Simulating cavity filter temperature drift in CST Microwave Studio

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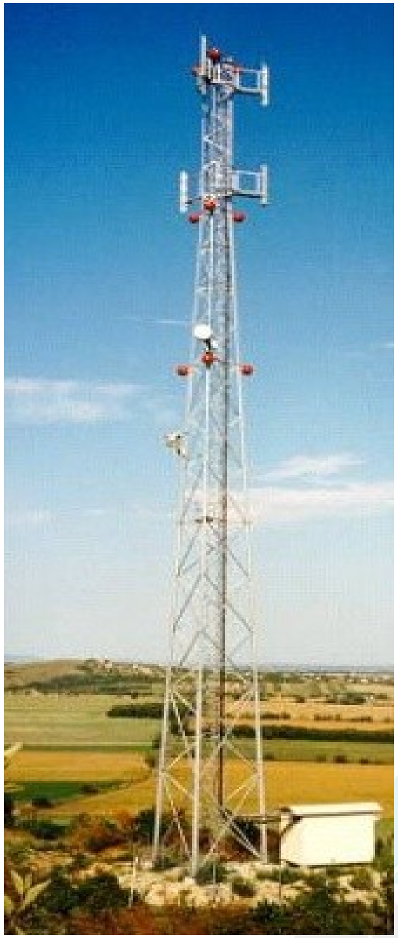
Presentation Outline

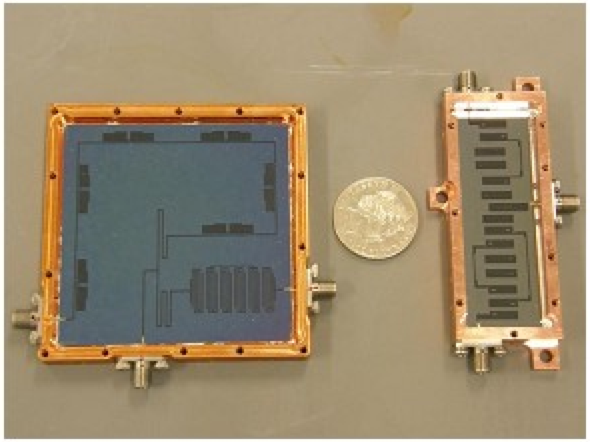
- Role of CST Microwave Studio (MWS)
  - Conventional solutions
  - HTS solutions
  - Ceramic solutions
- Practical Problem and Current Work
  - Definition
  - CST MWS solution
- Q&A and further discussion on (any) topic

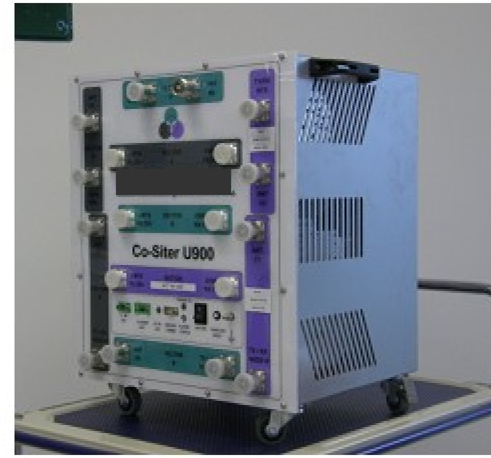
Market overview

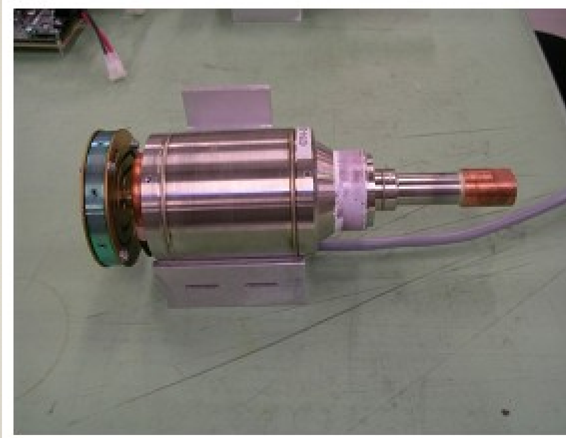
- Cellular wireless infrastructure
- Spectrum re-farming (U900)
- Interference mitigation (Custom)
- Co-siting & co-location (Sharing)
- Low noise solutions
- LTE – filtering & range extension



