Design Charts for Shielded Dielectric Rod and Ring Resonators

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ABSTRACT

Some useful charts are presented to design precisely dielectric rod and ring resonators placed symmetrically in conductor cavities. When a resonant frequency of the $TE_{01\delta}$ mode and necessary material constants are given, the optimum dimensions for offering the best separation from other resonances, the frequency-temperature coefficient, and the unloaded Q can be determined from these charts.

INTRODUCTION

For dielectric rod resonators placed in conductor shields, the lowest order mode $TE_{01\delta}$ is used commonly because it has the highest Q value in all resonant modes. But, other resonances exist rather closely to this mode and cause the poor spurious responses in dielectric resonator filters [1], [2]. This drawback is fairly improved by using a dielectric ring instead of a rod [3]. The oputimum design of these resonators is performed to offer the best separation from other resonances in the case of the relative permittivity ε_r of 37.5 [4]. In addition, various types of temperature-stable, low loss ceramics having ε_r=20 to 100 are developed as rasonator materials. A signficant feature of these ceramics is that the loss tangent tan δ increases with increasing ε_r as well as the frequency; so the lower ε_r is suitable for the realization of the proper size and high-Q at the millimeter wave, while the higher ε_r suits at the lower microwave frequency. In the design of these resonators, therefore, it is essential to know the behavior of the resonant modes in the broad range of ε_r.

This paper investigates the resonant properties of dielectric rod and ring resonators placed symmetrically in conductor cavities. The rigorous analysis can be made by the mode matching technique [4]-[6]. Since the computation is tedious, however, the computed results are given as functions of ε_r in some design charts. Giving a resonant frequency of the $TE_{01\delta}$ mode and necessary material constants, we can determine the optimum dimensions for offering the best separation from other resonances, the frequency-temperature coefficient, and the unloaded Q from these charts. The resonant properties of some high-Q dielectric resonators are discussed.

ANALYSIS

A shielded dielectric ring resonator analyzed is shown in Fig. 1. A dielectric ring having relative permittivity ε_r, diameter D, inner diameter D_x, and length L is placed symmetrically in a cylindrical conductor cavity having diameter d and height h. We put D_x=0 for rod shape. The rigorous analysis of any resonant mode can be performed by the mode matching technique [4]-[6]; that is, the resonant frequencies are computed from the condition that the following determinant vanishes:

$$\det H(f;\ \varepsilon_r,\ D,\ X,\ G,\ S,\ S_x)=0 \qquad (1)$$

where $X=(D/L)^2$, $G=M/D=(h-L)/2D$, $S=d/D$, and $S_x=D_x/D$. The matrix elements are omitted here.

The temperature coefficients of the resonant frequencies will be expressed as shown below. Let a small change of any quantity x be Δx. For any mode of the ring resonator, a small change of the resonant frequency Δf_0 is given by

$$\frac{\Delta f_0}{f_0}=A_r\frac{\Delta\varepsilon_r}{\varepsilon_r}+A_D\frac{\Delta D}{D}+A_x\frac{\Delta D_x}{D_x}+A_L\frac{\Delta L}{L}+A_d\frac{\Delta d}{d}+A_h\frac{\Delta h}{h} \qquad (2)$$

where

$$A_r=\frac{\varepsilon_r}{f_0}\frac{\partial f_0}{\partial\varepsilon_r} \quad A_D=\frac{D}{f_0}\frac{\partial f_0}{\partial D} \quad A_x=\frac{D_x}{f_0}\frac{\partial f_0}{\partial D_x}$$
$$A_L=\frac{L}{f_0}\frac{\partial f_0}{\partial L} \quad A_d=\frac{d}{f_0}\frac{\partial f_0}{\partial d} \quad A_h=\frac{h}{f_0}\frac{\partial f_0}{\partial h}. \qquad (3)$$

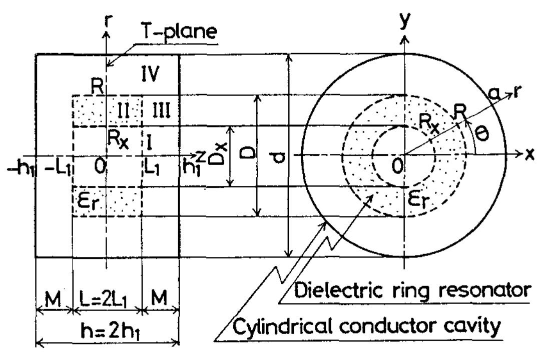

Fig. 1. Configuration of a dielectric ring resonator.

