Temperature Compensations for Microwave Resonators and Filters

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Reference

- T.S. Saad. "Doubly Compensated Tunable Cavity." Mar. 1953 [T-MTT]: 25-28.
- *J.R. Cogdell, A.P. Deam and A.W. Straiton. "Temperature Compensation of Coaxial Cavities." Mar. 1960 [T-MTT]: 151-155.*
- *Chi Wang and K.A. Zaki. "Temperature compensation of combline resonators and filters." 1999 Vol. III [MWSYM]: 1041-1044 vol.3.*
- Hui-Wen Yao and A.E. Atia. "Temperature characteristics of combline resonators and filters." 2001 MTT-S International Microwave Symposium Digest 01.3 (2001 Vol. III [MWSYM]): 1475-1478 vol.3.
- Kyrocera Dielectric Resonator Data Sheet
- Trans-Tech Technical Design Note
- US Patent # 6,600,394

Presentation Outline

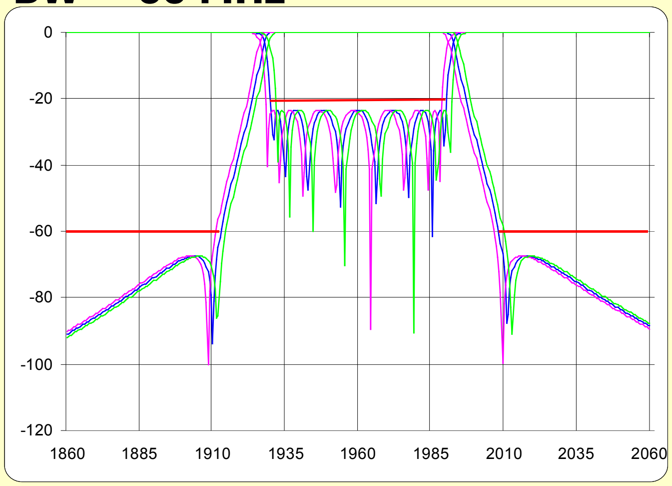
- Background
  - Effects of Environmental Requirements on Filter Designs
  - Characteristics of Commonly Used Metallic Materials
  - General Filter Design Procedure
- Temperature Compensation on Comb-line Filters
  - Principle of Resonator Compensations
  - Effects of Resonator Dimensions on Resonant Frequency over Temperature
  - Design Example
- Temperature Compensation on Dielectric Loaded Resonators and Filters
  - Characteristics of Dielectric Materials
  - DR Design Examples

Motivations

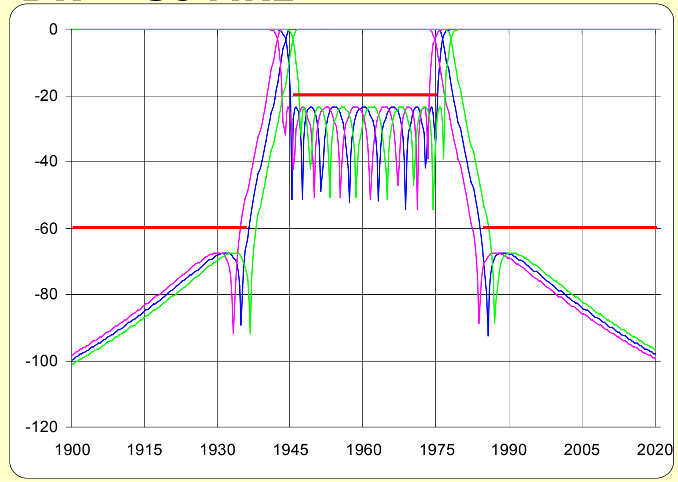
- Performance of a Microwave Filter over Temperature is Usually an Important Factor for the Design, Especially for Narrow Bandwidth Filter
- Low Coefficient of Thermal Expansion (CTE) Material, Such as Invar, Usually Can Achieve the Desired Temperature Characteristics, But Too Expensive for Most of the Applications
- Other Low Cost, High Electrical Performance Materials Such as Aluminum and High Dielectric Constant Ceramics Are More Desirable in Practical Applications
- Comb-line and Dielectric Loaded Resonators and Filters are Widely Used in many Applications and Can Be Well Temperature Compensated

Typical Uncompensated Aluminum Combline Filter Performance over Temperatures

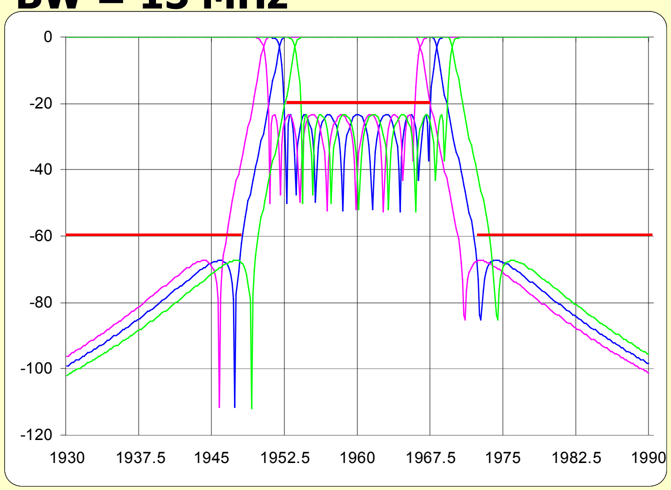
BW = 60 MHz



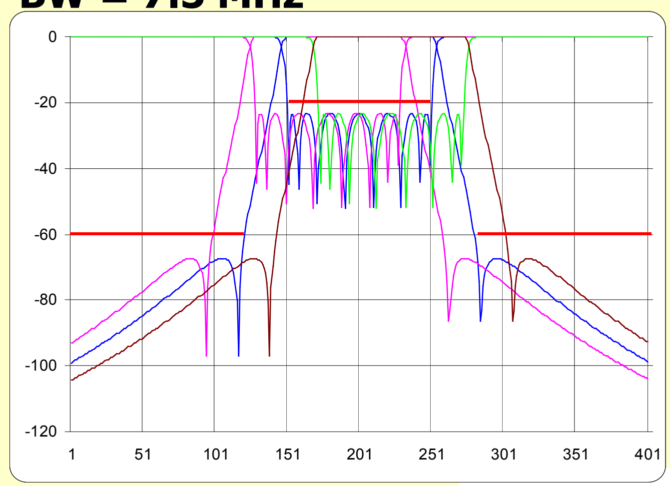
BW = 30 MHz



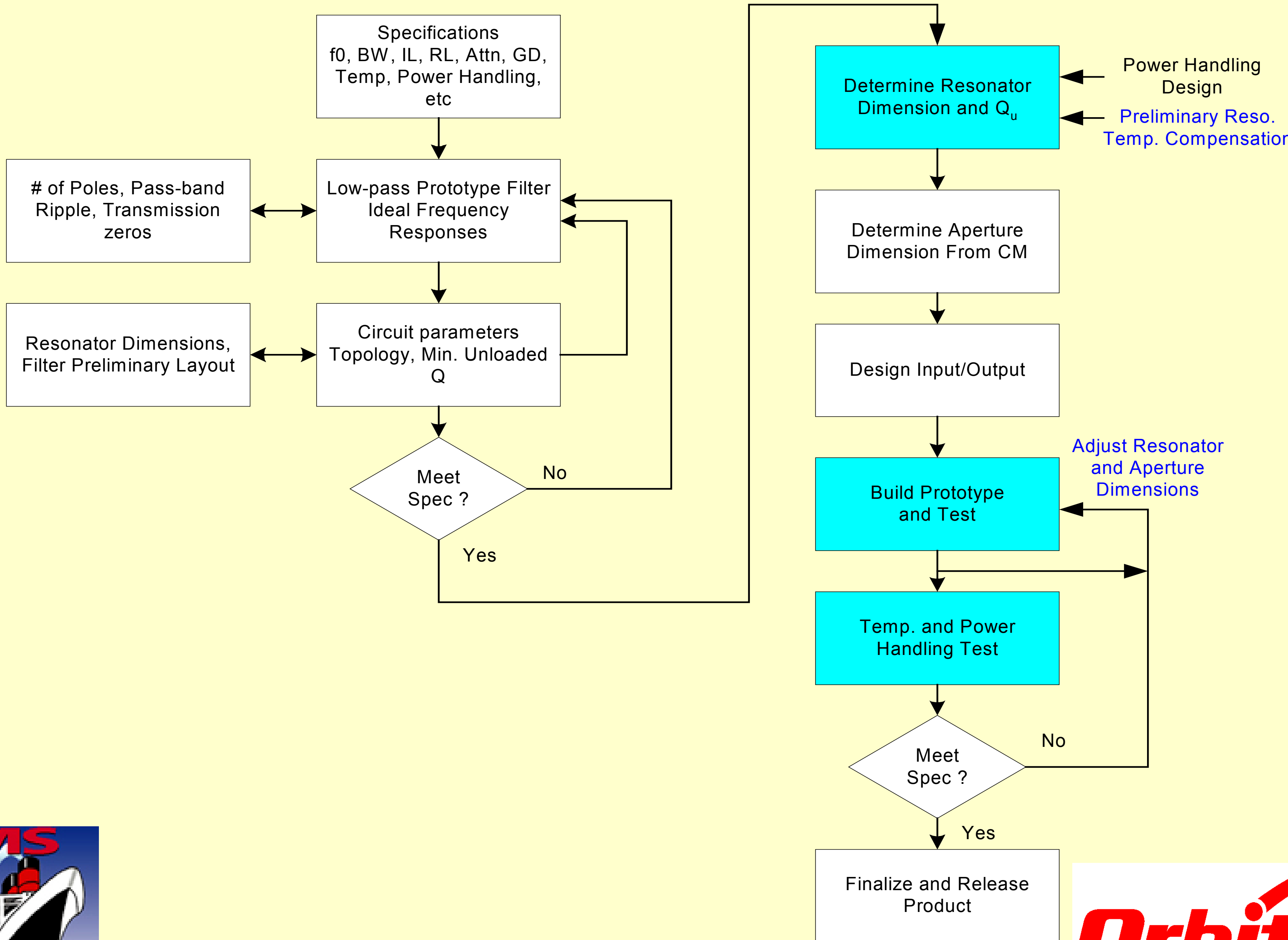
BW = 15 MHz



BW = 7.5 MHz



Filter Design Procedure



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Principle of Temperature Compensation