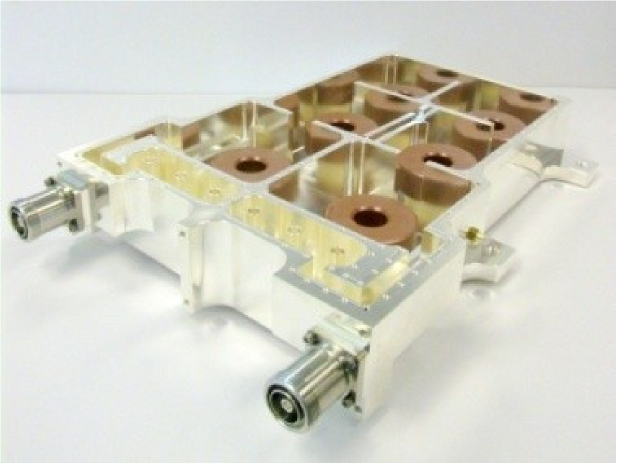
HTS solutions

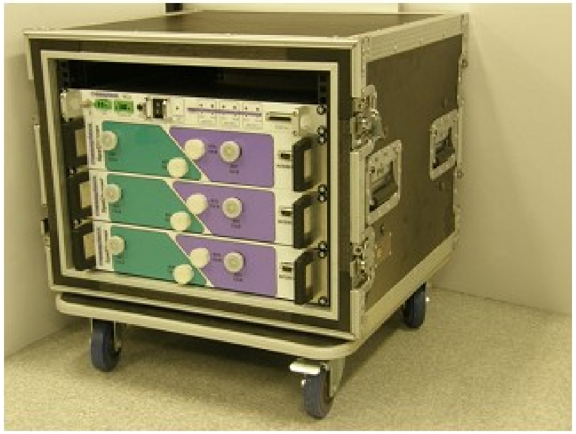


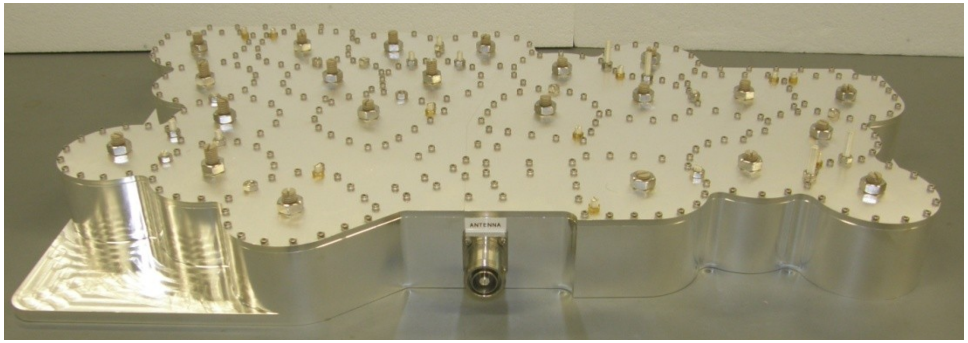


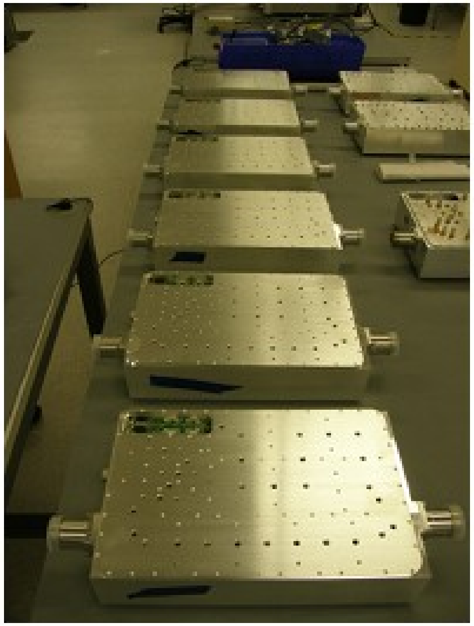


Conventional solutions

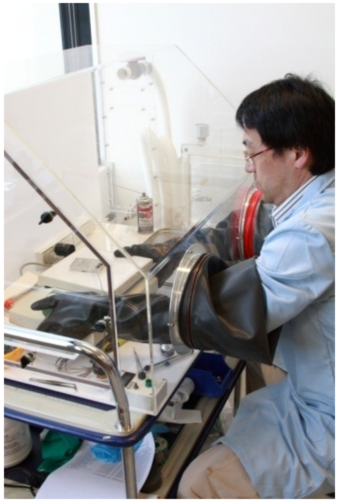




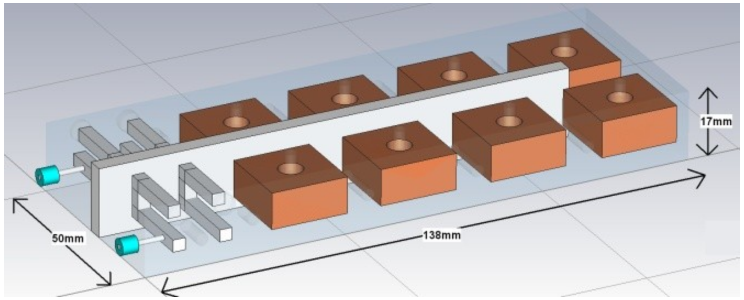


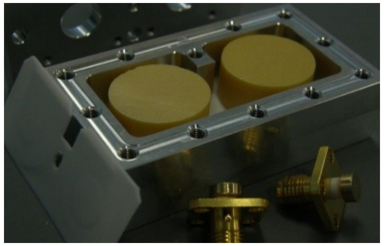


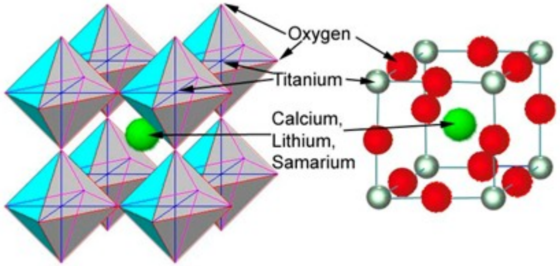
Materials solutions



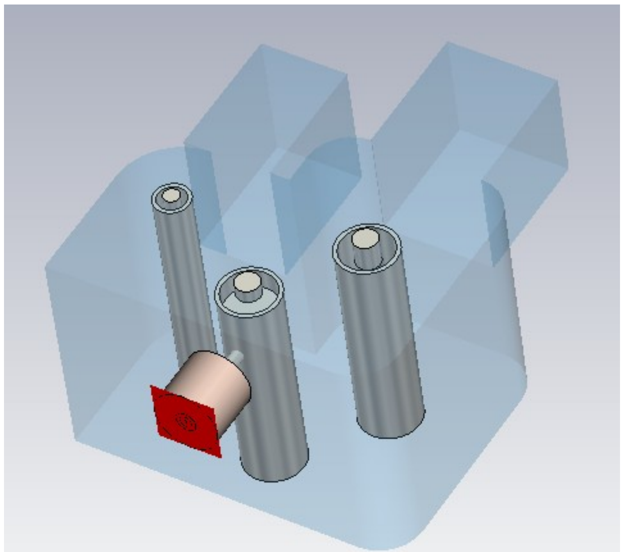
Novel ceramic materials

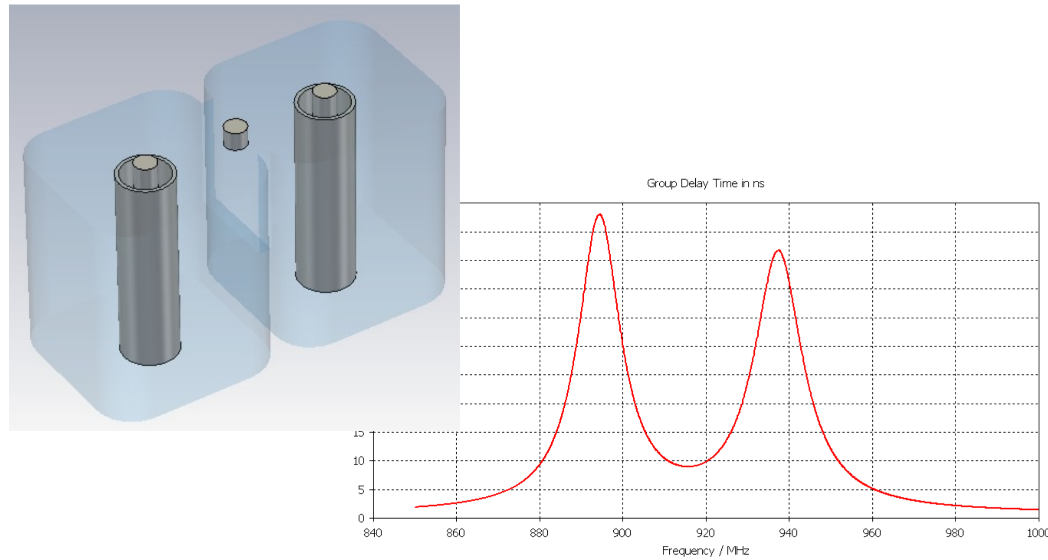






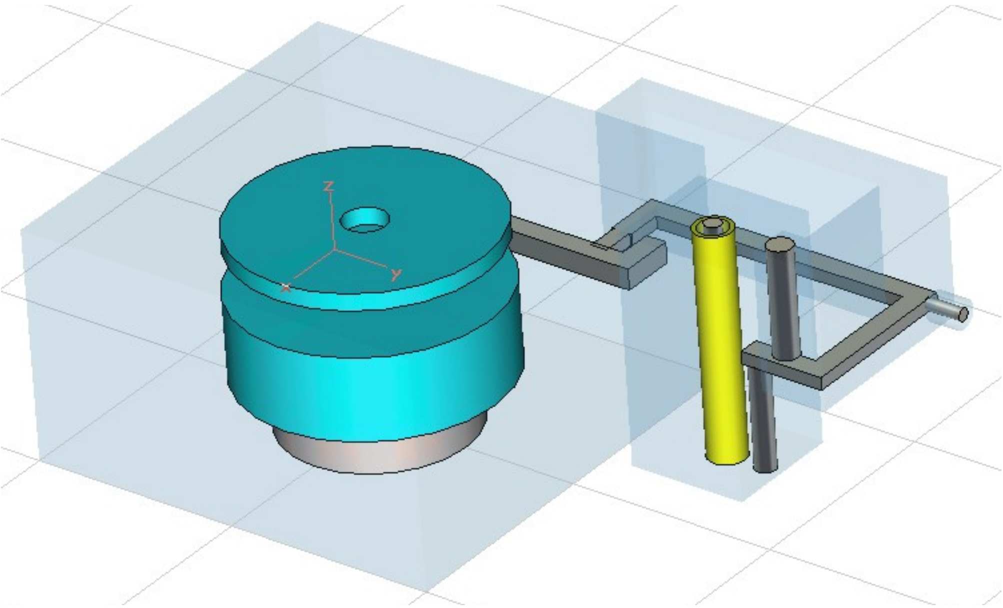
Application of CST MWS

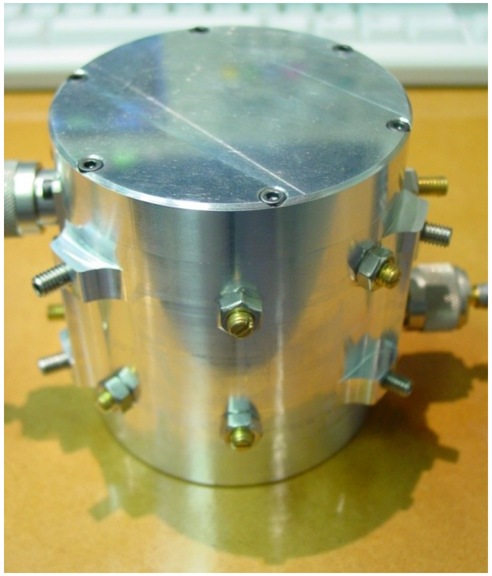




Metallic cavity (combline) filters fully designed in CST MWS.
First design usually works.

Application of CST MWS





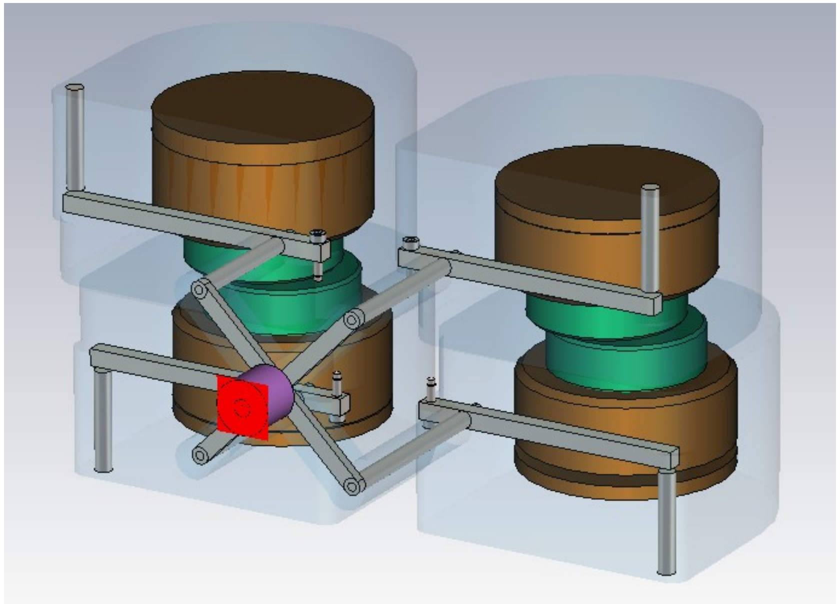
Dielectric resonator filters are also designed in CST MWS

Application of CST MWS

More complicated structures are increasingly simulated

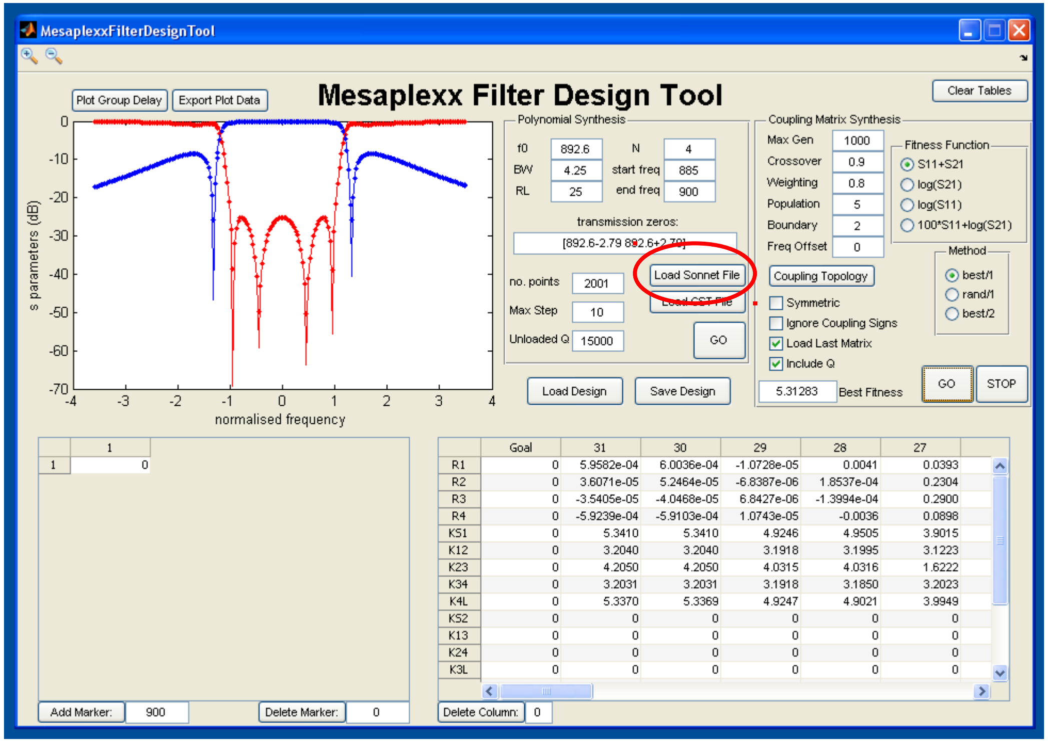
“Supercomputer”

Integration with SolidWorks



Have dealt with situations where lumped element and transmission line approach breaks down in a practical application

Design and Characterisation



Coupling matrix optimisation

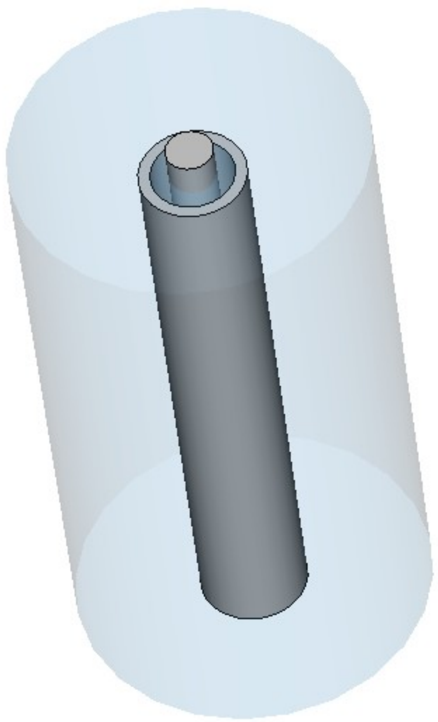
Design

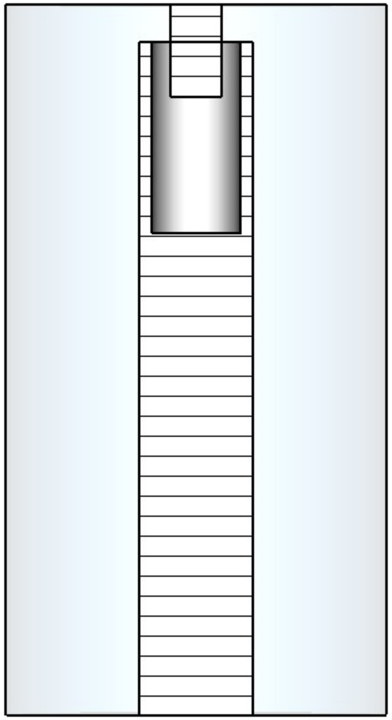
Tuning

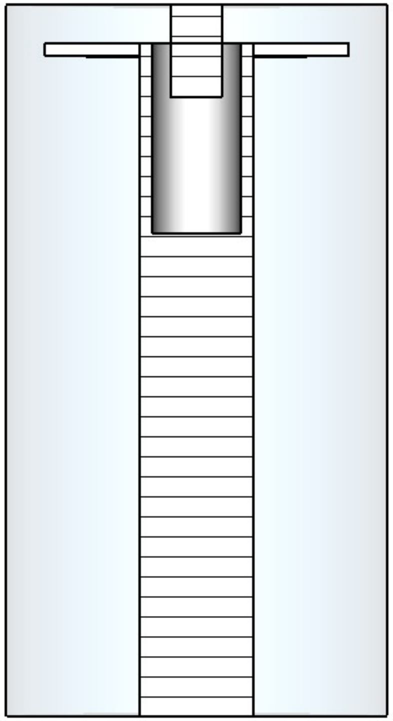
Characterisation

Problem 1

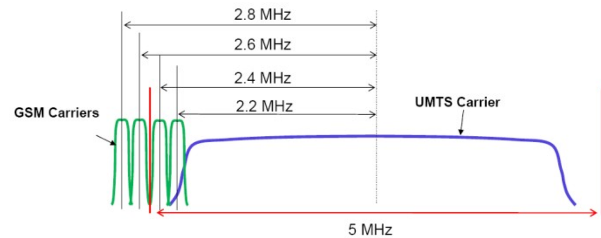
Frequency drift due to dimensional and/or material change?