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An actual value of the constant A_r can be accurately computed from (1) by approximating $\partial f_0/\partial \varepsilon_r$ by $\Delta f_0/\Delta \varepsilon_r$; the other constants A_D, A_x (A_x=0 for the rod), A_L, A_d and A_h can be obtained similarly. Furthermore, if these small changes are caused by the temperature change ΔT °C of the structure, the following expression can be derived from (2):

$$\tau_f = A_r \tau_r + A_\alpha \tau_\alpha + A_c \tau_c \tag{4}$$

where

$$A_\alpha = A_D + A_x + A_L \qquad A_c = A_d + A_h$$

$$\tau_f = \frac{\Delta f_0}{f_0 \Delta T} \qquad \tau_r = \frac{\Delta \varepsilon_r}{\varepsilon_r \Delta T} \tag{5}$$

$$\tau_\alpha = \frac{\Delta D}{D\Delta T} = \frac{\Delta D_x}{D_x \Delta T} = \frac{\Delta L}{L \Delta T} \qquad \tau_c = \frac{\Delta d}{d\Delta T} = \frac{\Delta h}{h \Delta T}.$$

Also τ_f and τ_r are the temperature coefficients of f_0 and ε_r, and τ_α and τ_c are the coefficients of the thermal linear expansion of the dielectric and conductor, respectively.

The unloaded Q, Q_u of the $TE_{01\delta}$ mode can be derived by the perturbations of cavity walls and of cavity material [7]; that is,

$$Q_u = \left(\frac{1}{Q_d} + \frac{1}{Q_c}\right)^{-1}, \qquad Q_c = \left(\frac{1}{Q_{cy}} + \frac{1}{Q_{ce}}\right)^{-1} \tag{6}$$

where

$$Q_d = \frac{-1}{2A_r}\frac{1}{\tan\delta} \qquad Q_{cy} = \frac{-1}{2A_d}\frac{d}{\delta_s} \qquad Q_{ce} = \frac{-1}{2A_h}\frac{h}{\delta_s} \tag{7}$$

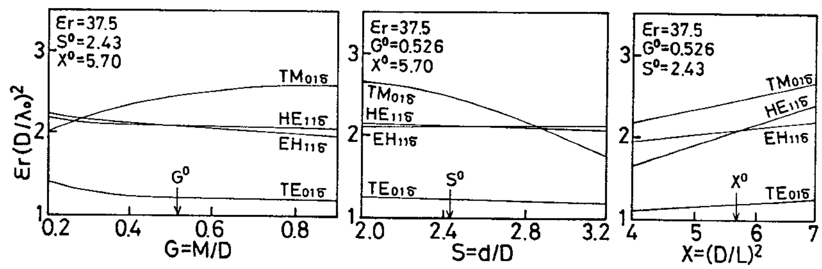
and

$$\delta_s = (\pi f_0 \mu \bar{\sigma} \sigma_0)^{-1/2}, \quad \bar{\sigma} = \sigma/\sigma_0, \quad \sigma_0 = 58\times10^6 \text{ [S/m]}. \tag{8}$$

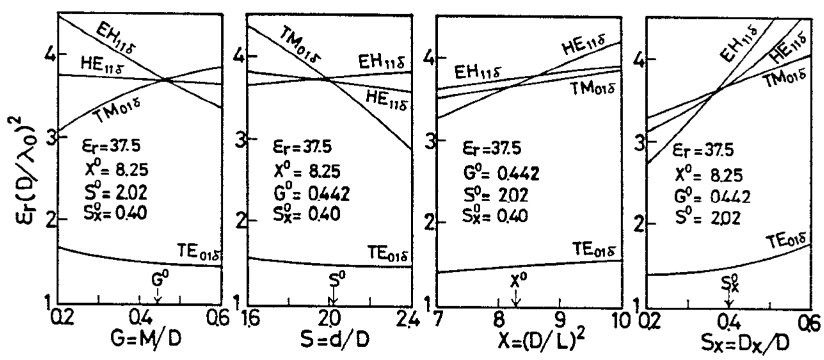
Also, Q_d and Q_c are ones due to the dielectric and conductor losses, and Q_{cy} and Q_{ce} are ones due to the conductor losses of the cylinder and end plates, respectively. $\tan\delta$ is the loss tangent of dielectric, δ_s is the skin depth of conductor, σ is the conductivity, $\bar{\sigma}$ is the relative conductivity, and σ_0 is the conductivity of the international standard annealed copper.