- The Principle for Temp. Compensation of Microwave Resonators is Simple:

$$\tau_f = \Delta f / \Delta T = \sum \Delta f_i / \Delta T = 0$$

- Easiest but Most Expensive Way is to Use All Zero Frequency Thermal Coefficient Materials
  – Too Expensive or Not Always Practical
- More Cost Effective Ways of Temperature Compensations are Needed and Available by Intelligently Using the Resonator and Material Properties

Typical CTE* of Commonly Used Metals

Material Name	CTE (ppm/C)	Comment
Invar	< 1.3	Typical 0.9 ppm/C
Titanium	8.5	
Stainless Steel 410	10.2	
Stainless Steel 316	16	
Copper	16.8	
Beryllium Copper	16.7	
Brass	18.4	
Aluminum 7075-T6	23.4	Safe to use 24 ppm/C for all Aluminums
Aluminum 6061	23.6	

**** CTE - Coefficient of Thermal Expansion***

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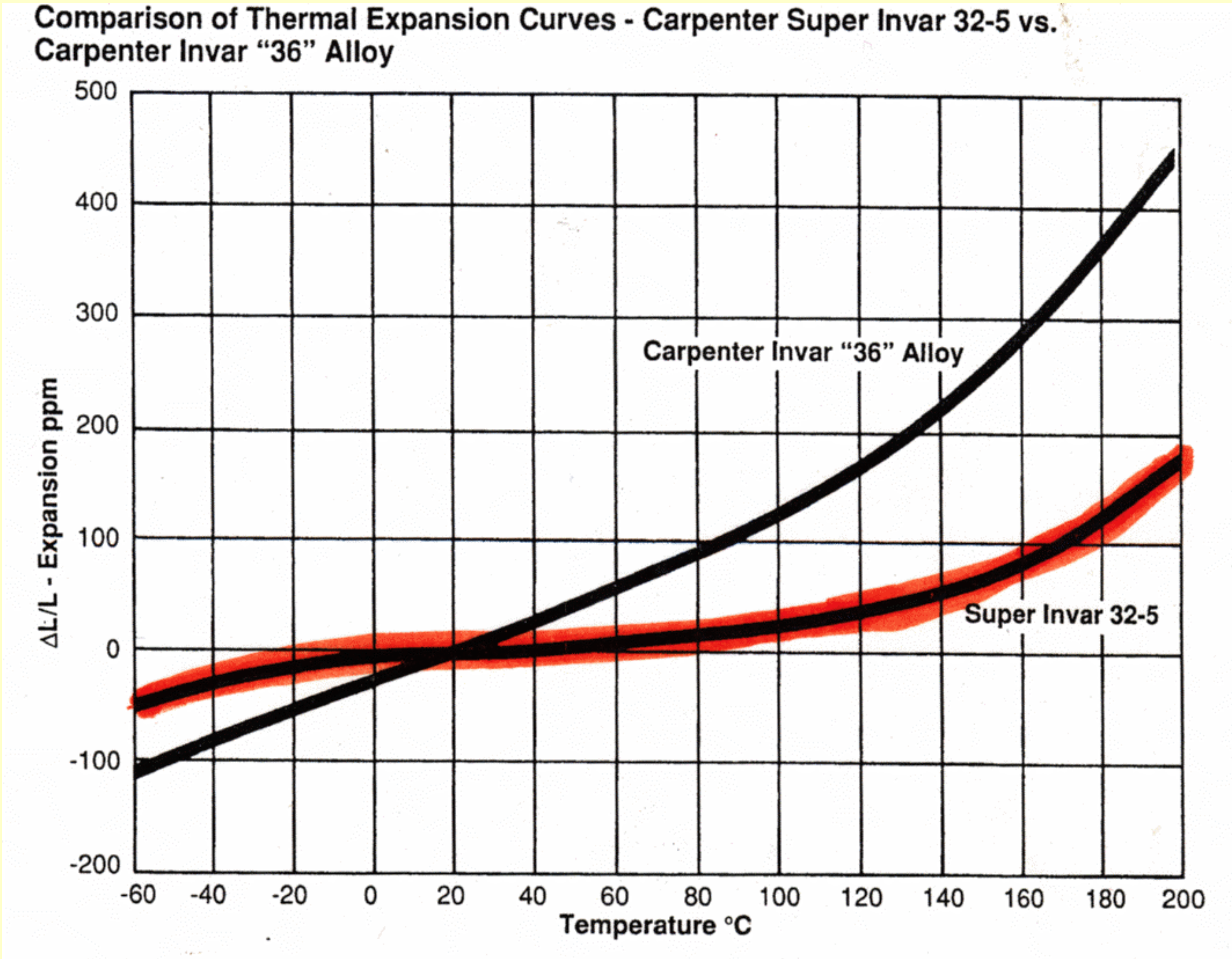
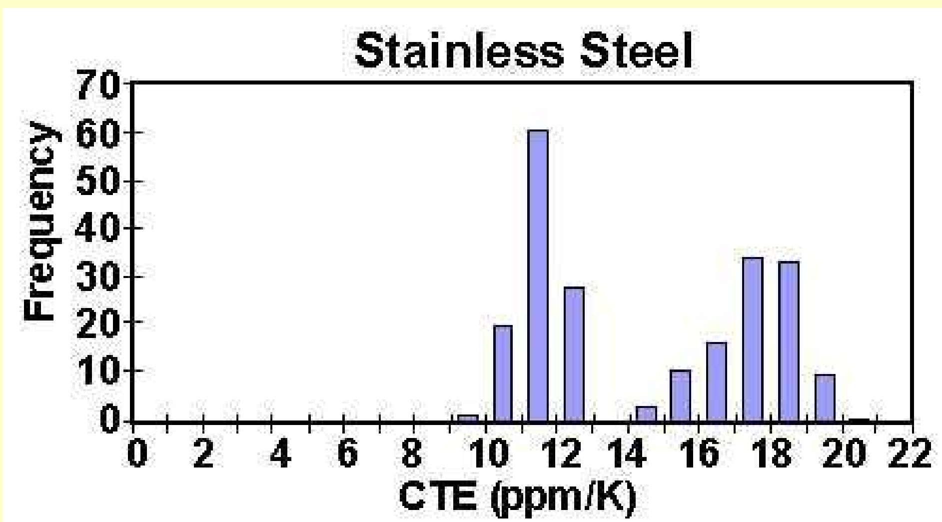
Temperature Characteristics of Invar



Characteristics of Stainless Steels

- CTE of stainless steels can vary significantly
- The CTE for 300 series stainless steel runs in the 14 to 19 ppm/°C range, while that of 400 series stainless steel is between 10 and 12 ppm/°C.
- It is critically important to know the type of stainless you are using; the bias between the two main types of steel being nearly 100 %.

stainless steel 304	17.4
stainless steel 310	14.7
stainless steel 316	16.0
stainless steel 410	10.2
steel 1008 & 1018	12.1
steel 4340	11.4
steel 15-7PH	9.0
steel 17-4PH	10.8
steel 17-9PH	10.7
steel 17-7PH	10.5