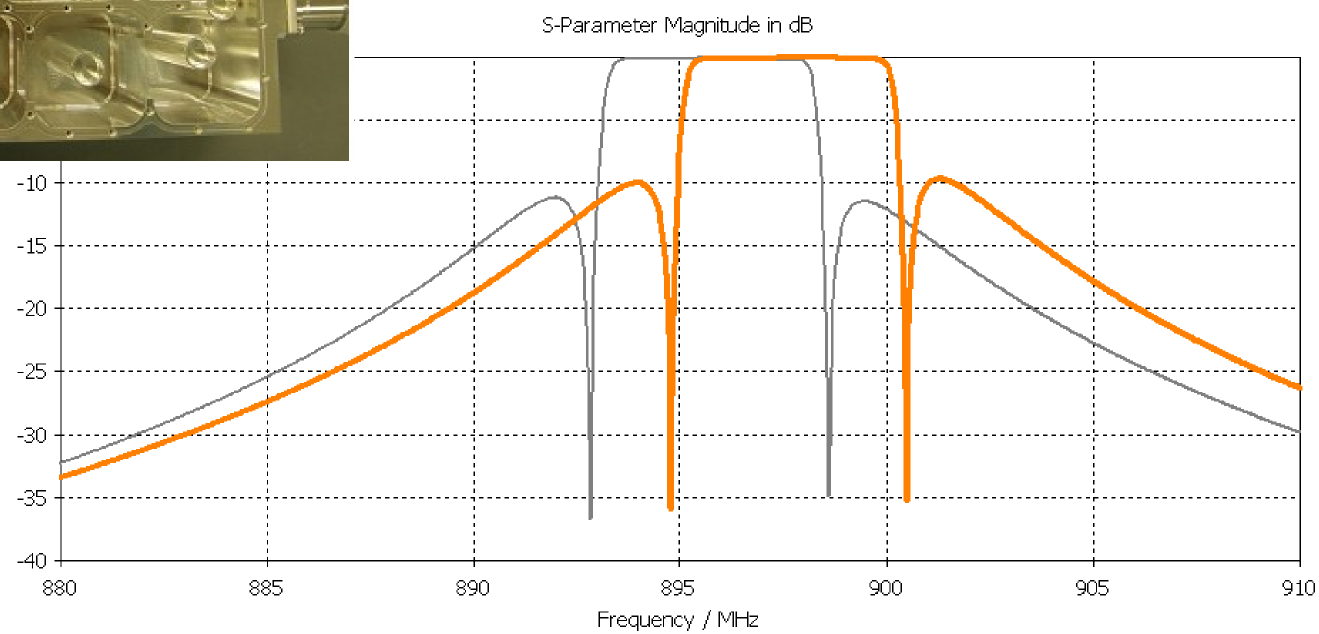




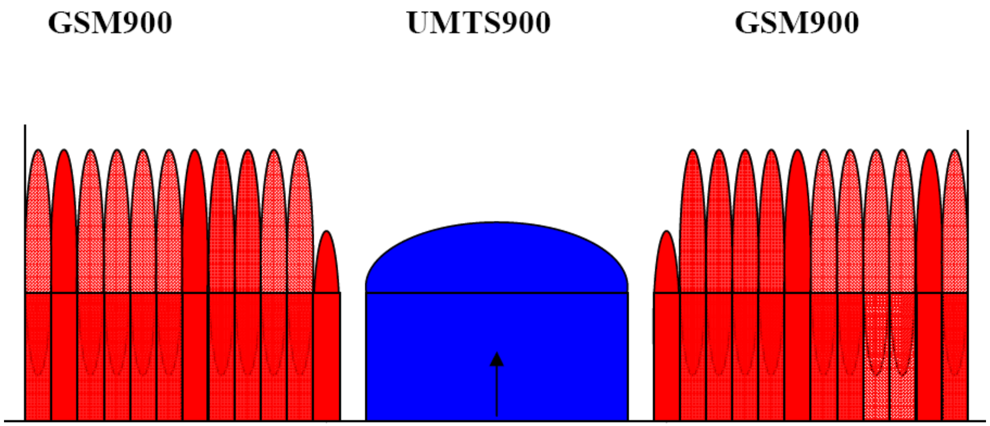


Change in performance

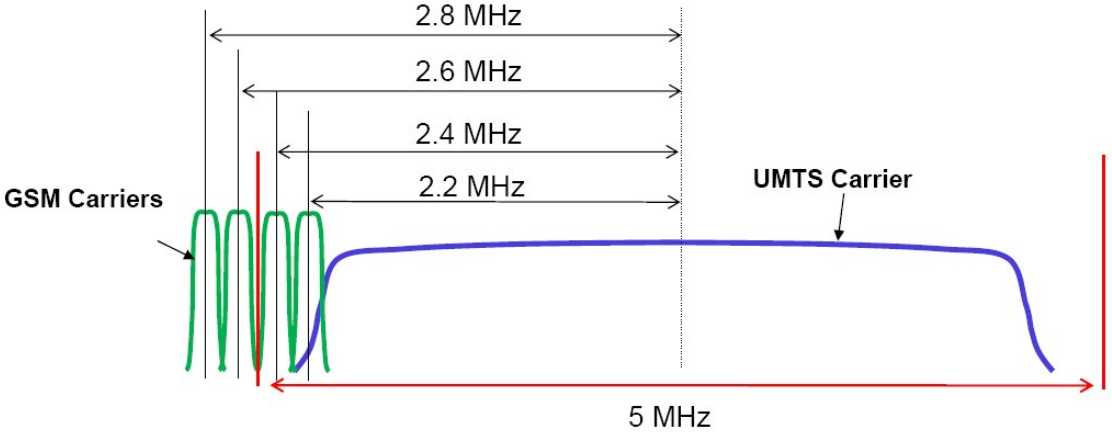




Change in performance



Keep the drift to less than 1 GSM ch



Current approach

Resonance condition:

$$2\pi f \cdot Z \cdot C \cdot \tan(\theta) = 1$$

Cross-section impedance function of cavity and resonator dimensions.

Resonator length

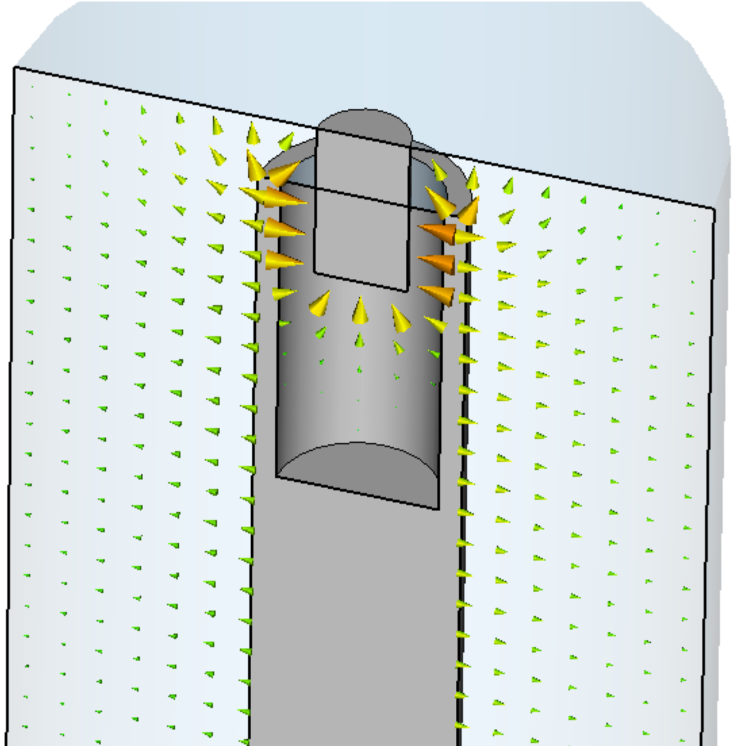
$$Z_{\mathrm{coax}} = 60 \cdot \ln\left(\frac{\text{cavity\_diameter}}{\text{resonator\_diameter}}\right)$$

$$Z_{\mathrm{slab}} = 60 \cdot \ln\left(\frac{4 \cdot \text{cavity\_diameter}}{\pi \cdot \text{resonator\_diameter}}\right)$$

$$C = C_{screw} + C_{plate} + C_{fringing}$$

Approximating capacitance

$$C = C_{screw} + C_{plate} + C_{fringing}$$



A combination of calculation, approximation, and empirical estimation. Not always easy To get right.

Temperature expansion

Thermal expansion coefficient: $\alpha = \frac{1}{L_0} \frac{\partial L}{\partial T}$

Linear:

Vol:

Area:

$$\frac{\Delta V}{V_0} = \alpha_V \cdot \Delta T \leftarrow \frac{\Delta A}{A_0} = \alpha_A \cdot \Delta T \leftarrow \frac{\Delta L}{L_0} = \alpha_L \cdot \Delta T$$

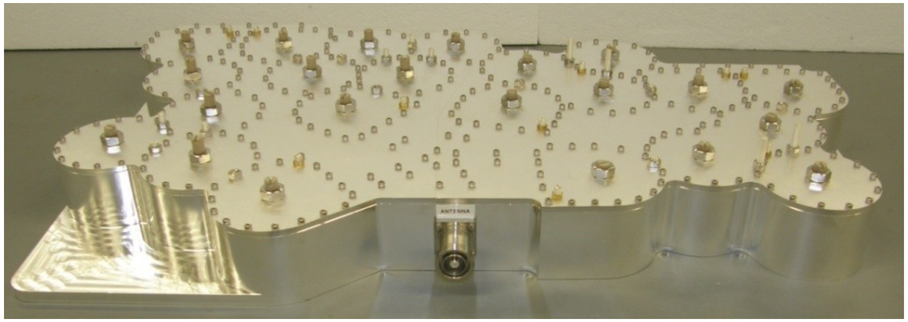
$\alpha_V \approx 3\alpha_L$
isotropic
materials

$\alpha_A \approx 2\alpha_L$
isotropic
materials

$\alpha_L << 1$
small ΔT

Typical values

Material	Linear CTE · 10^-6/˚C
Rubber	**77**
Lead	**29**
Aluminium	**23**
Brass	**19**
Copper	**17**
Gold	**14**
Steel	**11 – 13**
Platinum	**9**
Silicon	**3**
Invar	**1.2**



< 20 kg !!

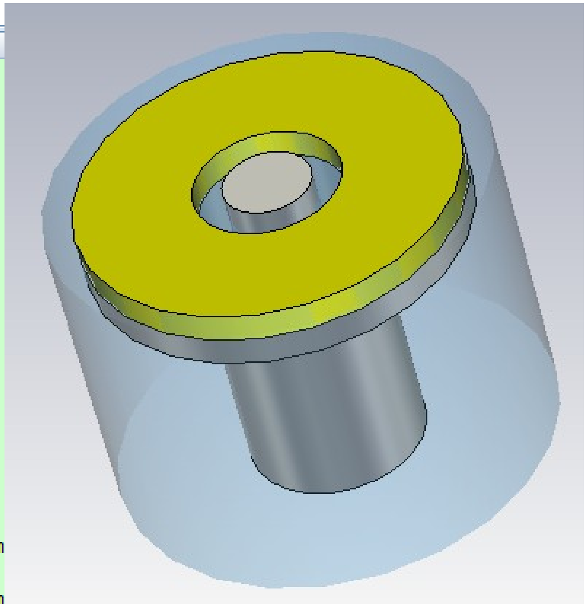
Damage to machine
when impurities are added

Automation of current approach

	A	B	C	D	E
1	**PARAMETER NAME**	**SYMBOL**	**UNIT**	**VALUE**	
2					
3	start search frequency value	FS	MHz	1.0000	
4	resonant frequency	F0	MHz	1810.1488	
5	previous resonant frequency	F0P	MHz	1810.1488	
6	frequency drift due to temperature change	DF	MHz	0.0000	
7	correction factor	RFCF	ratio	1.1000	
8	resulting frequency	F0R	MHz	**1645.5898**	
9	optimised?			no	
10				CALCULATE	
11					
12					
13	temperature change	T	K	0.0000	
14	cavity coefficient of expansion	HCE	mm/K	2.30E-05	
15	resonator coefficient of expansion	RCE	mm/K	2.30E-05	
16	tuning screw coefficient of expansion	SCE	mm/K	1.35E-05	
17					
18	cavity diameter	B	mm	6.7500	
19	cavity diameter at new T	BT	mm	6.7500	in
20	cavity height	H	mm	7.4500	
21	cavity height at new T	HT	mm	7.4500	in
22					
23	base resonator diameter	D	mm	3.4000	
24	base resonator diameter at new T	DT	mm	3.4000	increases
25	base resonator length	LR	mm	7.2500	
26	base resonator length at new T	LRT	mm	7.2500	increases
27					
28	base resonator impedance	Z	Ohm	41.1460	
29	base resonator impedance at new T	ZT	Ohm	41.1460	
30					
31	top hat diameter	THD	mm	5.4000	
32	top hat diameter at new T	THDT	mm	5.4000	increases
33	top hat length	THL	mm	0.0000	not added to the total resonator length
34	top hat length at new T	THLT	mm	0.0000	not added to the total resonator length

Resonator | Qcalc | g&CBW | g&CBW-HI | CBWcalcSC | CBWcalcSCrev | CBWcalcGD | SkinDepth | Sheet1

Ready



Automation of current approach

	A	B	C	D	E	F
34	top hat length at new T	THLT	mm	0.0000		not added to the total resonator length
35						
36	top hat impedance	ZTHT	Ohm	13.3886		
37	top hat impedance at new T	ZTHT	Ohm	13.3886		
38						
39	total resonator length	TRL	mm	7.2500		
40	total resonator length at new T	TRLT	mm	7.2500		increases
41						
42	tuning screw diameter	TSD	mm	1.6000		
43	tuning screw diameter at new T	TSDT	mm	1.6000		increases
44	tuning screw insertion into counterbore	TSI	mm	1.0000		
45	tuning screw insertion into counterbore at new T	TSIT	mm	1.0000		increases
46	counterbore diameter	CB	mm	1.9000		
47	counterbore diameter at new T	CBT	mm	1.9000		increases
48	tuning screw capacitance	TSC	pF	0.3237		
49	tuning screw capacitance at new T	TSCT	pF	0.3237		increases
50						
51	disc dielectric constant	DDC	ratio	9.9000		
52	thermal coefficient of dielectric constant	TC	ppm	0.0000		
53	disc dielectric constant at new T	DDCT	ratio	9.9000		
54	disc outer diameter at new T	DOD	mm	5.4000		same as the top hat diameter
55	disc inner diameter at new T	DID	mm	2.1000		counterbore diameter + 0.2 mm
56	disc thickness	DTH	mm	0.2000		
57	disc thickness at new T	DTHT	mm	0.2000		increases
58	disc area	DA	mm^2	13.9550		or: PI()*(1/4)*(DOD^2-0.9*DID^2)-5.83-LCA
59	disc capacitance	DCAP	pF	6.1161		must exclude moons automatically
60	disc capacitance at new T	DCAPT	pF	6.1161		increases; must exclude moons autom.
61						
62	lumped capacitor 1	LC1	pF	0.0000		
63	lumped capacitor 1 temperature coefficient	LCTC1	%	-0.1000		estimate from the graph
64	lumped capacitor 1 tolerance	LCTOL1	pF	0.1000		
65	lumped capacitance 1 at new T and with tolerance -	LCT1	pF	0.0000		negative tolerance assumed
66						
67	lumped capacitor 2	LC2	pF	0.0000		

Ready | Resonator | Qcalc | g&CBW | g&CBW-HI | CBWcalcSC | CBWcalcSCrev | CBWcalcGD | SkinDepth | Sheet1