DESIGN CHARTS

Define the frequency ratio F_r by $F_r = f_r/f_0$, where f_0 and f_r are the resonant frequencies of the $TE_{01\delta}$ mode and of the next higher-order modes, respectively. When ε_r is given, the optimum dimension ratios X^o, G^o, S^o, and S_x^o (S_x^o=0 for the rod) can be determined from (1) to obtain the maximum value of F_r, F_{rmax} [4]. Fig. 2 shows mode charts of the $TE_{01\delta}$ rod and ring resonators around these optimum dimension ratios in the case of ε_r=37.5. The behavior of the higher-order modes can be specified from these charts. For convenience, the field plots of the principal modes for the rod resonator is shown in Fig. 3 [5].



(a) the rod resonator



(b) the ring resonator

Fig. 2. Mode charts of dielectric rod and ring resonators around the optimum dimension ratios in the case of ε_r=37.5.

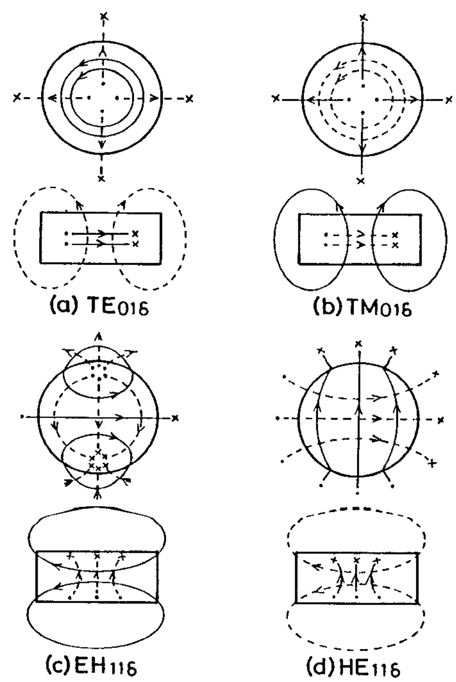


Fig. 3. Field plots of the principal modes for the rod resonator. (—— E, ----- H)

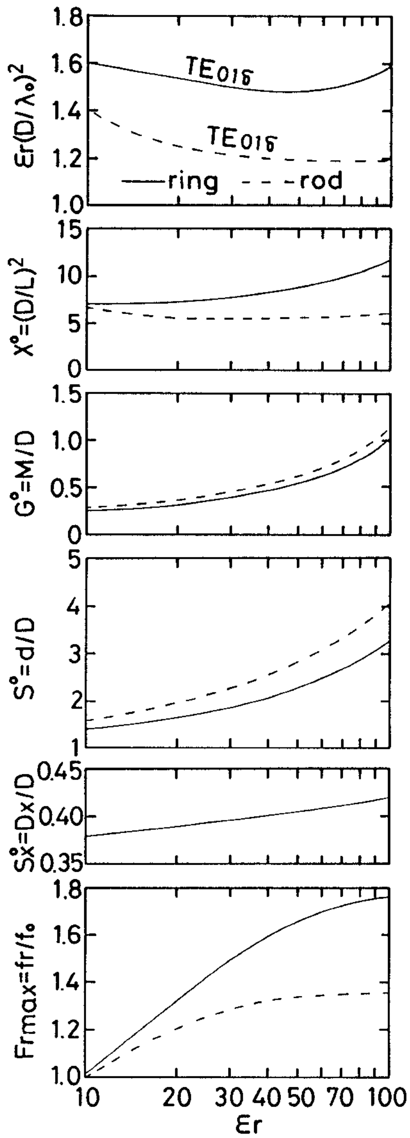


Fig. 4. Design charts to obtain the resonant frequency of $TE_{01\delta}$ mode, the optimum dimensions, and the F_{rmax} value.

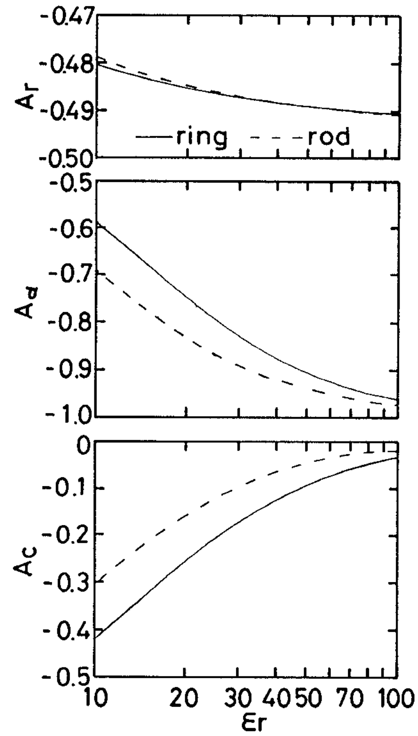


Fig. 5. Design charts to obtain τ_f at the optimun dimension ratios.