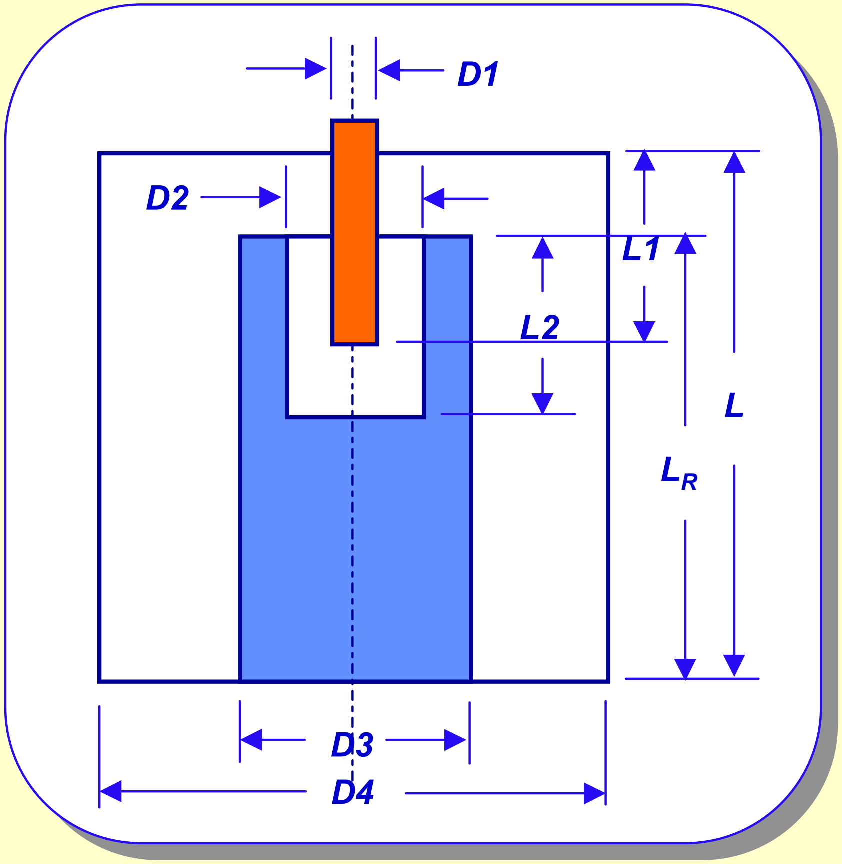


Temp. Compensations for Comb-line Resonators and Filters

- Comb-line Resonators and Filters Can Operate in Wide Frequency Range – 400 MHz to 10+ GHz
- Temperature Characteristics are Mainly Determined by Metals That Constructed the Resonators
  - Aluminum is mostly commonly used for resonator housings
  - Temperature drift is usually too high for narrow band applications
- Resonators Usually Need to be Temperature Compensated when BW is Less Than 15 MHz
- Dissimilar Materials with Less CTE are Usually Used for Resonator Rods and Tuning Screws for Temperature Compensation

Effects of Elements on Resonant Frequencies over Temperature

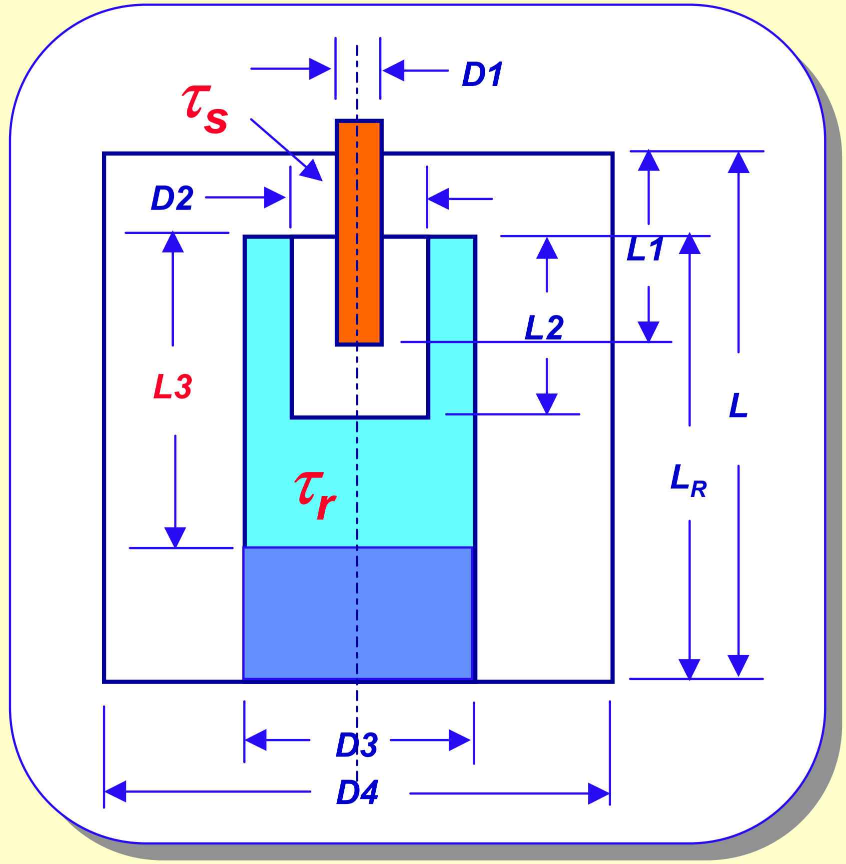
- Condition: T ↑
- Cavity
  - ΔD4 → F_0 ↓↓ (Can't Help !)
  - Δ L → F_0 ↑
- Resonator Rod
  - Δ D3 → F_0 ↓
  - Δ D2 → F_0 ↑
  - Δ L_R → F_0 ↓↓↓
  - Δ L2 → ~ Unchange
- Tuning Screw
  - Δ D1 → F_0 ↓
  - Δ (L-L1) → F_0 ↑↑↑↑



- ***Overall Typical f0 ↓***

Resonator Compensations

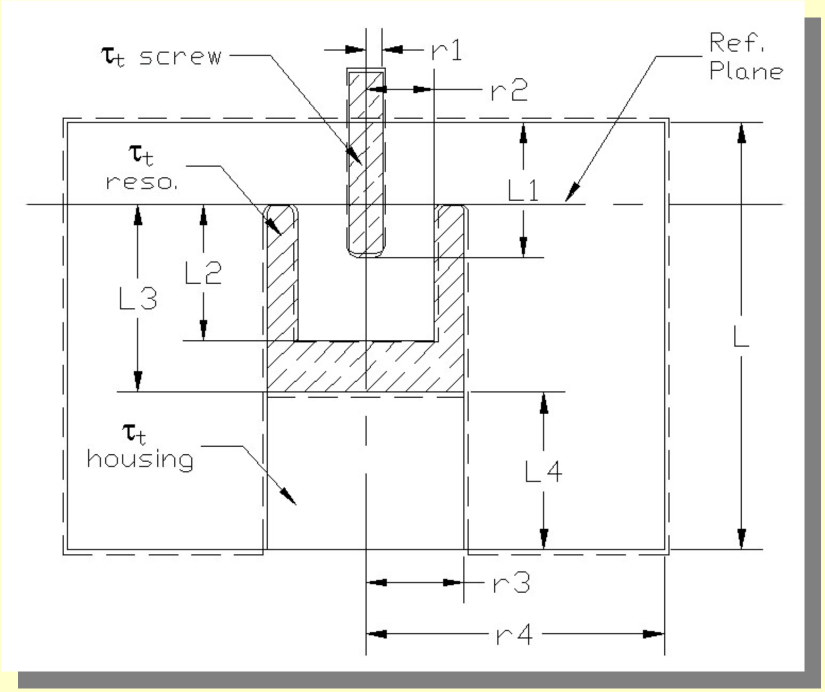
- Critical Dimensions
  - ΔL_R and Δ (L-L1)
- Compensation Goal
  - $F_0 \downarrow$ Due to ΔL_R and Δ D4 == $F_0 \uparrow$ Due to Δ (L-L1)
    - ➢ Decrease ΔL_R
    - ➢ Increase Δ (L-L1) or Decrease Δ L1



- Realizations
  - Using Low CTE (τ_s) Material for Tuning Screw
  - Partial or Full Height Dissimilar Material (τ_r) for Resonator
    - Tuning Screw is Usually Cost Less Than Resonator
    - Less Expensive Material is Desirable for Resonator

