RESONANT FREQUENCY STABILITY ANALYSIS OF DIELECTRIC RESONATORS WITH TUNING MECHANISMS

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ABSTRACT

The Finite Element Method is applied to calculate the resonant frequency stability and the quality factor of dielectric resonators with tuning mechanisms. The resonant frequency temperature dependence is studied as a function of the tuning. Results for cylindrical and ring resonators tuned with metal and dielectric screws are included.

INTRODUCTION

The recent availability of dielectric materials with a very linear temperature coefficient (1) allows the construction of high temperature stability filters and oscillators. The design of dielectric resonators with high temperature stability requires rigorous theoretical methods to calculate the effect of material expansions and permittivity variations on the resonant frequency.

T.Higashi et al. (2) proposed an approximated method to calculate the frequency variation of a cylindrical dielectric resonator on microstrip substrate. More recently Y.Kobayashi et al. (3),(4) reported results using a mode matching method to analyze the resonant frequency stability and the quality factors of dielectric resonators inside metal cavities. However, no theoretical studies using rigorous methods have been reported to analyze the thermal stability and the quality factors of dielectric resonators including the effects of the microstrip substrate, the spacers, and the tuning mechanisms.

In this paper a method, based on the Finite Element Method, is presented to analyze the temperature frequency stability of dielectric resonators with complex geometry. The main factors that affect the stability of cylindrical and ring resonators tuned with finite width metal and dielectric screws are studied.

The conditions required to obtain a stable temperature coefficient over a wide mechanical tuning margin are studied. An example of using the results of the analysis to optimize the temperature stability of a Ka band resonator is presented.

ANALYSIS METHOD

In many applications dielectric resonators are mounted on microstrip substrates. The shape of the resonator is generally a cylinder or a ring. A tuning mechanism, usually formed by a metal or dielectric screw, is located over the resonator. It is also used a dielectric spacer to hold the resonator. Fig.1 shows several configurations.

The thermal variations of the structure resonant frequency are due to the expansions of the structure dimensions and permittivity variations of the dielectric materials. If a linear increment of all structure dimensions (L_i) and material permittivities (ε_i) is assumed, the temperature effect can be expressed as

$$\Delta L_i = L_i \cdot \alpha_{Li} \cdot \Delta T \qquad (1)$$
$$\Delta \varepsilon_i = \varepsilon_i \cdot \tau_{\varepsilon i} \cdot \Delta T \qquad (2)$$

α_{Li} : L_i expansion coefficient
$\tau_{\varepsilon i}$: ε_i temperature coefficient

The effect of these variations on the resonant frequency of the TE modes of axisymmetric resonators can be calculated solving the following eigenvalue equation.

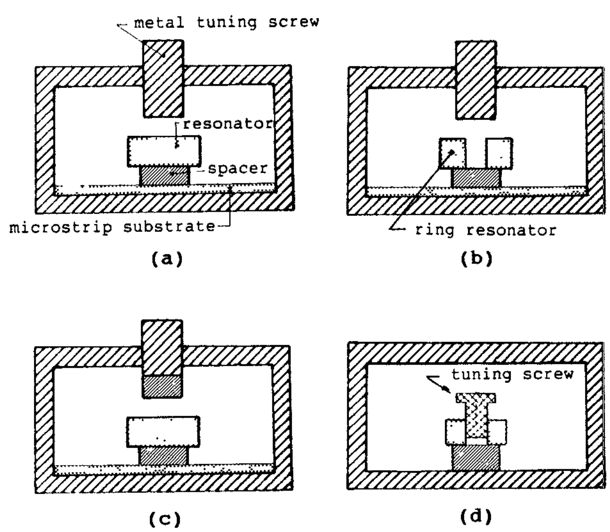

Fig.1 Configurations of the analyzed dielectric resonators. (a) Cilindrical with spacer and metal tuning screw. (b) Ring resonator. (c) Cilindrical with dielectric screw. (d) Ring resonator with tuning screw inside.