	A	B	C	D	E	F
67	lumped capacitor 2	LC2	pF	0.0000		
68	lumped capacitor 2 temperature coefficient	LCTC2	%	-0.1000		
69	lumped capacitor 2 tolerance	LCTOL2	pF	0.1000		
70	lumped capacitance 2 at new T and with tolerance +	LCT2	pF	0.0000		positive tolerance assumed
71						
72	lumped capacitor 3	LC3	pF	0.0000		
73	lumped capacitor 3 temperature coefficient	LCTC3	%	-0.1000		
74	lumped capacitor 3 tolerance	LCTOL3	pF	0.1000		
75	lumped capacitance 3 at new T and with tolerance -	LCT3	pF	0.0000		negative tolerance assumed
76						
77	lumped capacitor 4	LC4	pF	0.0000		
78	lumped capacitor 4 temperature coefficient	LCTC4	%	-0.1000		
79	lumped capacitor 4 tolerance	LCTOL4	pF	0.1000		
80	lumped capacitance 4 at new T and with tolerance +	LCT4	pF	0.0000		positive tolerance assumed
81						
82	total lumped capacitance	LC	pF	0.0000		
83	total lumped capacitance at new T	LCT	pF	0.0000		
84	number of lumped capacitors		-	0.0000		
85	area occupied by each capacitor		mm^2	0.0000		
86	total lumped capacitance area	LCA	mm^2	0.0000		
87						
88	fringing capacitance	FC	pF	0.1764		
89	fringing capacitance at new T	FCT	pF	0.1764		increases
90						
91	electrical resonator length	EL	deg	15.7588		
92	electrical resonator length at new T	ELT	deg	15.7588		increases
93						
94	total capacitance required for resonance	CAP	pF	7.5723		
95	actual capacitance that we have	ACAP	pF	6.6162		
96	total capacitance required for resonance at new T	CAPT	pF	7.5723		
97	actual capacitance that we have at new T	ACAPT	pF	6.6162		
98						
99	gap required for resonance	RGAP	mm	0.1730		
100	gap required for resonance at new T	RGAPT	mm	0.1730		increases

Ready | Resonator | Qcalc | g&CBW | g&CBW-HI | CBWcalcSC | CBWcalcSCrev | CBWcalcGD | SkinDepth | Sheet1

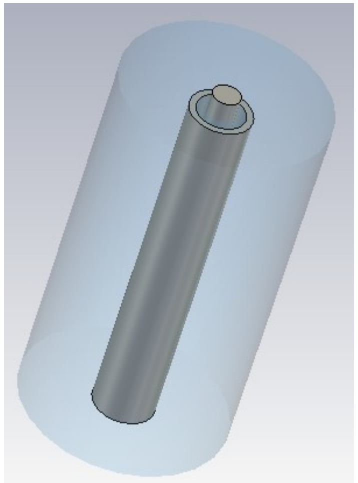
	A	B	C	D	E	F
79	lumped capacitor 4 tolerance	LCTOL4	pF	0.1000		
80	lumped capacitance 4 at new T and with tolerance +	LCT4	pF	0.0000		positive tolerance assumed
81						
82	total lumped capacitance	LC	pF	0.0000		
83	total lumped capacitance at new T	LCT	pF	0.0000		
84	number of lumped capacitors		-	0.0000		
85	area occupied by each capacitor		mm^2	0.0000		
86	total lumped capacitance area	LCA	mm^2	0.0000		
87						
88	fringing capacitance	FC	pF	0.1764		
89	fringing capacitance at new T	FCT	pF	0.1764		increases
90						
91	electrical resonator length	EL	deg	15.7588		
92	electrical resonator length at new T	ELT	deg	15.7588		increases
93						
94	total capacitance required for resonance	CAP	pF	7.5723		
95	actual capacitance that we have	ACAP	pF	6.6162		
96	total capacitance required for resonance at new T	CAPT	pF	7.5723		
97	actual capacitance that we have at new T	ACAPT	pF	6.6162		
98						
99	gap required for resonance	RGAP	mm	0.1730		
100	gap required for resonance at new T	RGAPT	mm	0.1730		increases
101	difference	DIFF	um	-27.0388		
102	difference at new T	DIFFT	um	-27.0388		
103						
104	difference between required and actual capacitances	ERR	pF	0.95612007		
105	difference between required and actual capacitances	ERRT	pF	0.95612007		
106						
107	v4.0/21-12-2005					
108	Some bugs from the previous version fixed.					
109						

Only works for
“static” analytic cases

CST MWS solution

Name	Value	Description	Type
HCE	coeff_alum	Housing coefficient of expansion	Undefined
RCE	coeff_alum	Resonator coefficient of expansion	Undefined
SCE	coeff_steel	Screw coefficient of expansion	Undefined
Trise	0	Temperature rise (change)	Undefined
cavdia	30		Undefined
cavdiafin	cavdia*(1+HCE*Trise)	Cavity diameter @ T	Undefined
cavlen	56		Undefined
cavlenfin	cavlen*(1+HCE*Trise)	Cavity lenght @ T	Undefined
cbdia	7		Undefined
cbdiafin	cbdia*(1+RCE*Trise)	Counterbore diameter @ T	Undefined
cblen	15		Undefined
cblenfin	cblen*(1+RCE*Trise)	Counterbore depth @ T	Undefined
coeff_alum	2.3*10^(-5)	Coefficient of expansion of aluminum	Undefined
coeff_brass	0	Coefficient of expansion of brass	Undefined
coeff_steel	1.7*10^(-5)	Coefficient of expansion of steel	Undefined
resdia	9		Undefined
resdiafin	resdia*(1+RCE*Trise)	Resonator diameter @ T	Undefined
reslen	53		Undefined
reslenfin	reslen*(1+RCE*Trise)	Resonator lenght @ T	Undefined
tsdia	4		Undefined
tsdiafin	tsdia*(1+SCE*Trise)	Tuning screw diameter @ T	Undefined
tslen	7.3		Undefined
tslenfin	tslen*(1+SCE*Trise)	Tuning screw length @ T	Undefined
			Undefined

Formulate parameters as a function of temperature



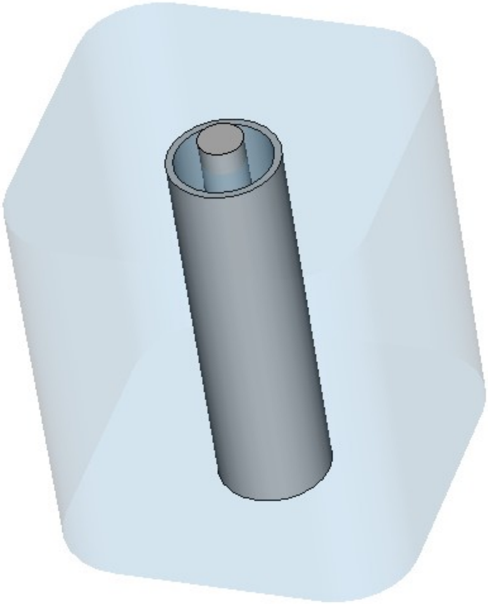
CST MWS solution

Name	Value	Description
HCE	coeff_alum	Housing coefficient of expansion
RCE	coeff_alum	Resonator coefficient of expansion
SCE	coeff_steel	Screw coefficient of expansion
Trise	0	Temperature rise (change)
cavdia	30	
cavdiafin	cavdia*(1+HCE*Trise)	Cavity diameter @ T
cavlen	56	
cavlenfin	cavlen*(1+HCE*Trise)	Cavity lenght @ T
cbdia	7	
cbdiafin	cbdia*(1+RCE*Trise)	Counterbore diameter @ T
cblen	15	
cblenfin	cblen*(1+RCE*Trise)	Counterbore depth @ T
coeff_alum	2.3*10^(-5)	Coefficient of expansion of aluminum
coeff_brass	0	Coefficient of expansion of brass

Practical case

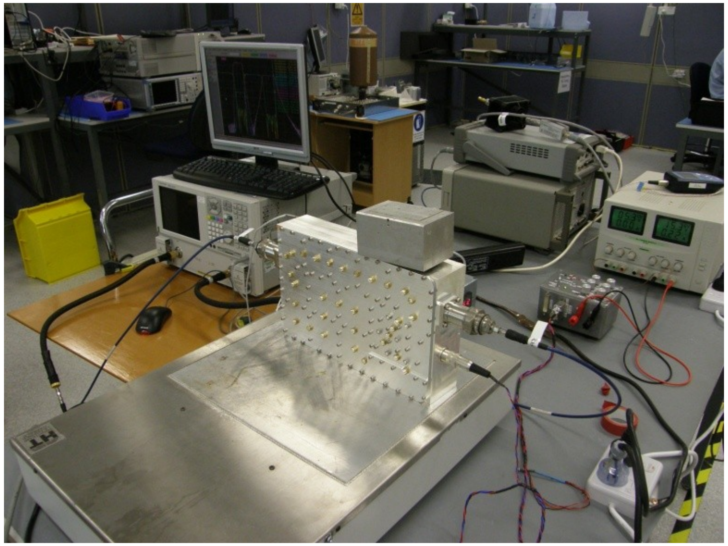
Spreadsheet calculation: -0.762 MHz drift, -20.2 ppm/˚C

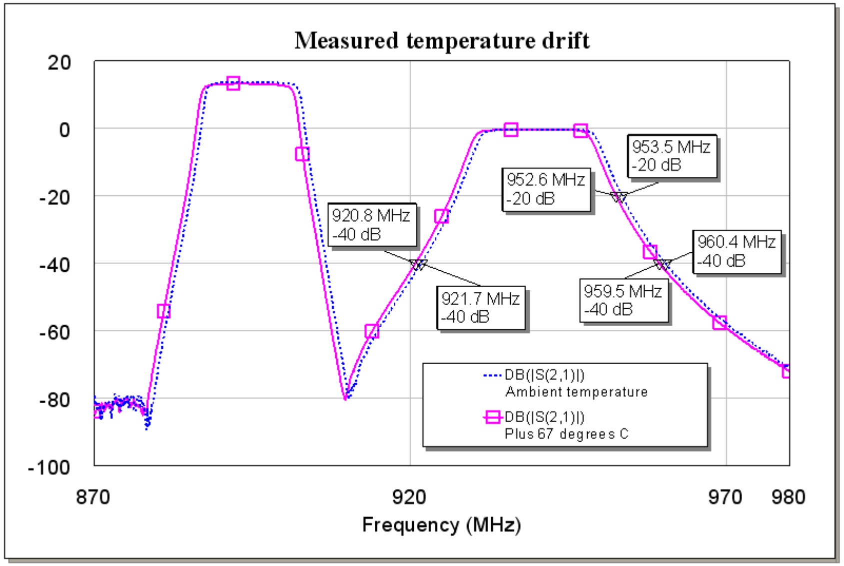
CST MWS: -0.9 MHz drift, -23.8 ppm/˚C



$$f_{\mathrm{drift}} = \frac{f_2 - f_1}{f_1} \cdot \frac{10^6}{\Delta T}$$

Measured results





Total temperature drift of -0.9 MHz was measured
(+40 ˚C temperature change, rate of -0.023 ˚C/MHz)

CST MWS works

Accuracy

Criterion: Establish logical convergence (experiments), by examining change in error, and referenced to mesh.

45 LPW: 269,500 meshcells, f_1 = **946.9** MHz f_2 = **946.0** MHz

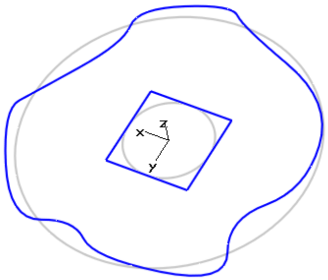
35 LPW: 141,120 meshcells, f_1 = **946.4** MHz f_2 = **945.5** MHz

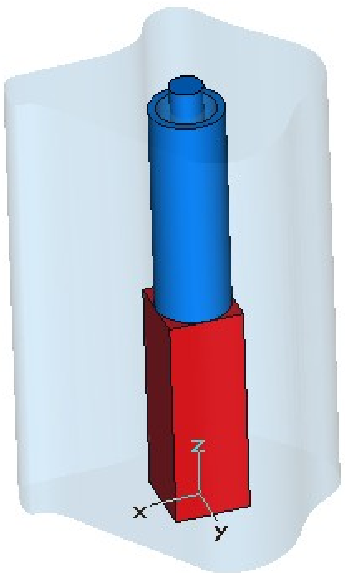
25 LPW: 54,400 meshcells, f_1 = **941.7** MHz f_2 = **940.8** MHz

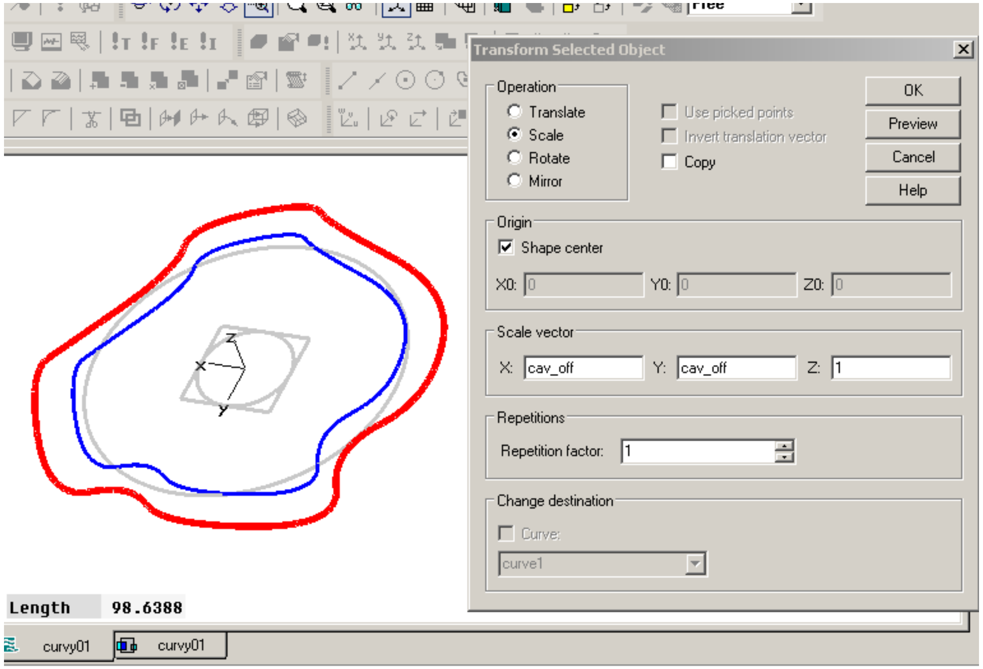
15 LPW: 17,248 meshcells, f_1 = **934.5** MHz f_2 = **933.6** MHz

Also confirmed convergence on basic coaxial case.