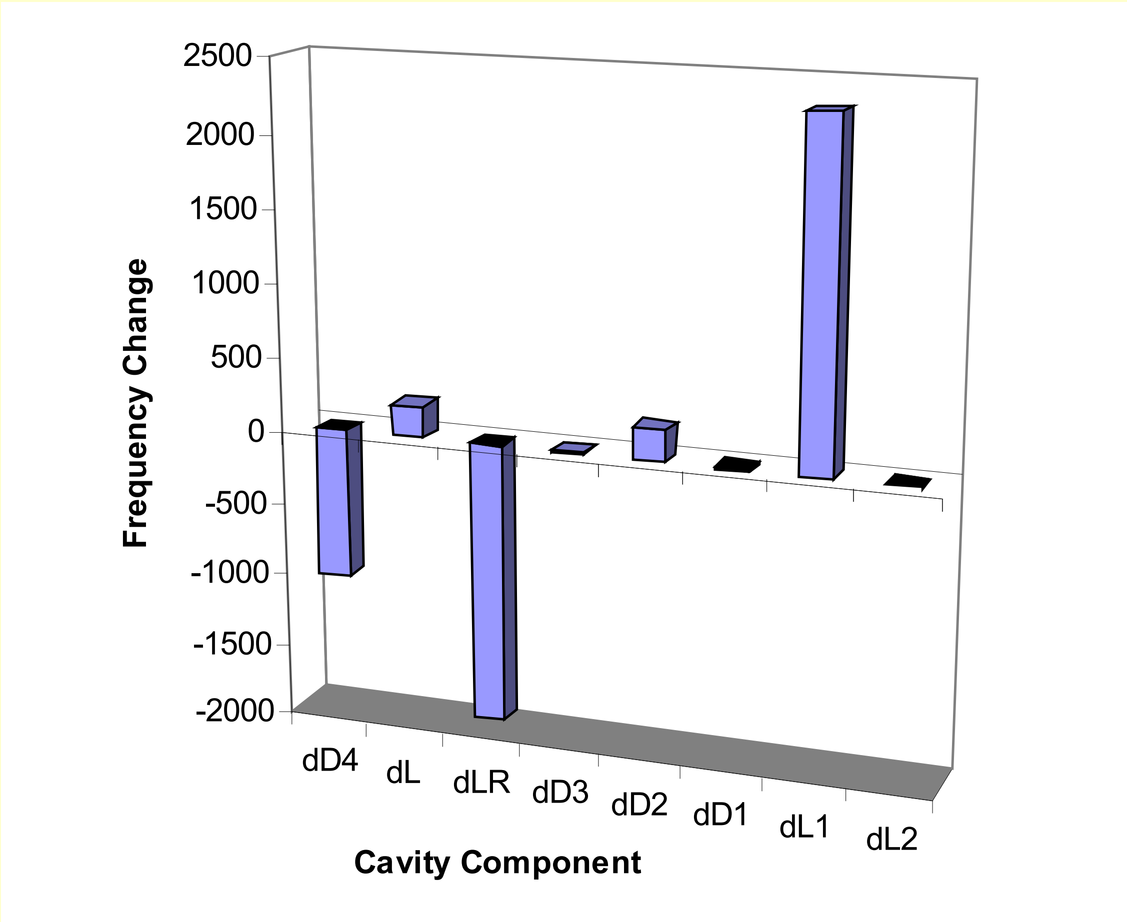
Numerical Methods

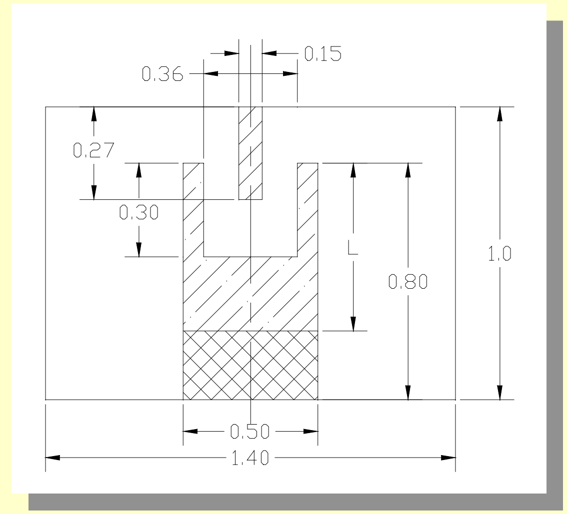
- Full-wave 3-D EM Simulator
  - Direct compute the resonant frequency change by changing the resonator dimensions
  - Numerical error may be greater than frequency change
- Incorporating Perturbation Techniques
  - Accurate and fast
  - More information can be obtained
- Suitable Reference Plan May Improve Accuracy



$$\frac{\Delta f}{f_0} = \frac{\int_{\Delta \tau} (\varepsilon E^2 - \mu H^2)\, d\tau}{4W}$$

Resonant Frequency Change by Each Cavity Component



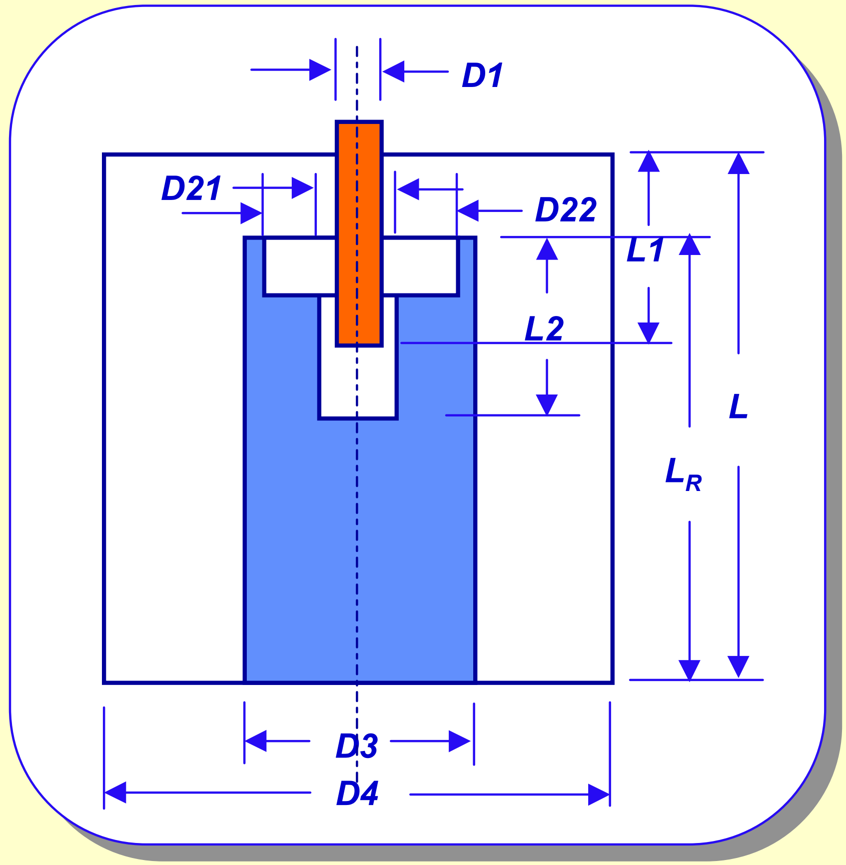


Overall Frequency Drift < 100 KHz

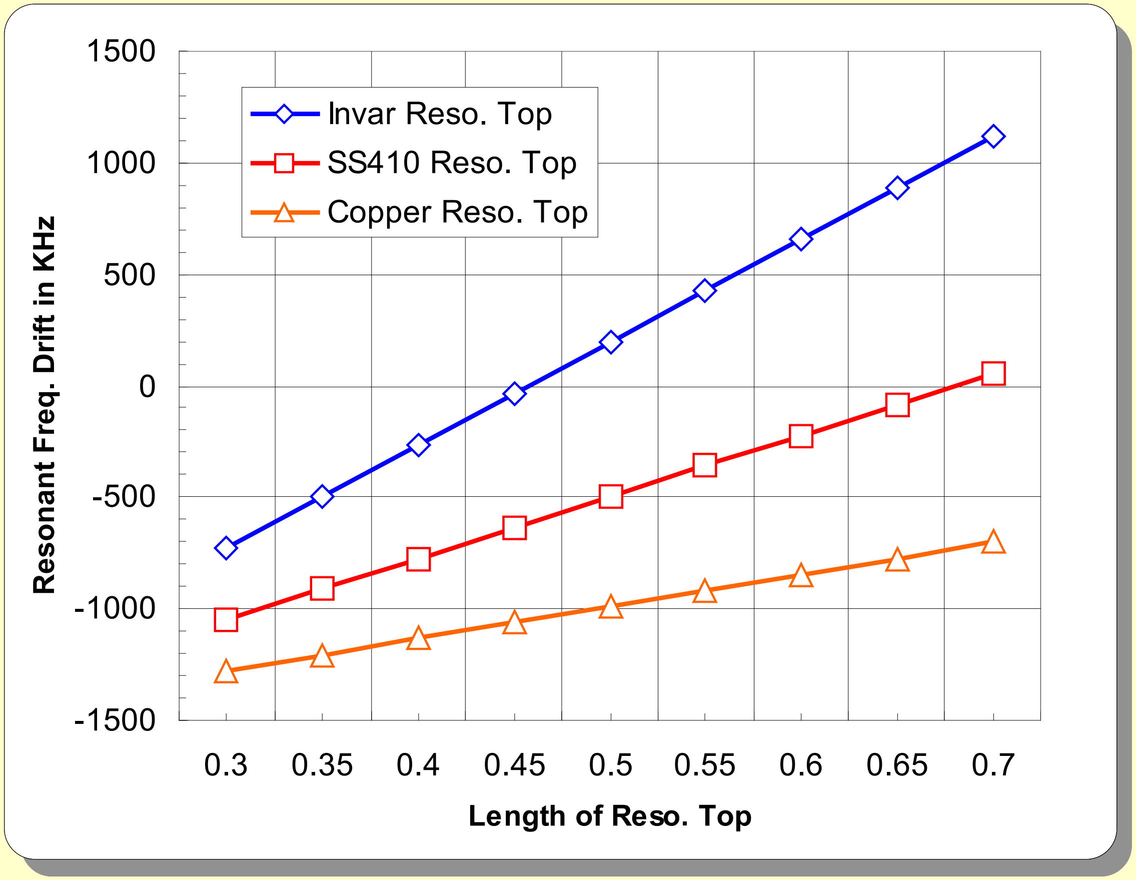
AL Housing, 0.675" SS410 Rod Top, Invar Tuning Screw, ΔT = 50 C,