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COMPARISON BETWEEN THE RESULTS OBTAINED USING THIS METHOD AND THOSE OBTAINED USING MODAL EXPANSION TECHNIQUES AND MEASUREMENTS (3),(4) FOR CYLINDRICAL DIELECTRIC RESONATOR.

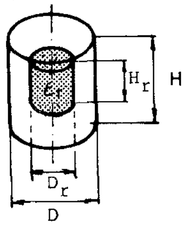
TABLE I. TEMPERATURE COEFFICIENTS COMPARISON

Resonator	Temperature coefficients								
	Modal expansion				This method				Experimental
	C_r	C_a	C_c	τ_f	C_r	C_a	C_c	τ_f	τ_f ppm/°C
(1)	0.450	0.948	0.056	4	0.4502	0.9445	0.0554	3.97	3.3
(2)	0.486	0.880	0.119	0.4	0.4861	0.8804	0.1194	0.36	0.2
(3)	-	-	-	0.1	0.4857	0.8646	0.1353	0.095	-
(4)	-	-	-	3.9	0.4854	0.8644	0.1355	3.94	-

TABLE II. QUALITY FACTORS COMPARISON

Resonator	Quality Factors						
	Modal expansion			This method			Experimental
	Q_c	Q_d ($\times10^4$)	Q_u	Q_c	Q_d ($\times10^4$)	Q_u	Q_u ($\times10^4$)
(1)	30.2	2.64	2.43	30.20	2.64	2.43	2.3
(2)	7.57	2.86	2.08	7.58	2.86	2.08	2.1
(3)	5.67	2.78	1.87	5.65	2.78	1.86	-
(4)	5.14	2.71	1.77	5.15	2.71	1.77	-

RESONATOR DATA:



C_{er}: resonator permittivity temperature coefficient
C_a : resonator size temperature coefficient
C_c : metal cavity size temperature coefficient
Q_c : Metal wall losses quality factor
Q_d : Dielectric losses quality factor
Q_u : Unloaded quality factor

Resonator 1
ε_r = 24 H_r = 2.19mm D_r = 5.5mm D = 22mm, D/H = 1.15 tgδ = 4.2E-5
σ_{cavity}= 5.22E7 α_{cavity} = 20.12 ppm/°C, $\tau_{\varepsilon r}$ = -26 ppm/°C, α_r = 7 ppm/°C
Resonator 2
ε_r = 27 H_r = 4.29mm D_r = 10.05mm D = 22.11mm, H=12.73 tgδ = 3.6E-5
σ_{cavity}=5.22E7 α_{cavity}=20.12 ppm/°C, $\tau_{\varepsilon r}$=-23.8 ppm/°C, α_r=10 ppm/°C
Resonator 3
ε_r = 24.4 H_r = 3.12mm D_r = 7.32mm D = 15.37mm, H=8.86 tgδ = 3.7E-5
σ_{cavity}=5.22E7 α_{cavity}=20.12 ppm/°C, $\tau_{\varepsilon r}$=-23.6 ppm/°C, α_r=10 ppm/°C
Resonator 4
ε_r = 24 H_r = 2.58mm D_r = 6.06mm D = 12.73mm, H=7.34 tgδ = 3.8E-5
σ_{cavity}=5.22E7 α_{cavity}=20.12 ppm/°C, $\tau_{\varepsilon r}$=-26.2 ppm/°C, α_r=10 ppm/°C

$$\frac{\partial^2 E_\varnothing}{\partial z^2} + \frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial (rE_\varnothing)}{\partial r}\right] + (w/c)^2 \varepsilon_r E_\varnothing = 0 \qquad (3)$$

The Finite Element Method (6), has been used to calculate the effect of the temperature variation on the resonant frequency. This method allows the study of complex structures with good precision and a moderate CPU time.