Extension to arbitrary shapes



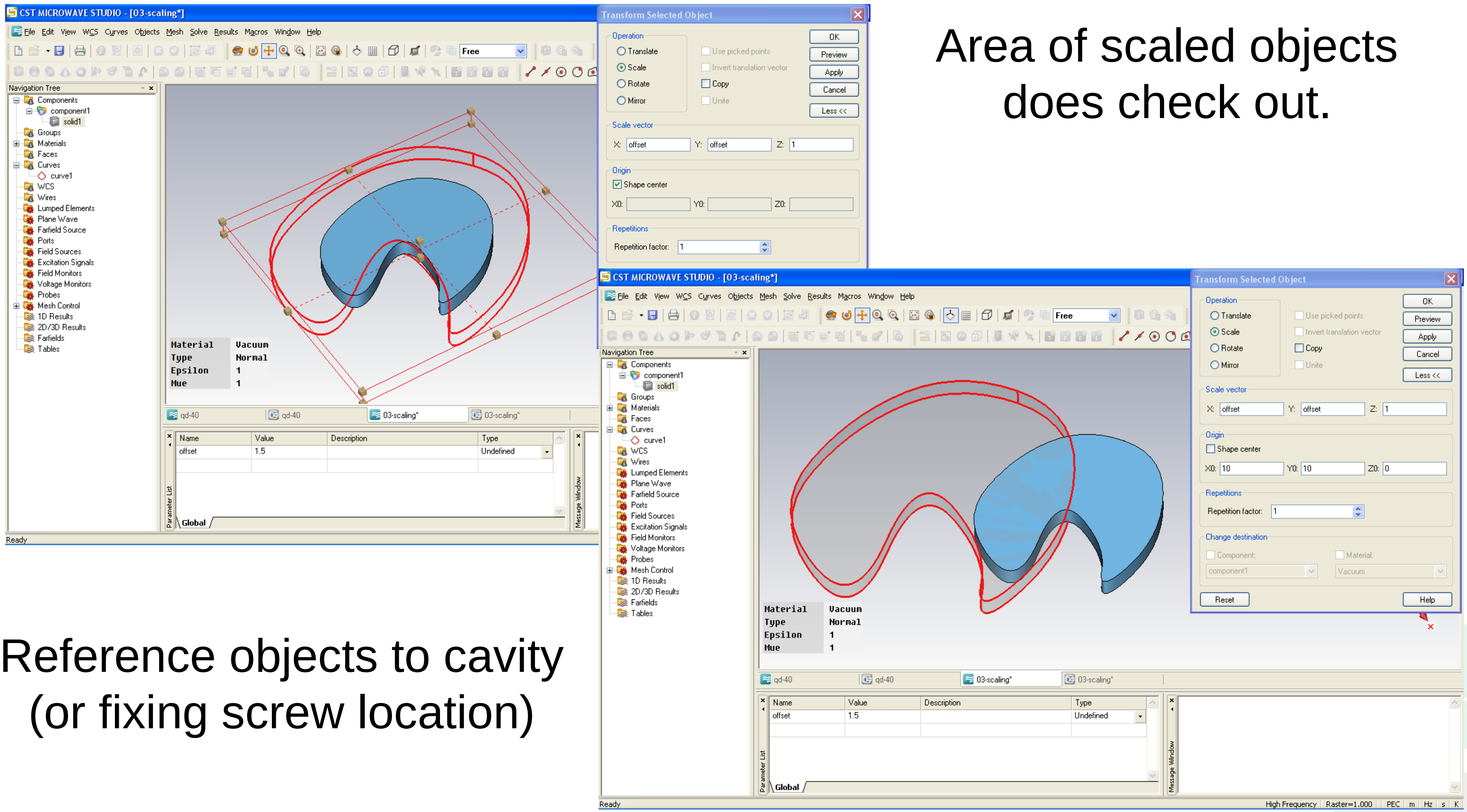




$$\frac{\Delta A}{A_0} = \alpha_A \cdot \Delta T$$

$\alpha_A \approx 2\alpha_L$
isotropic materials

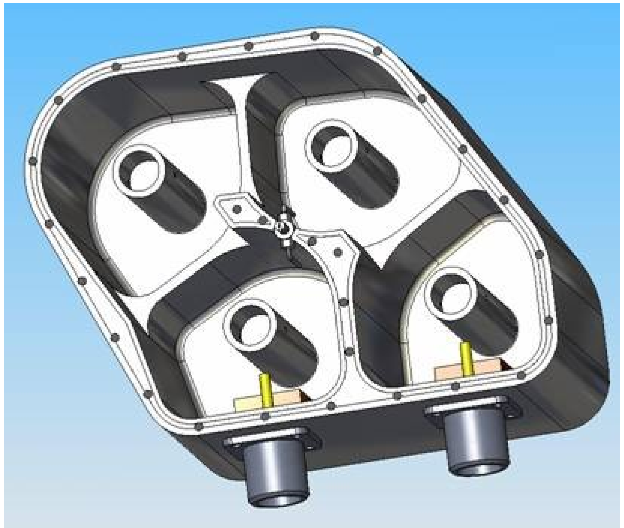
Scaling check



Area of scaled objects does check out.

Reference objects to cavity (or fixing screw location)

Other possibilities

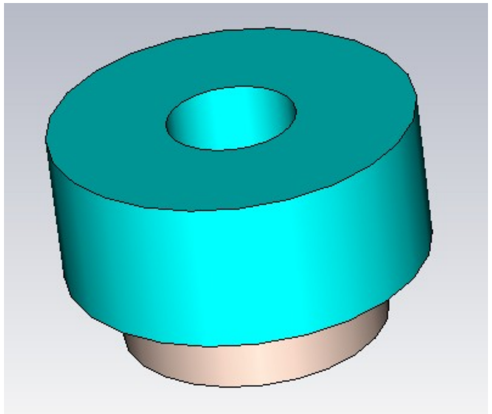


All other features
Optimisation (literature)

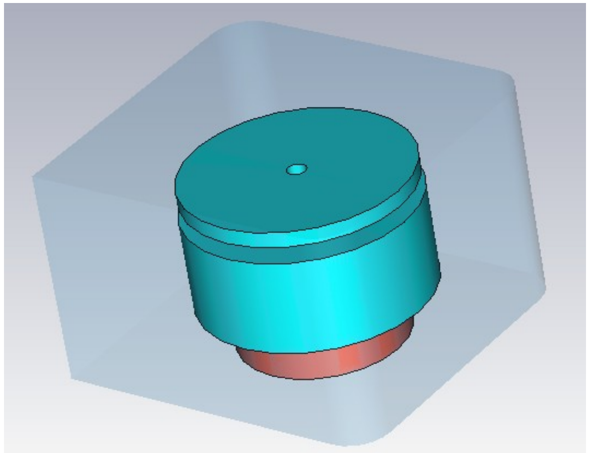
Entire filter with low mesh

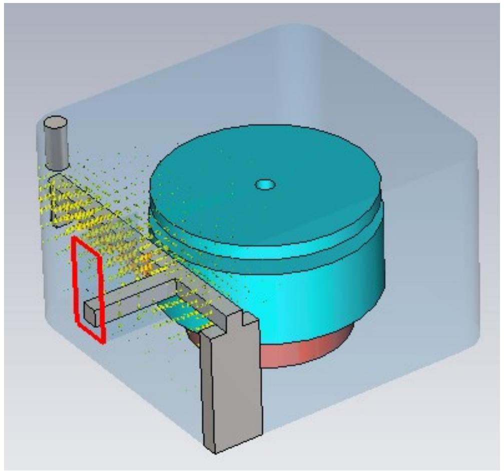
Problem 2

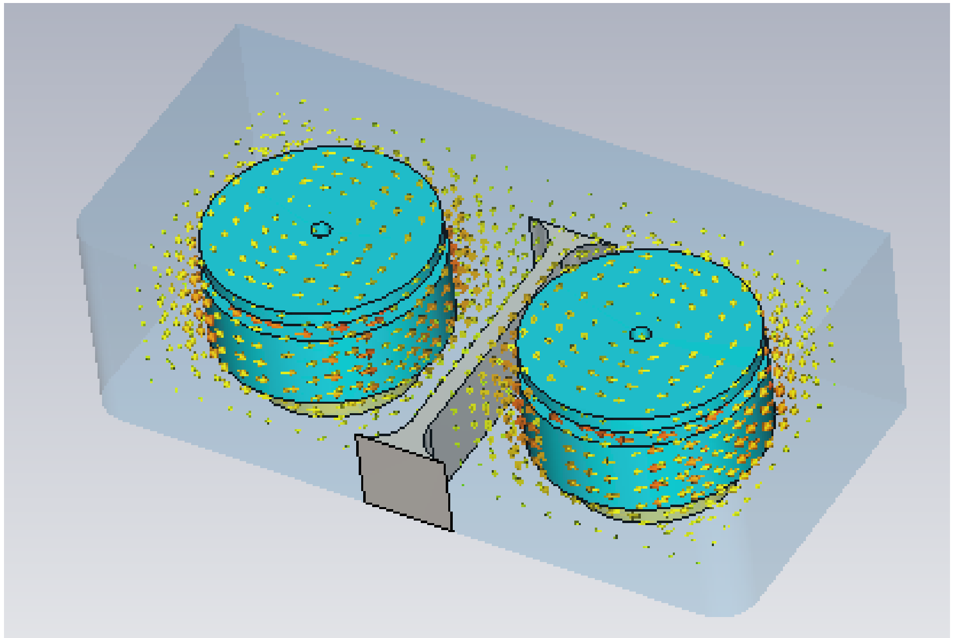
- Current work: Design ceramic filter
  - Calculate temperature drift and compensate
- Previous methodology applied
- However, a lot more CST MWS simulations



General design notes







Simulations have to be more precise than for combline resonators

Manufacturer info

Material Characteristics

Dielectric constant . . . . .43.0 ± 0.75

Temperature coefficient of resonant frequency
(τ_f) (ppm/°C) . . . .-6 to +6

τ_f

Q (1/tan δ) min . . . . .35,000 at 850 MHz
. . . . .9,500 at 4.3 GHz

Thermal expansion (ppm/°C) (20–200 °C) 6.5

Thermal conductivity (cal/cm sec°C) @ 25 °C . . . .~0.005

Non-linear coefficient (τ_f')(ppm/°C^2) . . . .-0.01

Specific heat (cal/g °C) . . . .~0.15

Density (g/cc) 5.00

Water absorption (%) . . . .<0.01

Composition .Zirconium Titanate Based

SKYWORKS

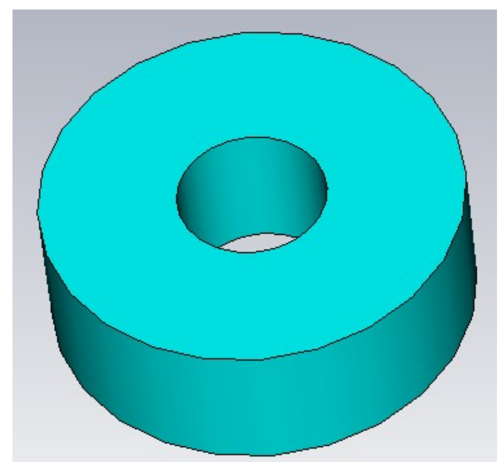
DATA SHEET

4300 Series: Temperature Stable Dielectric Resonators

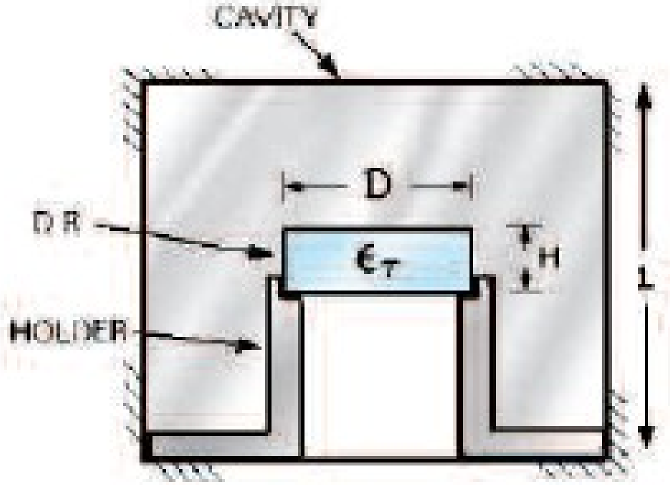
Temperature Characteristics

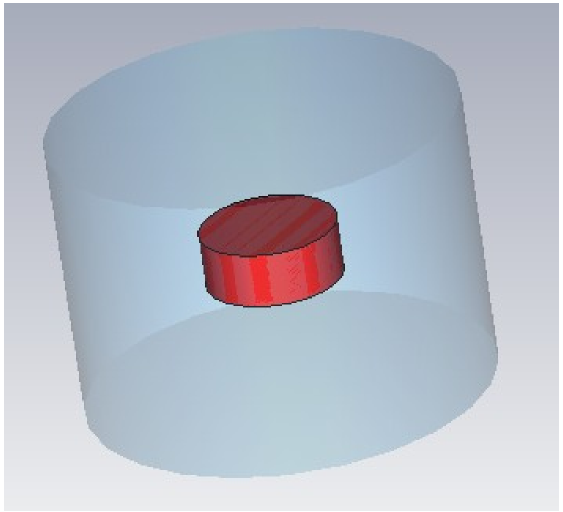
Series	Type	Dielectric Constant	Temperature Coefficient of f_o (τ_f) ± 2	Q at 4.3 GHz
D/C43	16	43.0 ± 0.75	+6	>9,500
D/C43	13	43.0 ± 0.75	+3	>9,500
D/C43	00	43.0 ± 0.75	0	>9,500
D/C43	03	43.0 ± 0.75	-3	>9,500
D/C43	06	43.0 ± 0.75	-6	>9,500

Contact factory for custom τ_f and other tolerances.