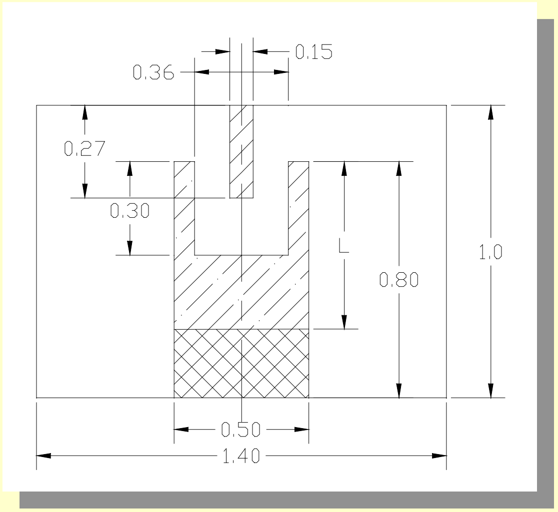
Rx Resonator Compensation

- Rx Resonator Allows Small Gap
- Dissimilar Material for Resonator Rod Can be Eliminated to Reduce Cost
- Compensation Method
  - Increase sensitivity of tuning screw
  - Reduce sensitivity of resonator top surface
  - Using Low CTE (τs) Material for Tuning Screw



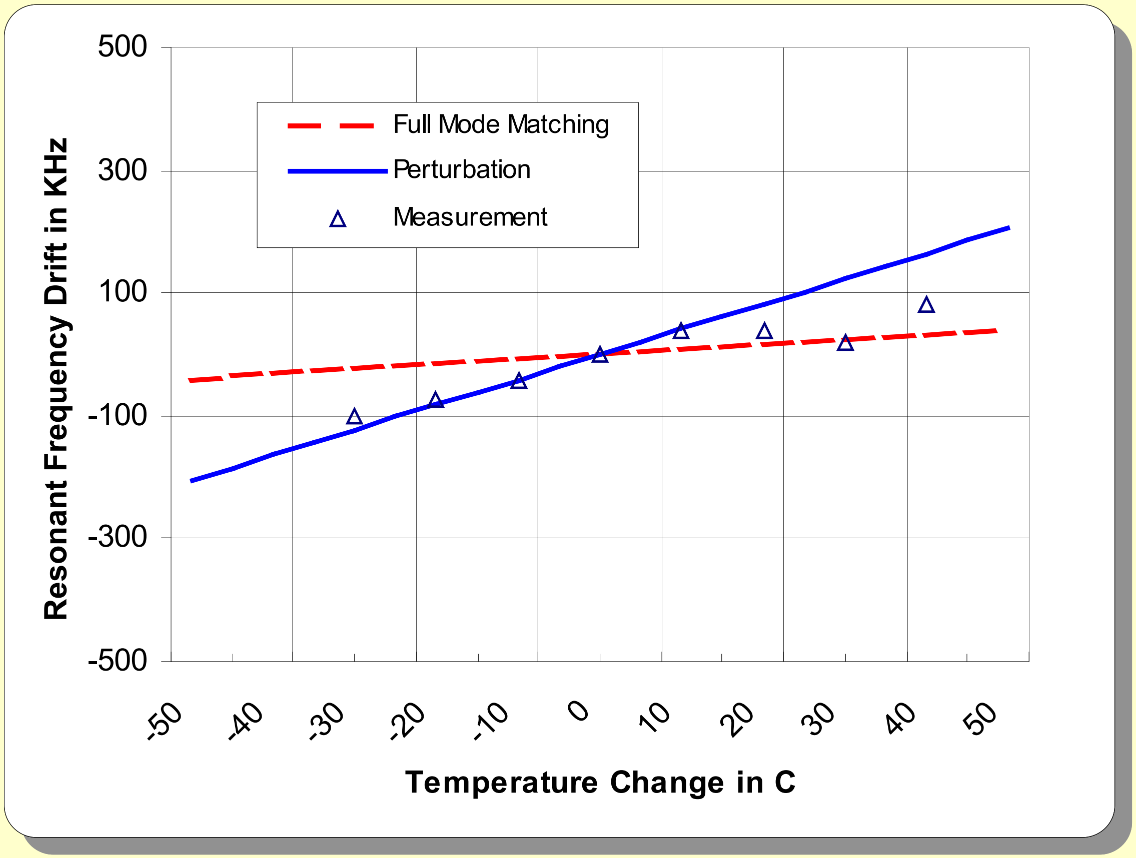
Frequency Drift vs. Length of Resonator Top Material

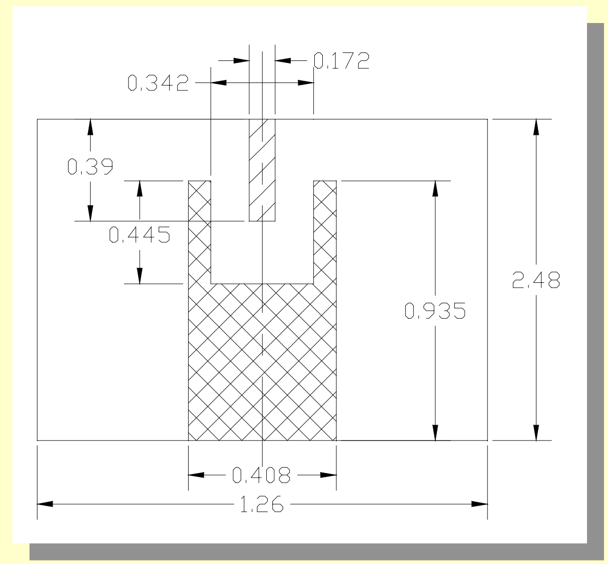




AL Housing, Invar Tuning Screw, ΔT = 50 C

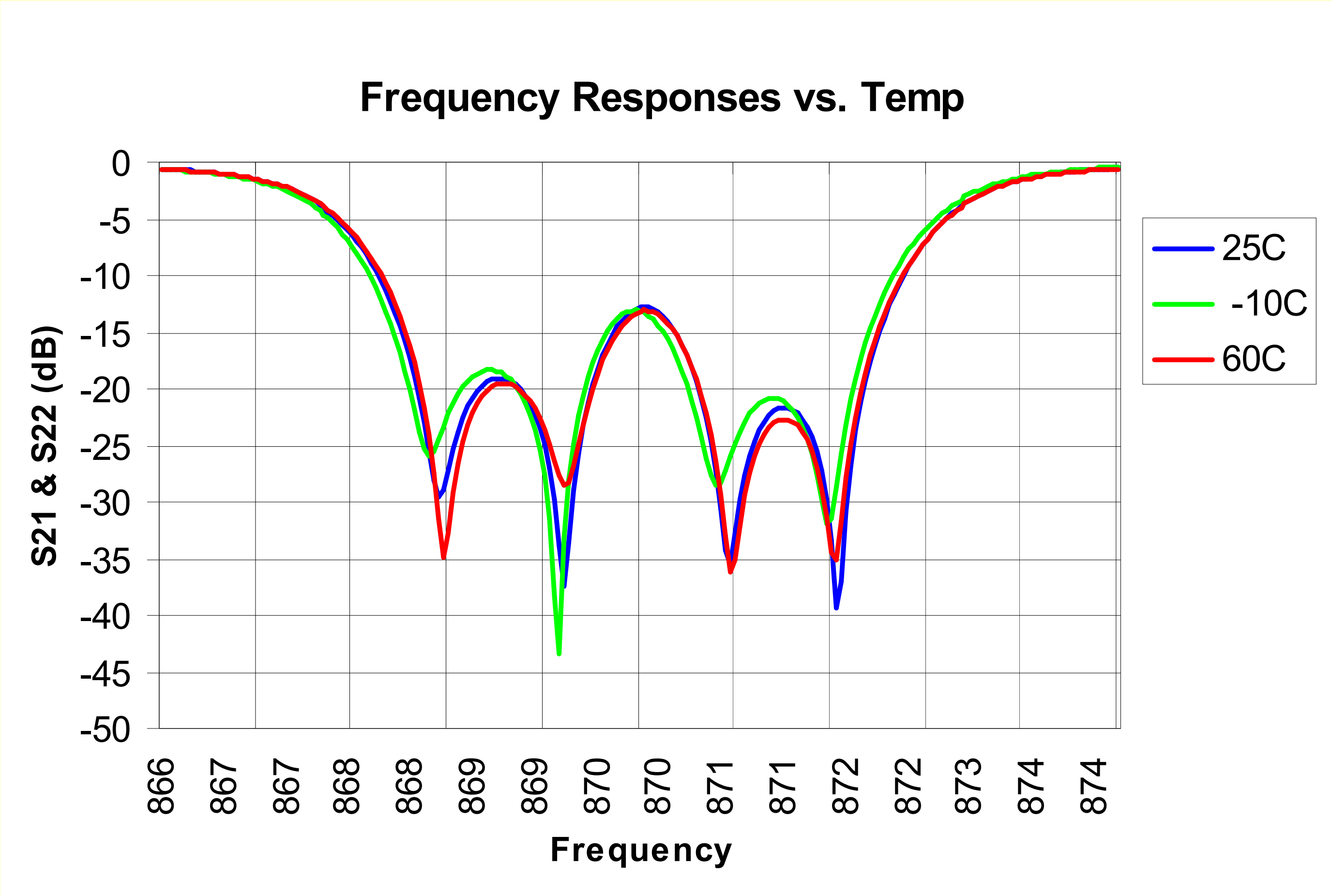
Computed and Measured Frequency Drift of the Cavity over Temperature





AL Housing, Brass Resonator Rod, Invar Tuning Screw, ΔT = 50 C

Measured Frequency Response of a 2-CH Diplexer



Courtesy of Radio Frequency Systems Inc.