The knowledge of the contribution of each geometrical parameter and permittivity variation to the total frecuency temperature coefficient is interesting to improve the stability. The total temperature coefficient of the structure can be expressed as

$$\tau_f = \sum_{i=1}^{NL} C_{Li} \cdot \alpha_{Li} + \sum_{i=1}^{NM} C_{\varepsilon i} \cdot \tau_{\varepsilon i} \qquad (4)$$

NL : Number of structure dimensions
NM : Number of dielectric materials
C_{Li} : Frequency variation coefficient of L_i
$C_{\varepsilon i}$: Frequency variation coefficient of material ε_i

The quality factor of the resonator, important to stabilize oscillators, is calculated using the field distribution of the mode obtained from the finite element analysis. The programation of this procedure is more complex than the incremental method (7) but requires less CPU time and allows the study of complex structures.

A computer program has been implemented to calculate the resonant frequencies, the thermal coefficients and the quality factor. The flexibility of the Finite Element Method allows the study of new structures entering their geometrical and thermal description as input data.

RESULTS

The results obtained with this method have been compared with those obtained by Y.Kobayashi et al. (3)-(4) using a modal expansion method, for a cylindrical resonator inside a metal cavity. Table I shows a comparison between the results calculated using this method for the temperature coefficients and those obtained by these authors using theoretical method and measurements. As it can be seen, the differences of temperature coefficients are smaller than 0.1 percent. Table II shows a comparison for the quality factors (losses in dielectrics and metals are considered separately). As it can be seen good agreement is also observed.

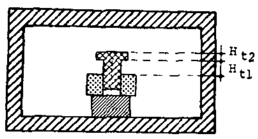
TABLE III. RING RESONATOR

Resonant frequency: 12.640 GHz

Metal losses quality factor : 4630

Dielectric losses quality factor: 7740

Temperat. variation: 2.55 ppm/°C
(See next table)



Parameter variable	Parameter value	variation ppm/°C	temperature coefficient	variation ppm/°C
dr	2.000	10.000	0.17333	1.733
D_e	3.000	10.000	0.07341	0.734
D_t	4.000	0.700	-0.00363	-0.003
D_r	5.500	10.000	-0.80546	-8.055
D	11.000	20.120	-0.06482	-1.304
H_e	1.000	0.700	-0.05732	-0.040
H_r	2.440	10.000	-0.31036	-3.104
H_{t1}	0.200	20.120	-0.00624	-0.126
H_{t2}	0.500	20.120	0.00158	0.032
H	8.940	20.120	-0.00040	-0.008
ε_r	30.0	-26.0	0.48816	12.692
ε_e	3.700	0.000	-0.00177	0.000

Total variation : 2.55 ppm/°C

Table III shows an example of the results for a ring resonator with metal screw inside the hole. It can be seen the effect of each part of the structure on the stability.

The optimization of the thermal behavior of a dielectric resonator requires to know the contribution of each part of the structure to the total thermal coefficient. This can be used to select the proper temperature coefficient of each material and to reduce the effect of materials with no linear expansion on the total thermal coefficient. One important problem to apply dielectric resonators in microwave circuits is the great dependence of the thermal coefficient of the mechanical tuning. In this paper the attention is focused mainly on this problem. The temperature coefficient, the tuning and the quality factors for several structures have been studied.

Fig.2a shows the frequency tuning and the coefficients to calculate the quality factor (Q_u) and the total temperature coefficients as a function of the location of the tuning screw for a cylindrical dielectric reonator. The temperature coefficients can be introduced in (4) to calculate the total temperature coefficient (τ_f). The quality factor of this resonator can be calculate using Fig.2a and the following formula

$$Q_u = \left[\sum_{i=1}^{NM} A_i \, tg\delta_i + \sum_{i=1}^{NS} B_i \sqrt{\sigma_{Cu}/\sigma_i} \right]^{-1} \qquad (5)$$

σ_{Cu} : Copper conductivity

As it can be seen most of the temperature coefficients are affected by the mechanical tuning.