Standard cavity: temperature





D = 0.5''
H = 0.2''
L = 1.05''
C = 1.5''
$f_0 \approx$ 4 GHz

$$\boxed{\tau_f = \left(\frac{1}{f_0}\right) \cdot \left(\frac{\Delta f_0}{\Delta T}\right)}$$

Composite coefficient

$$\tau_{\varepsilon} = \left(\frac{1}{\varepsilon}\right) \cdot \left(\frac{\Delta\varepsilon}{\Delta T}\right)$$

Dielectric constant

$$\tau_{C} = \left(\frac{1}{L}\right) \cdot \left(\frac{\Delta L}{\Delta T}\right)$$

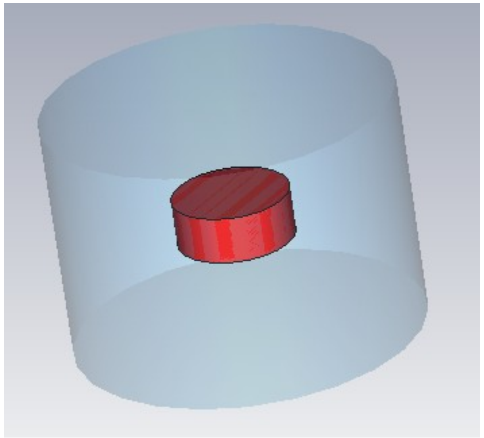
Cavity

$$\boxed{\tau_{f} = \left(\frac{1}{f_0}\right) \cdot \left(\frac{\Delta f_0}{\Delta T}\right)}$$

$$\alpha_{L} = \left(\frac{1}{H}\right) \cdot \left(\frac{\Delta H}{\Delta T}\right) = \left(\frac{1}{D}\right) \cdot \left(\frac{\Delta D}{\Delta T}\right)$$

Resonator (dimensions)

Extract τ_ε



Consider:
-dielectric const. change
-resonator dim. change
-cavity dim. change

f_0 at amb = 3959.39 MHz

f_0 at amb + 60° C = function of $\tau_{\varepsilon r}$ (change of ε with T)

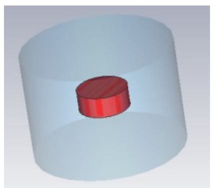
Change of $\tau_{\varepsilon r}$ until the overall quoted τ_f is obtained

Accuracy

Case	f_0 at amb MHz	f_0 at amb +60 deg C	τ_f ppm/deg C	Δf MHz
40 LPW 606,528	3953.604	3953.658	0.23	0.054
30 LPW 262,236	3956.217	3956.277	0.25	0.06
20 LPW 75,816	3962.602	3962.675	0.31	0.073
15 LPW 30,400	3972.118	3972.207	0.37	0.089

Used τ_ε = -15.3 ppm/deg C to get to approx τ_f = 0 ppm/deg C

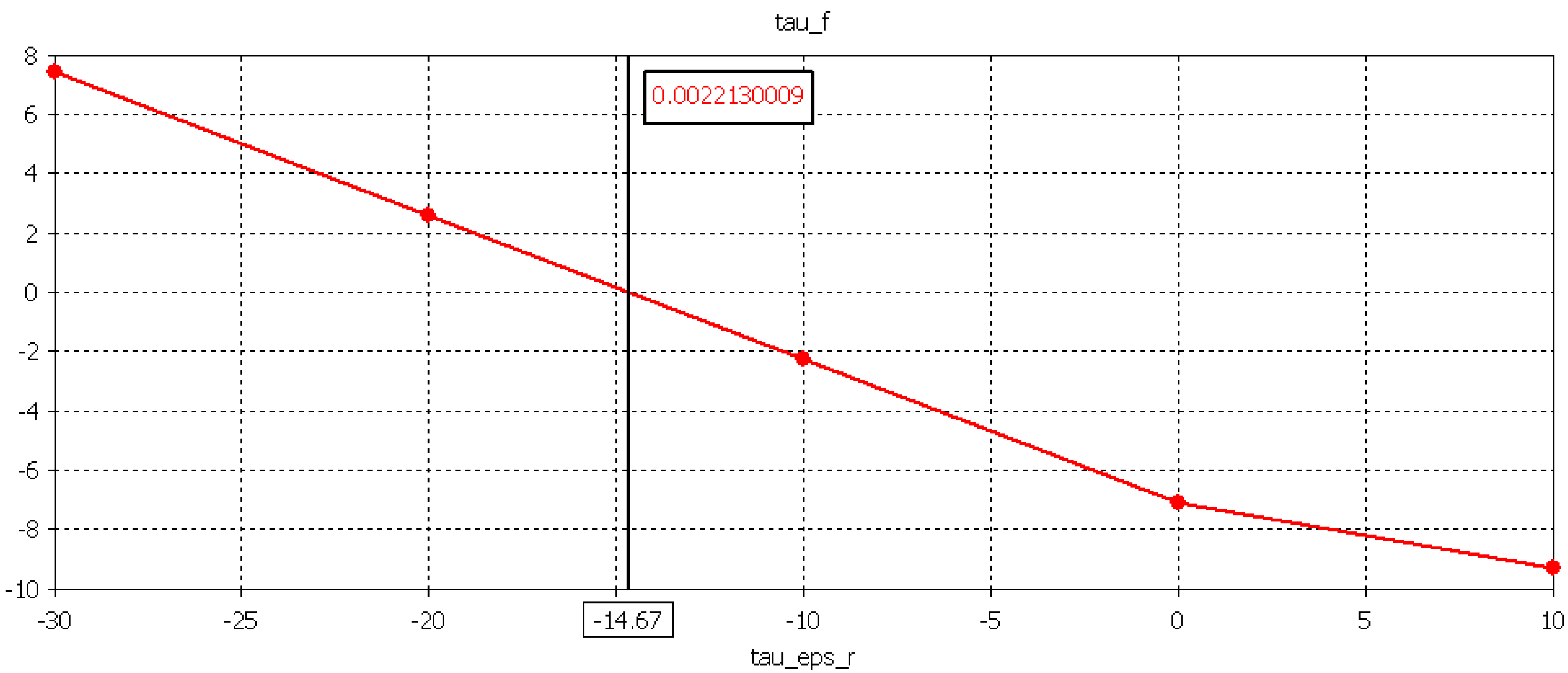
Conversion



Change τ_ε, calc f_0 at amb & temp, calc τ_f

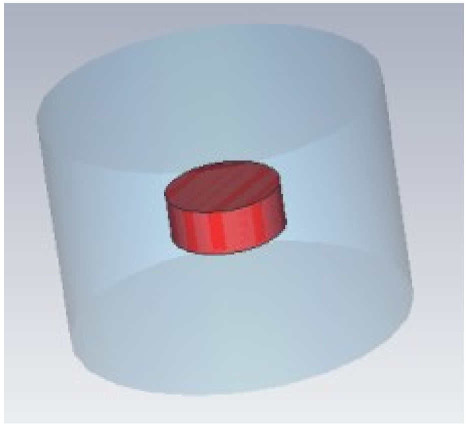
$$\varepsilon_{\mathrm{r,new}} = \varepsilon_{\mathrm{r,nom}} \cdot \left(1 + \tau_\varepsilon \cdot \Delta T\right)$$

$$\Delta T = 60\ \ \mathrm{deg\ C}$$



Extract τε: check

$$f_0 = \frac{8.553}{\sqrt{\varepsilon_r}\left(\frac{\pi}{4} D_r^2 L_r\right)^{1/3}} \longrightarrow \tau_f = \frac{3}{4}\left(A\tau_\varepsilon + B\alpha_L + C\tau_C\right)$$

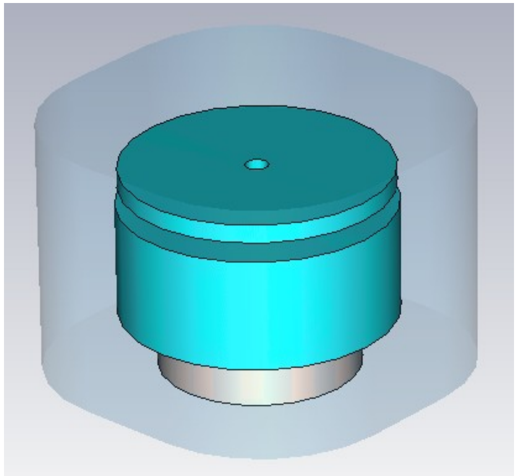


$$A \approx \frac{1}{2}, \quad B \approx 1, \quad C = [0.05, 1]$$

$$\tau_\varepsilon = \frac{4\tau_f}{3A} - B\alpha_L - C\tau_C$$

$$\tau_\varepsilon = -15.3 \text{ ppm/deg C}$$

Drift of the design



Representative cavity vs filter

$$\tau_{design} = 9.5 \text{ ppm/deg C}$$

MWS

f_0 @ 0 ˚C = 913.15 MHz

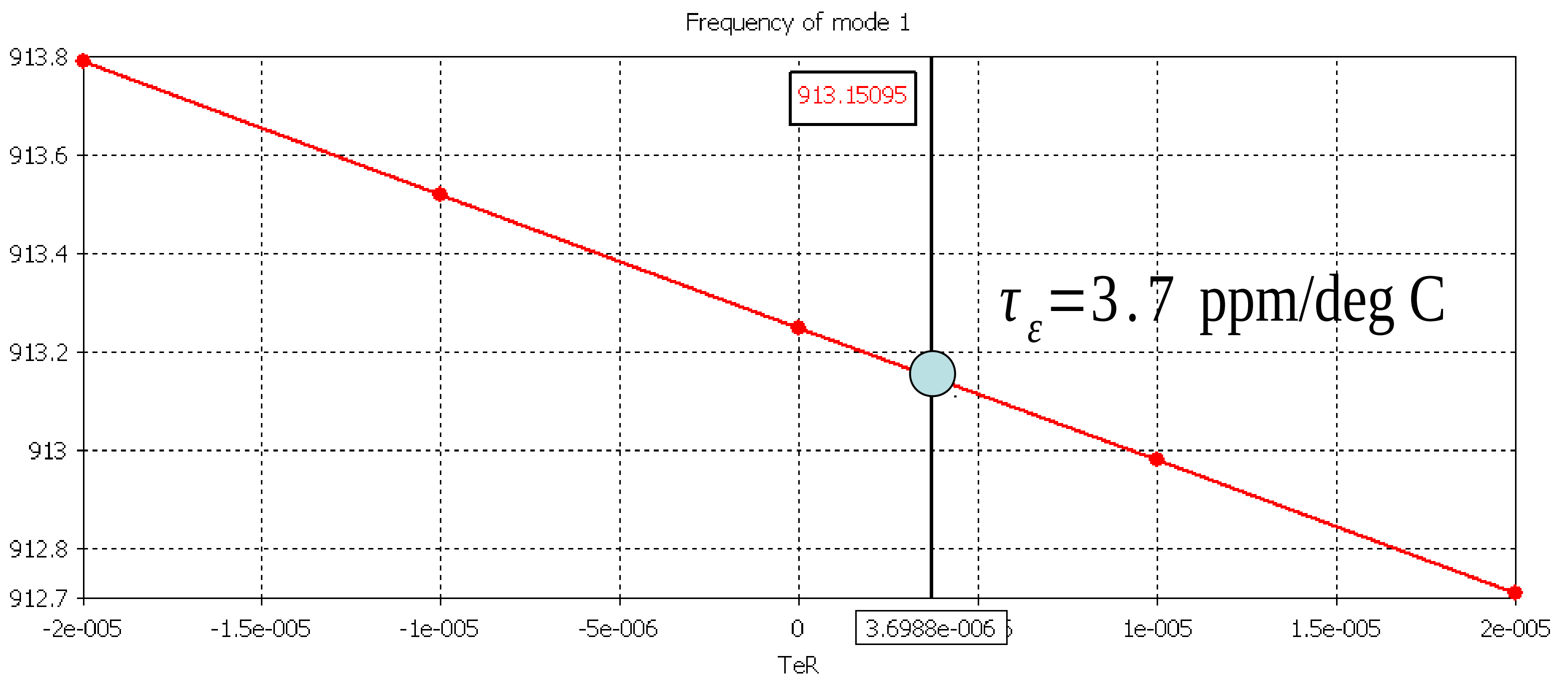
f_0 @ 60 ˚C = 913.67 MHz

We want $\tau_{design} = 0 \text{ ppm/deg C}$

Sweep τ_ε until design stabilises

Sweep desired τ_ε

Change until f_0 @ 0 ˚C and f_0 @ 60 ˚C are the same



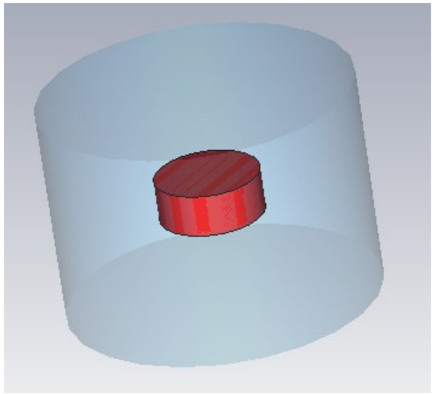
Work out required τ_ε so dopants can be selected