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Advantage of DR and DR Temp Compensation

- Temperature Characteristics of the DR and Filter Mostly Determined by Dielectric Material Used
- Dielectric Material is Temperature Stable and Frequency Temperature Coefficient is Adjustable
- Dielectric Material Operating over Wide Frequency Range
- DR Cavity Has Very High Unloaded Q
- DR Cavity or Filter Has Smaller Size
- Resonator Cavity for the Required Application can be easily Temperature Compensated by Adjusting the Temperature Coefficient of the Dielectric Material
- Temperature Compensation Essentially Does Not Increase the Cost of the Resonators or Filters

Temperature Coefficients of DR

Definitions

There are four temperature coefficients (T.C.): T.C. of dielectric constant, T.C. of the cavity, T.C. of thermal expansion, and T.C. of resonant frequency which is a function dependent on the other three. Their definitions are (relative to Fig. 1)

$$\tau_\epsilon = \frac{1}{\epsilon_\tau}\,\frac{\Delta\epsilon_\tau}{\Delta T}\;\ldots \qquad (1)$$

T.C. of dielectric constant

$$\tau_c = \frac{1}{L}\,\frac{\Delta L}{\Delta T}\;\ldots \qquad (2)$$

T.C. of the cavity

$$\alpha_L = \frac{1}{H}\,\frac{\Delta H}{\Delta T} = \frac{1}{D}\frac{\Delta D}{\Delta T}\;\ldots \qquad (3)$$

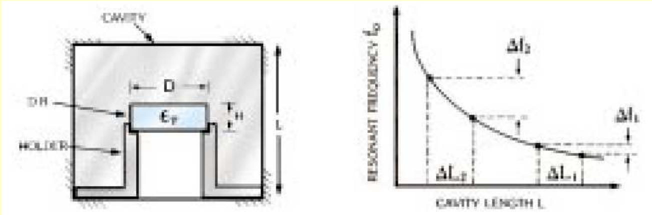
T.C. of thermal expansion

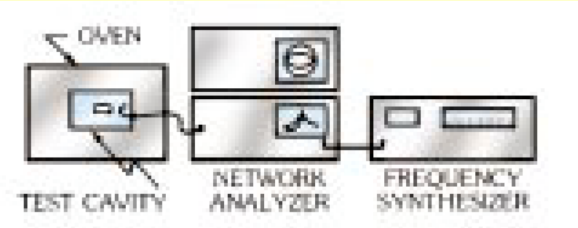
$$\tau_f = \frac{1}{f_o}\,\frac{\Delta f_o}{\Delta T}\;\ldots \qquad (4)$$

T.C. of resonant frequency

where Δf_O is the total frequency variation corresponding to the temperature shift ΔT, $\Delta\epsilon_t$ is the variation of the dielectric constant, ΔL the cavity expansion and ΔH, ΔD the resonator material linear expansions.

Trans-Tech Application Note





- τ_f is measured using the standard cavity defined by DR manufacture
- τ_f includes the effect of τ, τ_c , and α_L
- τ_f does not include the dielectric constant change of the different material with different τ_f
- τ_f and τ_c of DR are not the same as applications

KYOCERA DR Characteristics and Applications

Material		SM200	SY210C	SB350	SL390	SG390	SV430	SP450	SH790	SH880
Dielectric Constant		20	21	35	39	39	45	45	79	88
Qf		48,000	170,000	45,000	65,000	80,000	44,000	30,000	3,900	6,000
Q (measured frequency)		8,000 (6GHz)	34,000 (5GHz)	11,250 (4GHz)	17,100 (3.8GHz)	21,000 (3.8GHz)	12,500 (3.5GHz)	8,500 (3.5GHz)	1,500 (2.6GHz)	2,300 (2.6GHz)
Temp. Coeff. of Freq. [ppm / deg.C]		-25 +/- 30	-4…+4	0…+8	-3…+8	-3…+8	-7…+8	-7…+8	-35 +/- 30	+5 +/- 6
Density [g / cm^3]		3.7	7.0	4.8	5.6	5.6	4.8	4.8	5.7	5.7
Color		Light Yellow	Brown	Ivory	Dark Brown	Brown	Purple	Dark Brown	Dark Brown	Dark Brown
Application	TE Mode Resonator 800MHz			X			X			
	TE Mode Resonator 1900MHz		X	X	X	X	X	X		
	TE Mode Resonator 5-14GHz			X	X	X	X	X		
	TEM Mode Resonator			X			X			X
	Substrate	X		X			X		X	X
	Antenna	X		X			X			

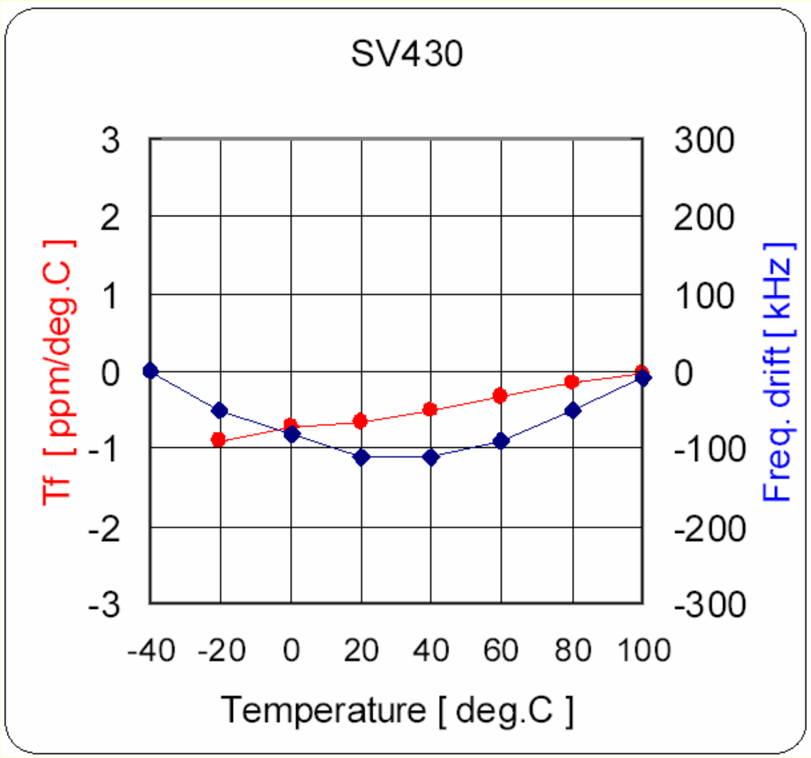
For Base Transfer Station

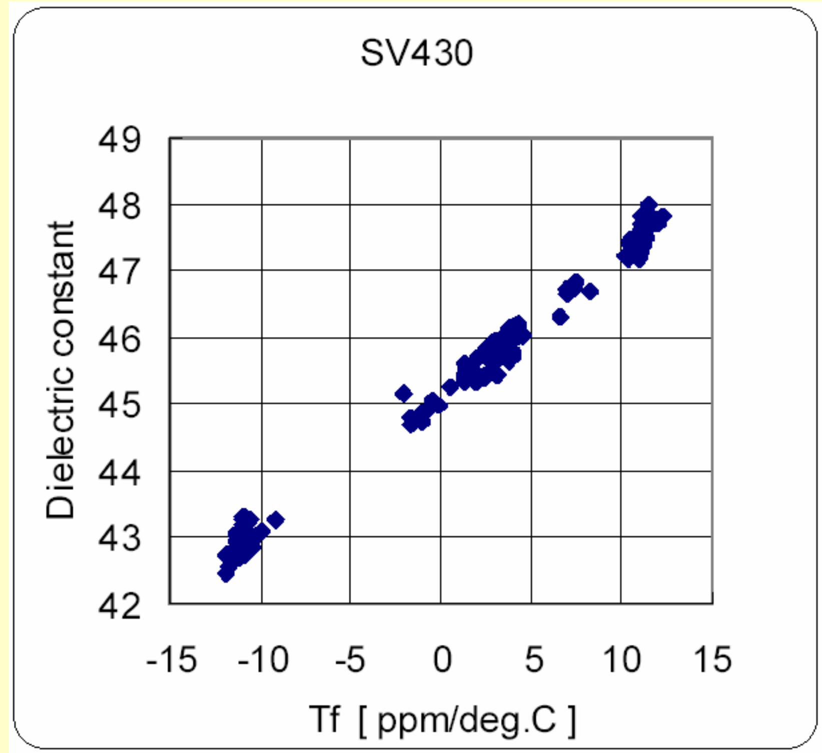
For Satellite Broadcasting

For Car Navigation GPS

Courtesy of KYOCERA

KYOCERA SV430 DR Measured Data





[Measurement]
Tf value and Freq. Drift

- Cavity ; Dia50mm x 30mmT , Cu
- Sample size ; Dia16.5mm x 8.5mmT TP
- Temp. range ; -40…T deg.C (Tf value)
  -40… 100 deg.C (Freq. Drift)