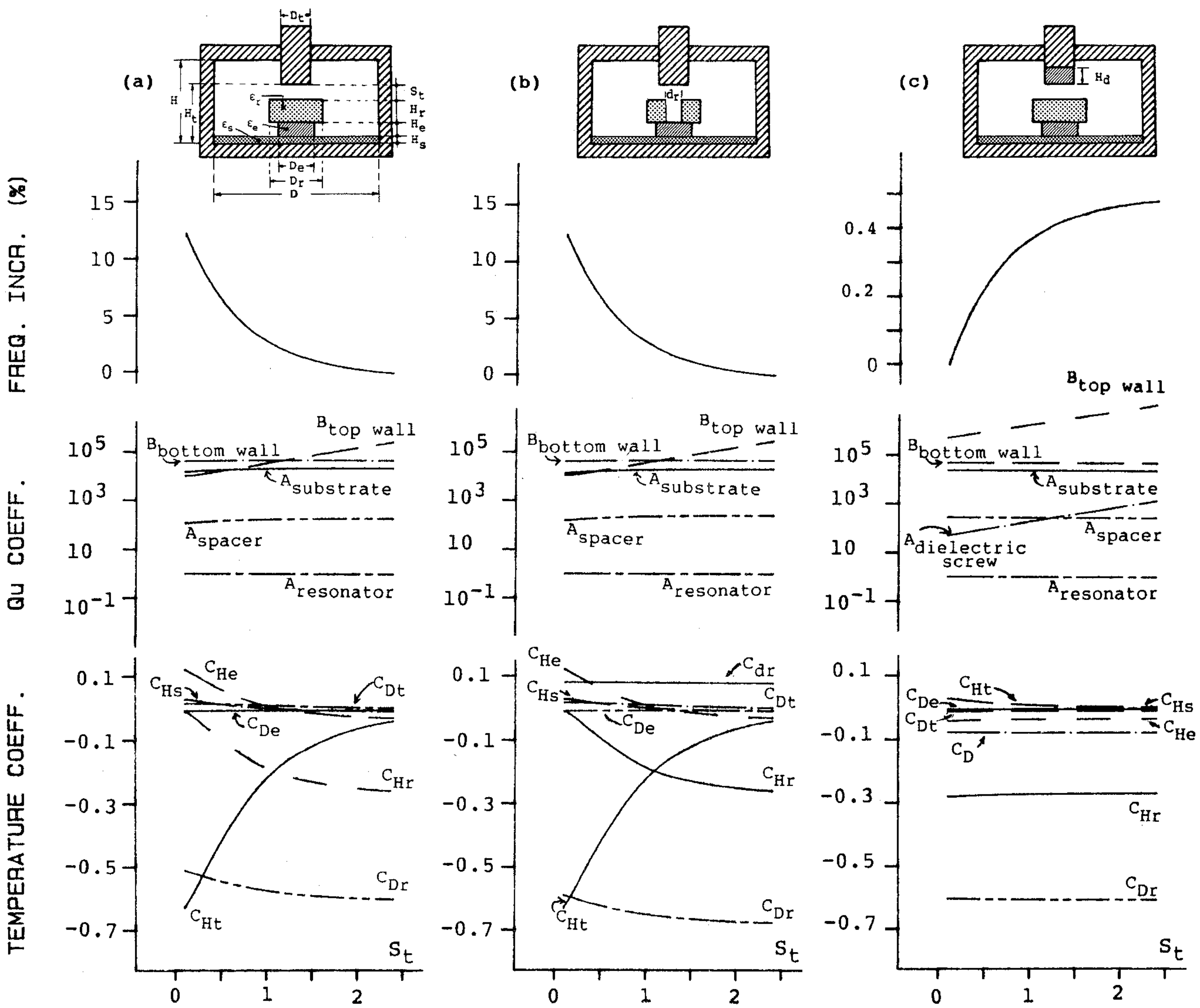


Fig.2 Geometrical temperature coefficient, quality factor coefficients and tuning as function of the tuning screw location. (a) Cylindrical resonator with metal screw. (b) Ring resonator with metal screw. (c) Cylindrical resonator with dielectric screw. H_s = 0.254 mm, H_e = 1 mm, H_r = 2.44 mm, H = 7.694 mm, d_r = 2 mm, D_e = 4 mm, D_r = 5.5 mm, D_t = 6.5 mm, D = 11 mm ε_r = 30, ε_e = 3.7, ε_s = 2.2, H_d = 3 mm

The coefficient with the greatest variation is that relate with the metal screw location (C_{Ht}).