Convert back to τ_f in std cavity

Have $\tau_\varepsilon = -14.7$ ppm/deg C

Want $\tau_\varepsilon = 3.7$ ppm/deg C

Translates into $\tau_f = -8$ ppm/deg C $\xleftarrow{\text{MWS}}$



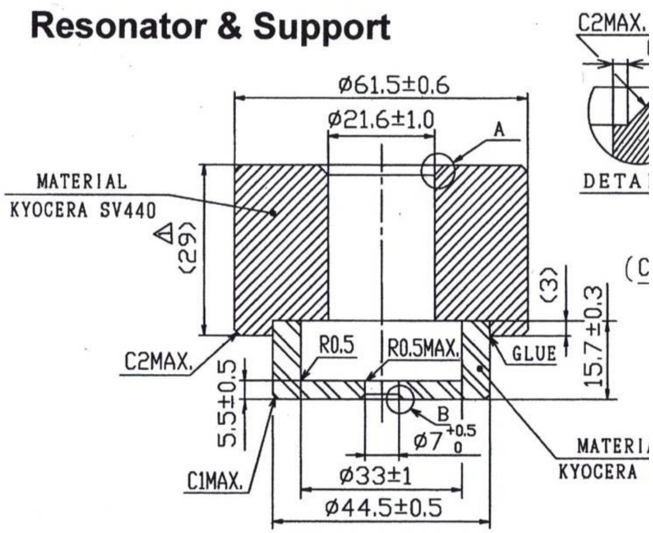
Rounded up to $\tau_f = -6$ ppm/deg C

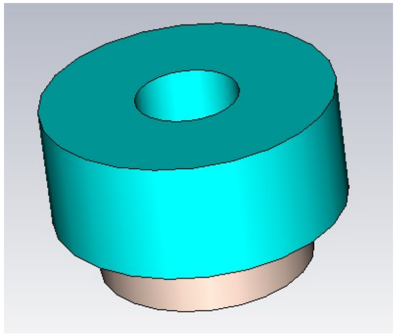
f_0 @ amb = 913.15 MHz

f_0 @ amb + 60 ˚C = 913.23 MHz

Therefore $\tau_{\text{design}} = -1.5$ ppm/deg C $\longrightarrow$ ORDER !

Standard cavity: frequency



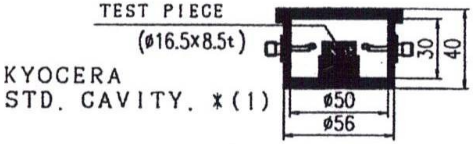


* CHARACTERISTICS

No.	THK.	fo	τf	Qu
1	(21.6)	949±3MHz	1.4±1ppm/℃	—
2	(20.4)	964±3MHz		
3	(22.5)	942±3MHz		
4	(26)	897±3MHz		

* CONDITION OF MEASUREMENT

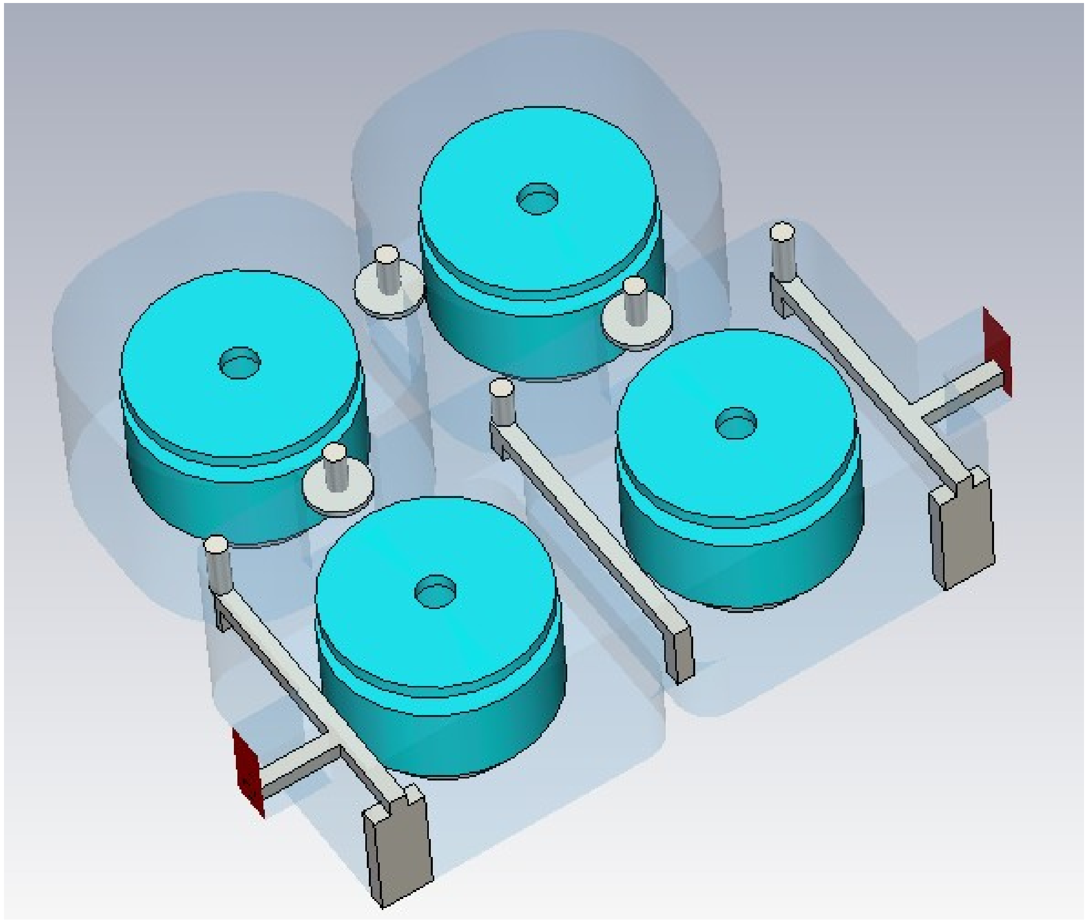
	CAVITY	SAMPLE	NOTE
fo	ø95.25x63.5t C-0209	RESONATOR + SUPPORT	———
Qu	ø95.25x63.5t C-0209	RESONATOR + SUPPORT	———
τf	KC STD *(1)	TEST PIECE ø16.5x8.5t	TEMP. RANGE 20~60℃



Summary

- Work out tau_epsilon from specs
- Work out expected design drift
- Work out required tau_epsilon
- Translate to tau_f in standard cavity
- Translate to standard cavity frequency
- Order
- Keep working...

Keep working...



Entire filter,
all parametrised...

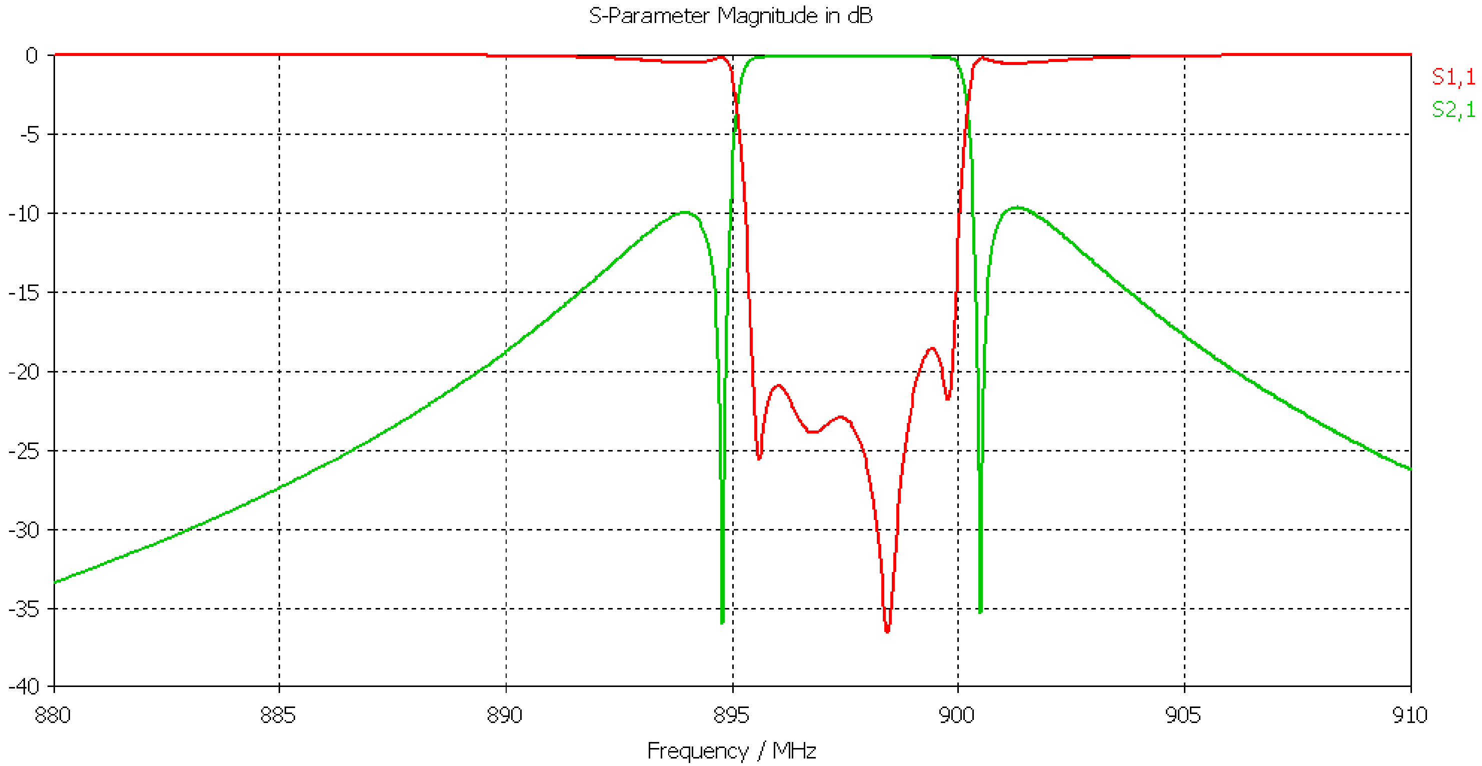
Spurious coupling
(coupling sign)