Er and Qf

- Method ; Rod resonance method
- Sample size ; Dia16.5mm x 8.5mmT TP

Courtesy of KYOCERA

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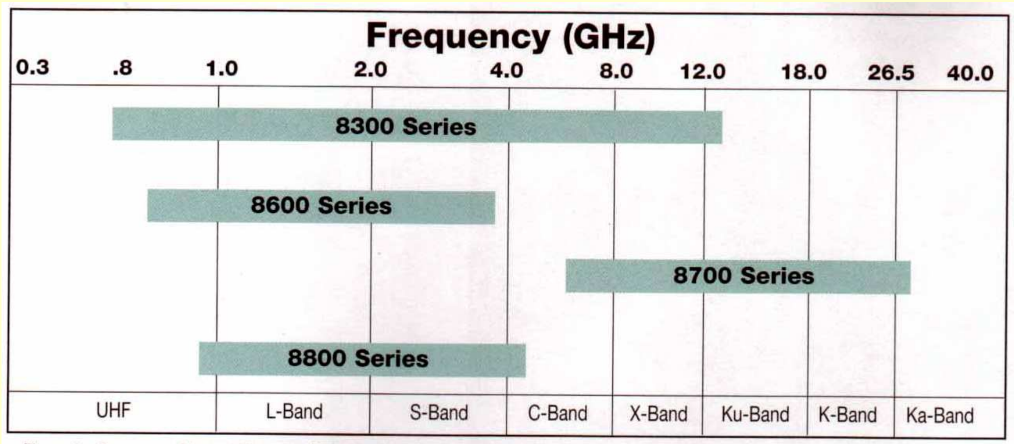
Trans-Tech DR Characteristics

Material Characteristics Summary



Product Characteristics		Series			
		8300	8600	8700	8800
Dielectric Constant		35.0 - 36.5	80.0	27.6-30.6	36.6-38.3
Q (1/tanδ)		>28,000 at 850	3,000 at 3.0 GHz	10,000 at 10.0 GHz	>6,000 at 4.5 GHz
Available Frequency (MHz)	Disc Type	800-13800	700-3618	5550-32150	790-5210
	Cylinder Type	800-9010	967-3618	5550-9870	1390-5210
	Available τ_f (ppm/°C)	9/6/3/0/-3	9/6/3	4/2/0	4
Available τ_f Tolerance (ppm/°C)		$\pm$2 or $\pm$ 1	$\pm$2.0/1.0	$\pm$2.0/1.0	$\pm$2.0/1.0
Composition		Barium Titanate	BaLnTi Oxide	BaZnTaTi Oxide	BaTitanium Oxide

8300 Series Data

Material Characteristics

Dielectric Constant	35.0-36.5
Temperature Coefficient of Resonant Frequency (τf) (ppm/°C)	-3 to +9
Q (1/tan δ) min	9,500 at 4.3GHz and 28,000 at 850 MHz
Insulation Resistance (ohm cm) (volume resistivity) @ 25°C	~10^{13}
Thermal Expansion (ppm/°C) (20-°C)	~10
Thermal Conductivity (cal/cm sec°C) @ 25°C	0.0045
Specific Heat (cal/g °C)	0.15
Density (g/cc)	>4.65
Water Absorption	<0.01
Composition	Barium Titanate
Color	Rust

Temperature Characteristics

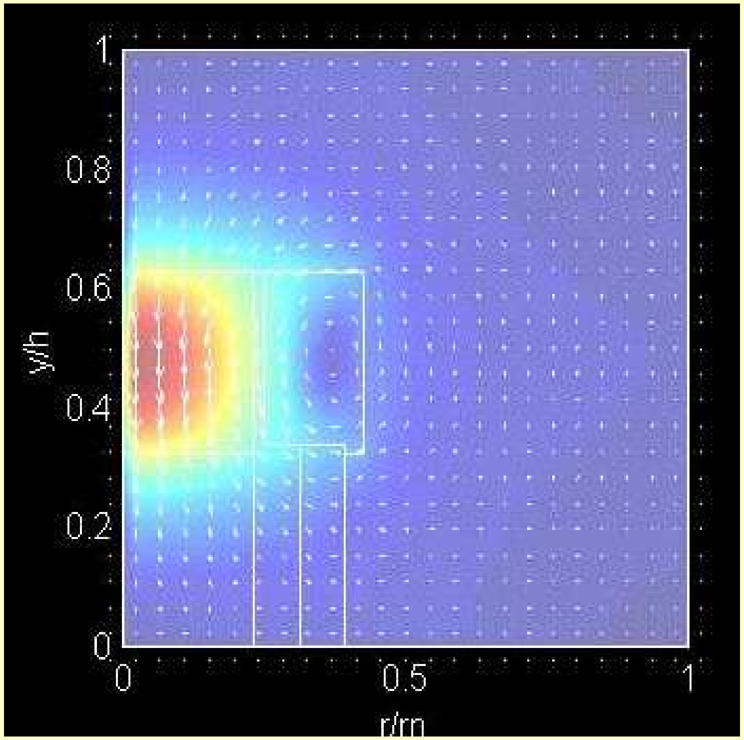
Series	Type	Dielectric Constant	Temperature Coefficient of f_o (τ_f)	Q at 4.5 GHZ
D/C83	74	36.5 $\pm$ 1	+9 ppm/°C	>9,500
D/C83	73	36.0 $\pm$ 1	+6 ppm/°C	>9,500
D/C83	72	35.7 $\pm$ 1	+3 ppm/°C	>9,500
D/C83	71	35.5 $\pm$ 1	+0 ppm/°C	>9,500
D/C83	70	35.0 $\pm$ 1	-3 ppm/°C	>9,500

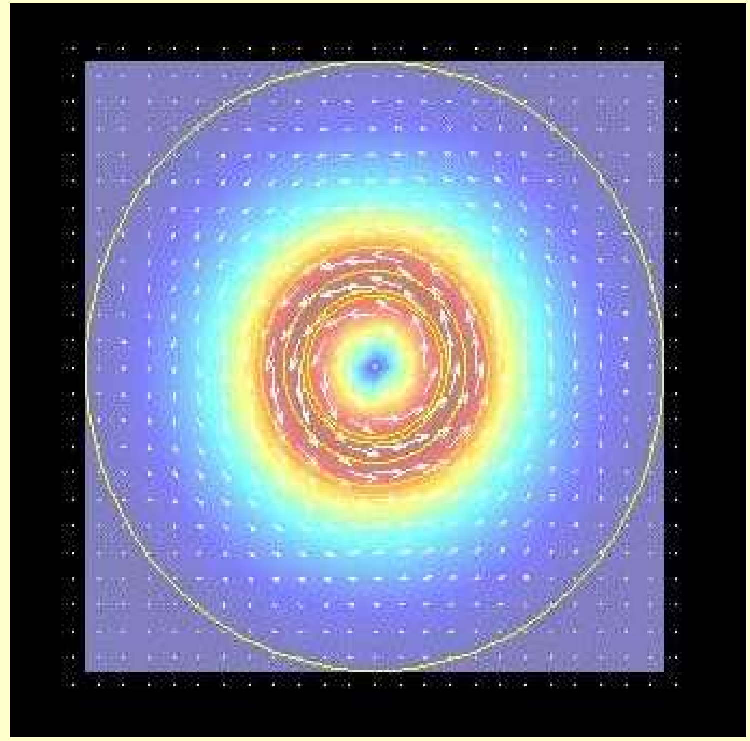
Trans-Tech Application Note

Temp. Compensation Procedure for Ceramic Resonators and Filters

- Temperature Characteristics of DR and Filter are Mainly Determined by Structure and Ceramics
  - Standard Test Cavity's Temp Characteristics are also included in the material τ_f
- Use Known DR Structure and Characteristics of Materials
  - Dielectric Constant ε_r, Temp Constant of Frequency τ_f, et al
  - Start from τ_f=0 or τ_f with Experience, Thus as τ_f=2
- Fix Cavity Size and Material
- Measure the Temp Drift of the Final Prototype
- Working with DR Supplier to Adjust τ_f and DR Dimension
- Final Temp Test to Verify Design