The main variation of the quality factor as the tuning is varied is due to coefficients relate with the dissipated power in the upper wall. The down wall coefficient depends on the height of the spacer and the substrate but are invariant with the tuning.

Similar curves have been obtained for a ring resonator with metal screw (fig.2b) and for a cylindrical resonator with dielectric tuning screw (fig.2c). As it can be seen the curves for the ring resonator are similar to those of the cylindrical resonator with metal screw. Dielectric screws provide a very small tuning margin. However, the

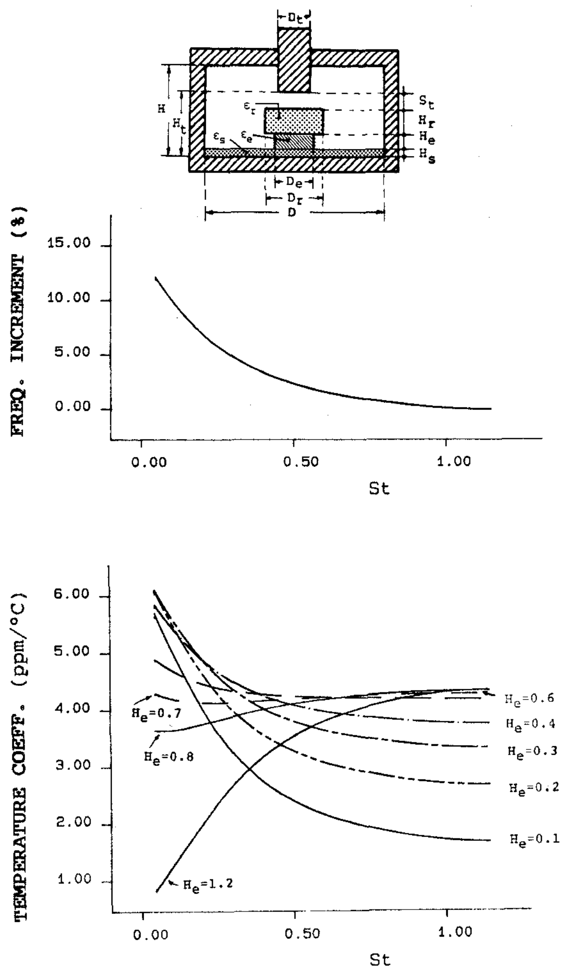


Fig.3 Total temperature coefficient of a dielectric resonator as function of the distance between the resonator and the tuning screw. Curves for several spacer heights are shown. H_s = 0.254 mm, H_r=1 mm, D=5 mm, D_r=2.2 mm, D_e=2.2 mm, ε_s= 2.2, ε_e=3.7, ε_r=30.1, α_{cavity}=20.12 ppm/°C, $\alpha_{\varepsilon r}$=10.1, $\alpha_{\varepsilon e}$=0.41, $\tau_{\varepsilon r}$ = -32.4.

thermal coefficients have small variation as tuning is varied.

The slopes of some of the temperature coefficients are opposed (fig.2a,2b) and if the structure dimensions and material are carefully selected certain degree of compensation between them can be obtained.

Fig.3 shows an example of calculation of the temperature dependence and the tuning for a Ka band dielectric resonator as a function of the distance between the resonator and the tuning screw. Curves for several heights of the quartz spacer are shown. As it can be seen there is an optimum height that minimizes the variation of the temperature coefficient over a wide mechanical tuning margin. This result is interesting to design oscillators with high temperature stability and a wide mechanical tuning margin.

CONCLUSION

A theoretical procedure based on the Finite Element Method to study the resonant frequency, thermal behavior and the quality factor of dielectric resonators has been developed.

The great flexibility of this method makes it interesting to study resonators with complex geometry. This allows the introduction of elements to improve the temperature dependence and the quality factor.

The quartz spacer can be used to reduce the sensibility of the temperature coefficient to the mechanical tuning point.

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