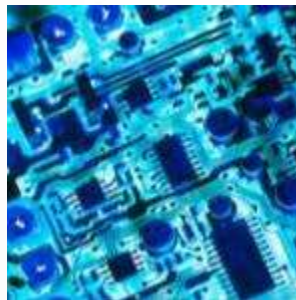
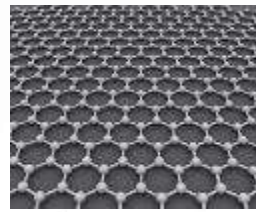
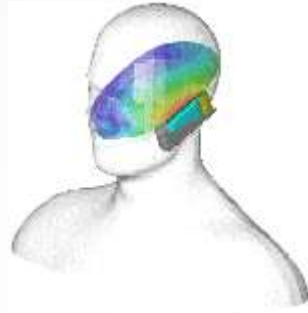
SCCR



85072A 10 GHz Split Cylinder Resonator

Software: N1500A option 003

Question?





KEYSIGHT
WORLD 2020