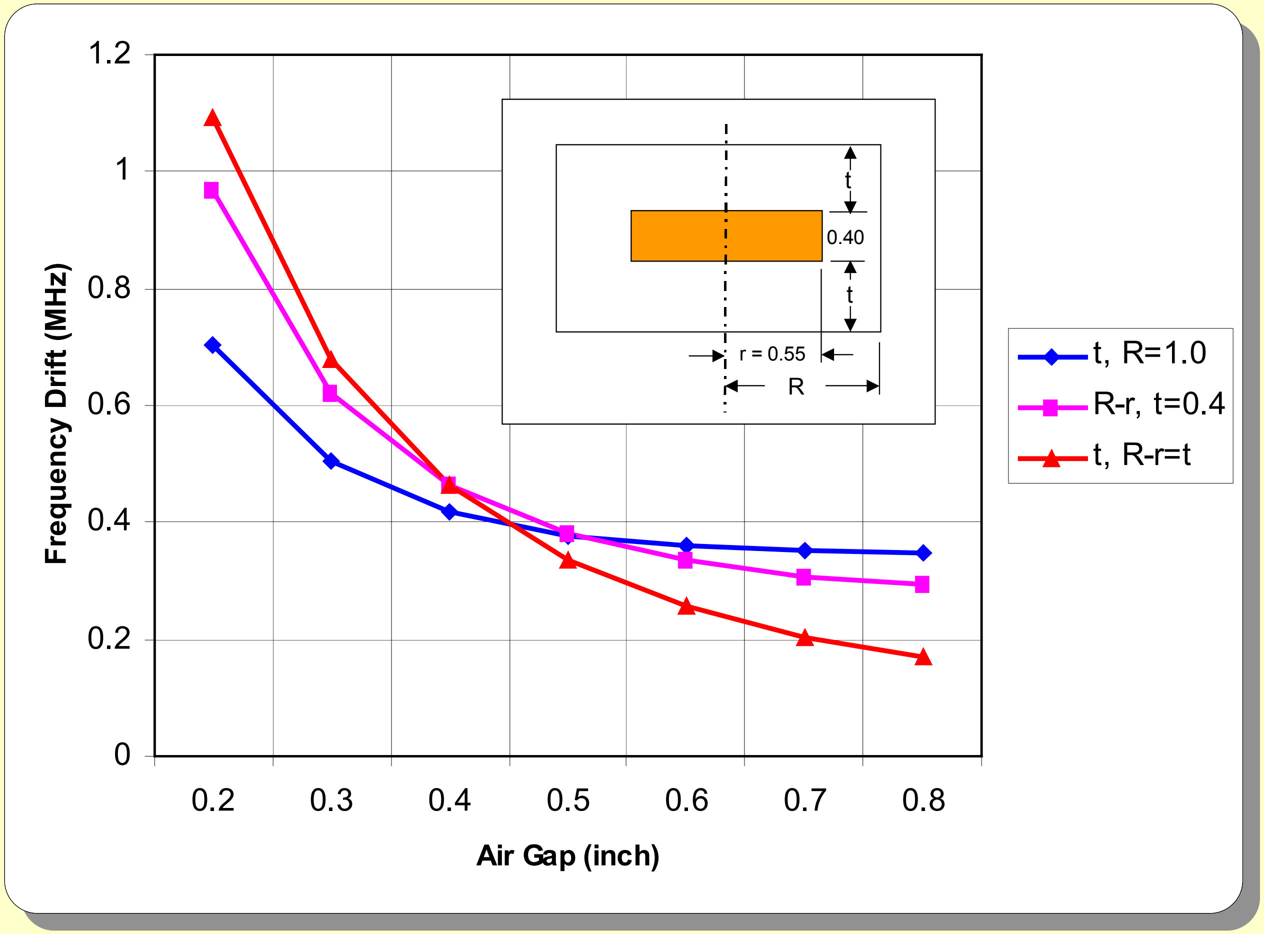
Fields Mostly Confined within Dielectrics





TYPICAL FIELD DISTRIBUTIONS OF A DIELECTRIC LOADED RESONATOR OPERATING AT TE_{01} MODE

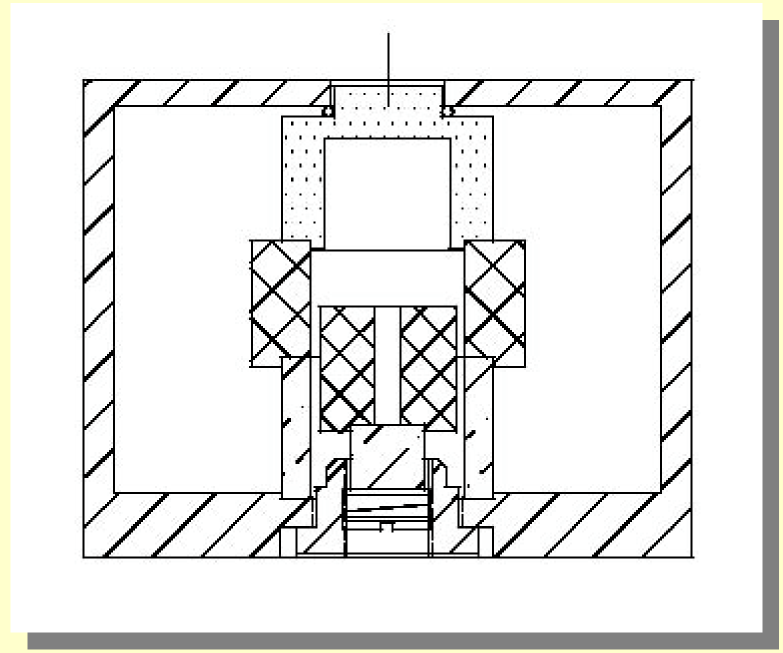
Effect of Cavity Size over Frequency Drift

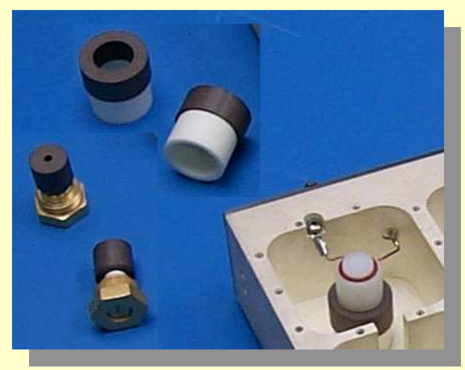


ε_r = 36 Material, AL Housing
Resonant Frequency ~ 2.1 GHz
50 C Temperature Change

Example: Tunable Dielectric Loaded Resonator

- Wide Tuning Rang > 5%
- Wide Operating Temp Range
- Self Locking
- All Critical Components Referenced at Lower Plane over Temp
- Similar CTE for DR and Support
- Same Length and Material for Tuner and DR support
- Low Loss and High Performance Adhesive over Temp

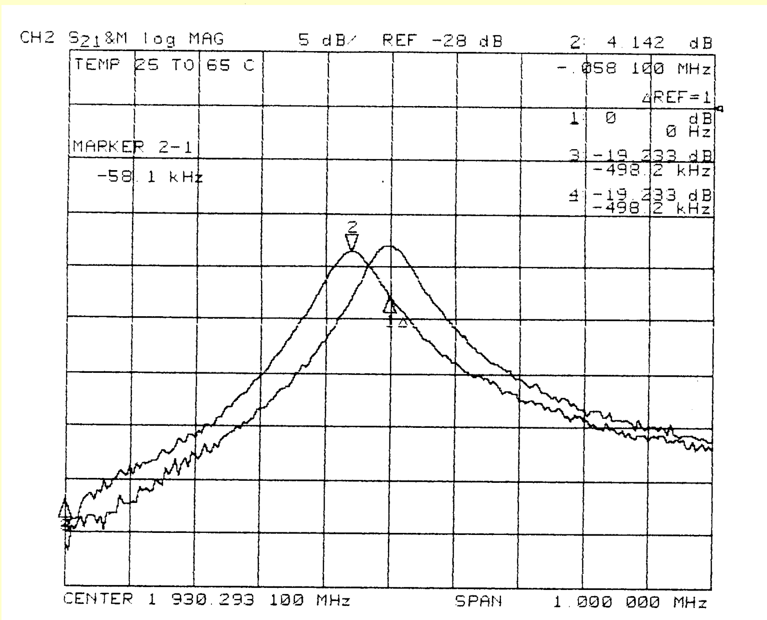


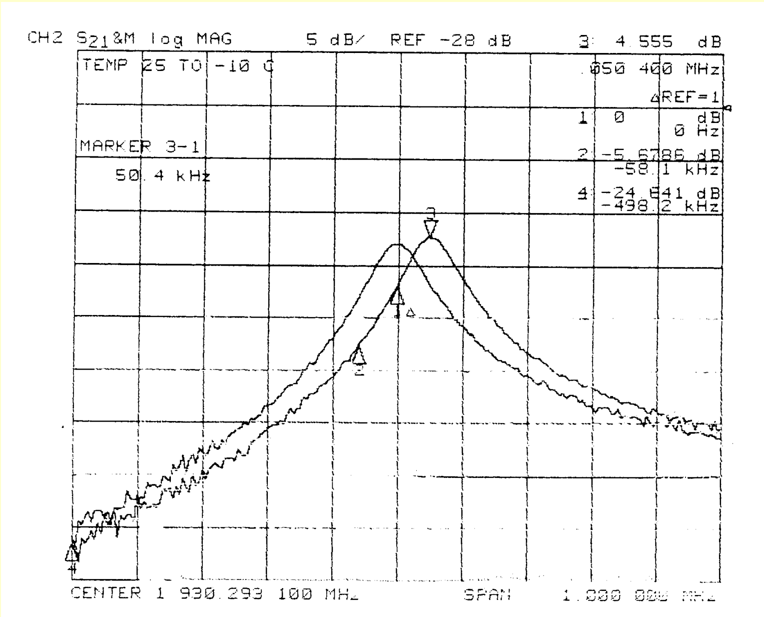


US Patent: 6,600,394

Measured Frequency Drift

- PCS Band: 1930 to 1990 MHz
- Operating Temperature Range: -10 ~ 65 C
- Frequency Drift < 60 KHz Total, or 1 ppm/C





Summary

- Material Properties Play Important Roles in Resonator's Temperature Characteristics and Compensations
- Comb-line and Dielectric Resonators and Filters can be Cost Effectively Temp Compensated by Properly Using the Material Properties
- Exact Material Characteristics Used in the Resonators and Filters Need to be Known in the Design, Build and Test
- Similar Design Principles also Apply to Other Types of Resonators and Filters
- Low Cost Material and Simple Structure are Preferred in the Filter Design