Temperature drift

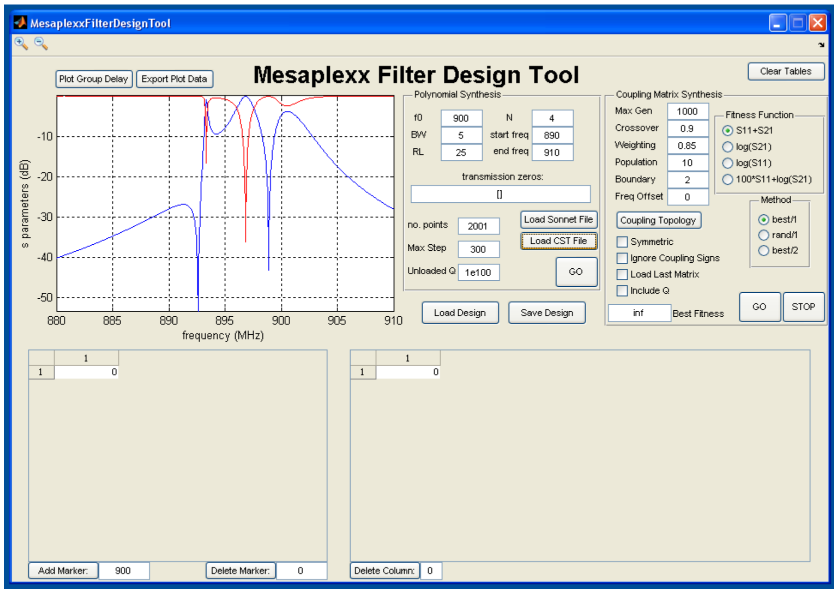
Verification

Tune and measure

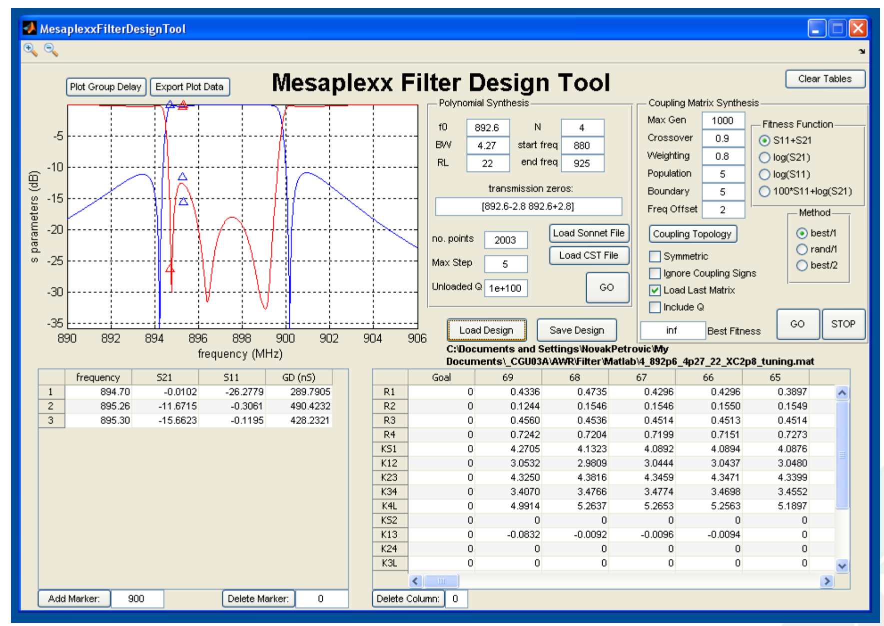
Tuned with the aid of Mesaplexx Filter Design Tool



Tuning

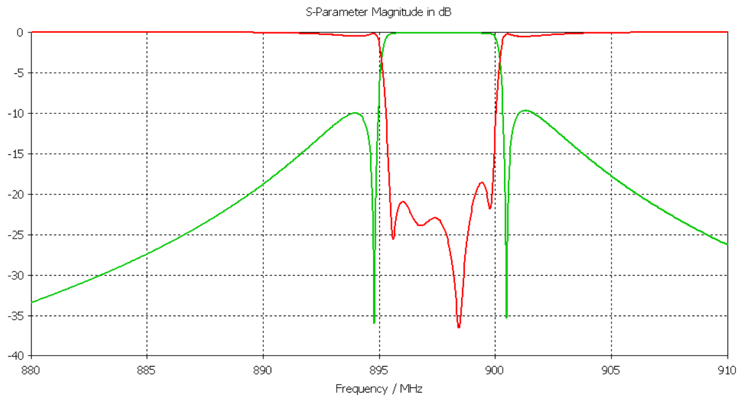


Extract coupling matrix by comparing to model



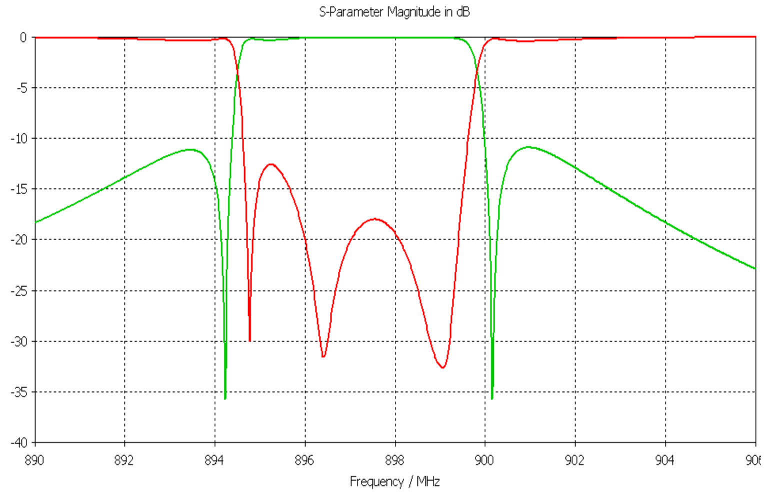
Note difference to desired, change (screws) manually, 5 – 50 times (?)

Accuracy



SPW = 4, MIN = 4
Tetrahedrons: 41,872
Adaptation: None
Accuracy = 1e-4
delta S = 0.01

~ 7 min



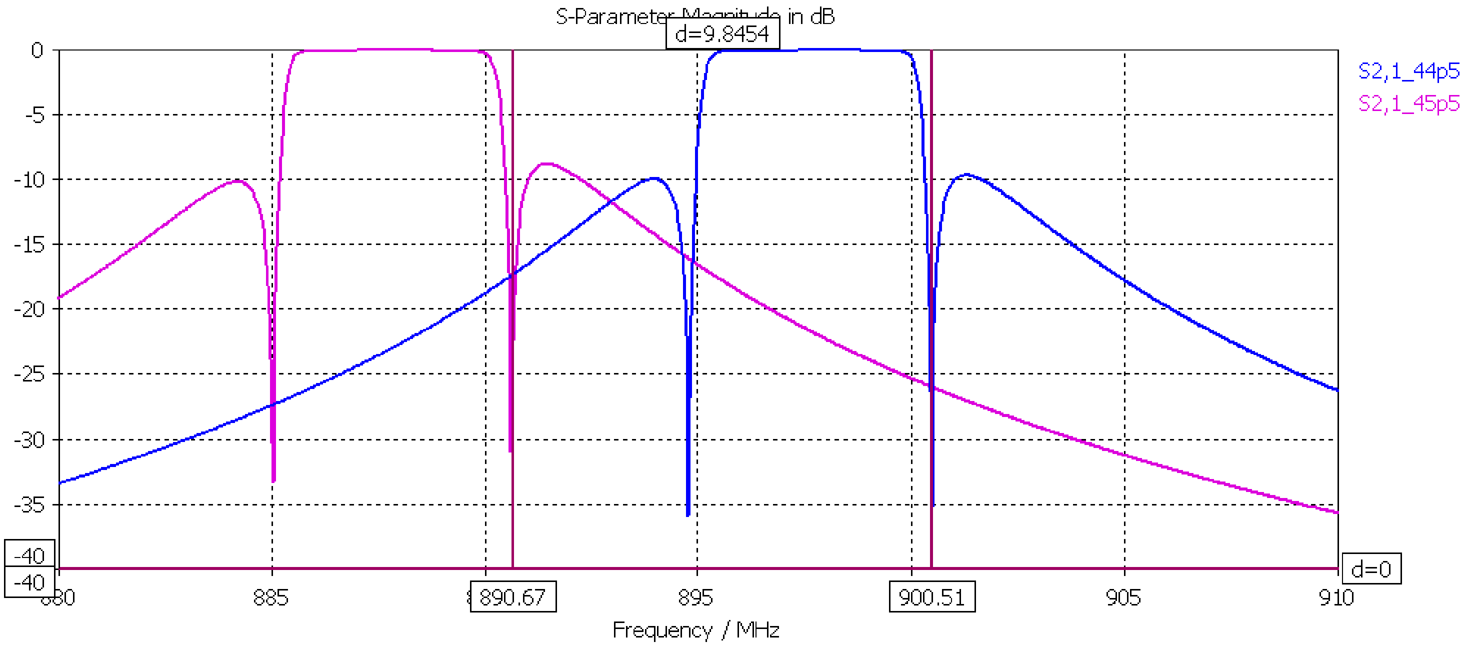
SPW = 6, MIN = 6
Tetrahedrons: 156,411
Adaptation: 1 @ 897.7 MHz
Accuracy = 1e-6
delta S = 0.01 (both)

~ 31 min

Drift illustration

Material Characteristics

Dielectric constant . . . . .43.0 ± 0.75

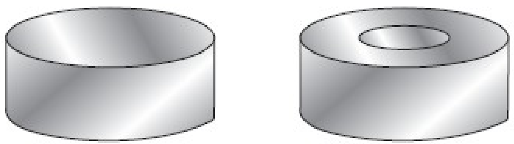


Relevance

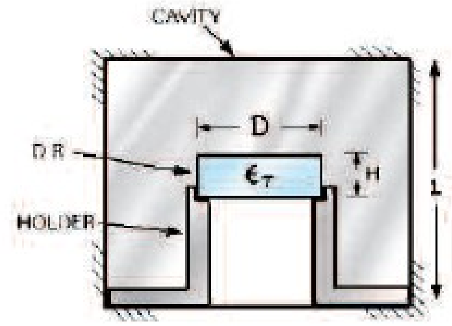
- Turn-around time (+ other suppliers)
- Qualification of custom-made ceramics
  - Q, ε_r, τ_ε (the difficult trio)
  - nonlinear coefficients, complex ε
  - cryogenic temperatures (contraction!)
- Tight specification (GSM channels)
- New tuners, dual-mode filters, ...

Unexpected twists

Dielectric supports contribute as well!

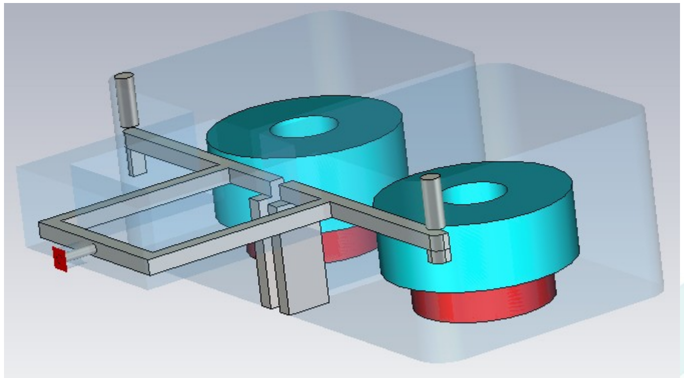


Disk Type　　Cylinder Type

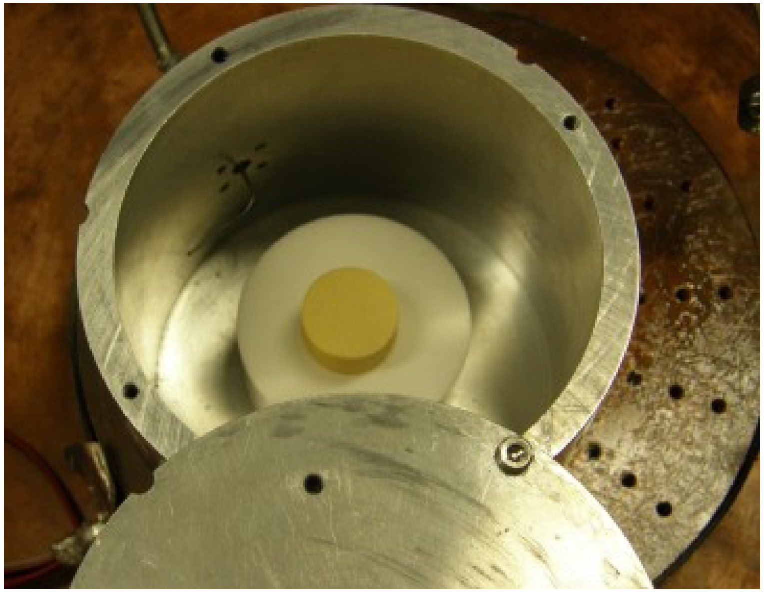


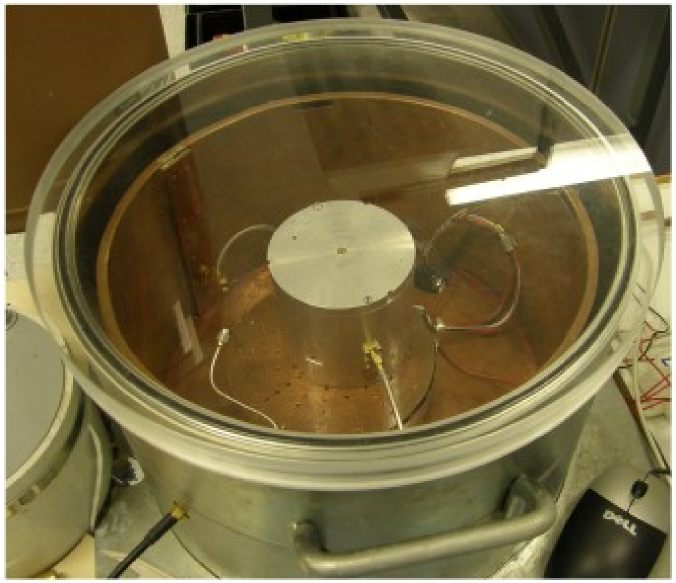
Material Characteristics

Composition	Alumina
Dielectric constant	9.5
Dielectric loss	<0.001
Temperature coefficient of (τ_f) (ppm/°C)	114
Volume resistivity (ohm cm) at 20 °C	10^{16}
Coefficient of thermal expansion (ppm/°C) (25–200 °C)	6.5
Thermal conductivity (cal/cm°C sec) at 25 °C	0.08
Water absorption (%)	<0.01



Parameter extraction





Extraction of material properties by numerical simulation.

Future work

- Power handling in comblines
  – Line integral to calculate voltage
- Thermal runaway in ceramic filters
  – Power handling
- Printed filters
- Lumped element extraction
- More macros

Thank you!