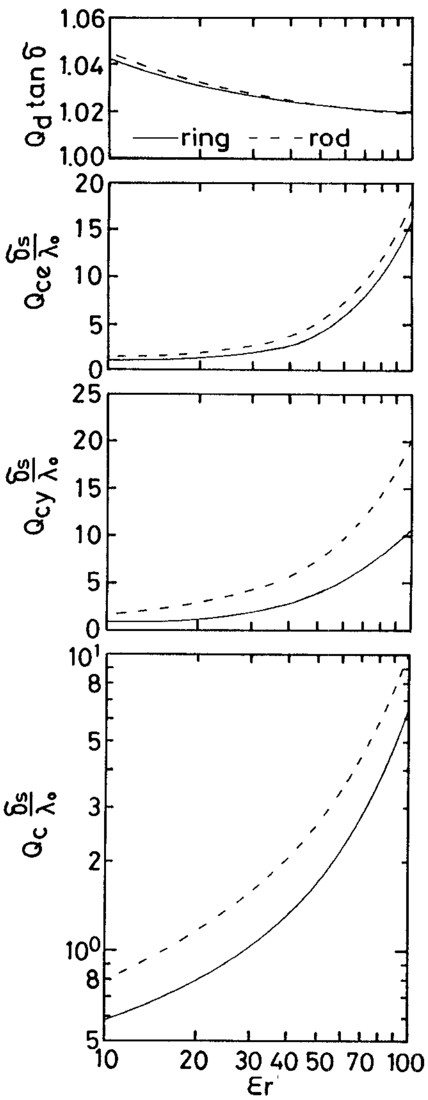


Fig. 6. Design charts to obtain Q_u at the optimum dimension ratios.

Fig. 4 shows design charts obtained from the optimum values computed in the cases of ε_r=10, 21, 37.5, and 100. Here, the solid and dashed lines indicate the cases of the ring and rod resonators, respectively. The difference between the F_{rmax} values for the rod and ring increases with ε_r; it is saturated near ε_r=100. On the other hand, as ε_r decreases to 10, the $TE_{01\delta}$ mode for the rod is no longer the lowest-order mode in any dimension; even for the ring, F_{rmax} is only 1.04.

To calculate τ_f, the constants given in (3) and (5) were computed at the optimum dimensions. These results are shown in Fig. 5. Furthermore, to calculate Q_u, the results computed using (7) are shown in Fig. 6.

DISCUSSIONS

The resonant properties are discussed for three $TE_{01\delta}$ rod resonators fabricated from copper-plated brass cavities ($\bar{\sigma}$=90%) and the following new low-loss BMT ceramics:

(1) $Ba(MgZrTaNb)O_3$ (Ube Industries, Ltd.)
(2) $Ba(SnMgTa)O_3$ (Murata Mfg. Co. Ltd.)
(3) $Ba_3MgTa_2O_9$ (Sumitomo Metal Mining Co. Ltd.)

The material constants ε_r, tan δ, and τ_r of these ceramics were measured by the dielectric rod resonator method [8]. Also, τ_c for the brass cavity was obtained from the measurement of temperature dependence on the resonant frequency of the TE_{011} mode. Then, giving ε_r and f_0, we get D, L, d, h, and F_{rmax} from Fig. 4; giving τ_r, τ_α, and τ_c, we get τ_f from Fig. 5; giving tan δ and σ, we get

Table 1. Calculated values for three $TE_{01\delta}$ dielectric rod resonators.

No.	No. 1	No. 2	No. 3
Ceramics	$Ba(MgZrTaNb)O_3$	$Ba(SnMgTa)O_3$	$Ba_3MgTa_2O_9$
ε_r	27.0	24.4	24.0
f_0 (GHz)	6.34	9.20	11.20
D (mm)	10.05	7.32	6.06
L (mm)	4.29	3.12	2.58
d (mm)	22.11	15.37	12.73
h (mm)	12.73	8.86	7.34
F_{rmax}	1.28	1.25	1.25
τ_r(ppm/°C)	-23.8±1.0	-23.6±1.4	-26.2±2.8
τ_α(ppm/°C)	10.0±0.5	10.0±0.5	7.0±1.0
τ_c(ppm/°C)	20.12	20.12	20.12
τ_f(ppm/°C)	0.4±0.7	0.1±0.8	3.9±1.6
$\tan\delta \times 10^5$	3.6±0.4	3.7±0.4	3.8±0.4
Q_d	28600	27800	27100
Q_c *	75700	56700	51400
Q_u	20800	18700	17700

* Calculated values for $\bar{\sigma}$=90 %

Q_u from Fig. 6. These calculated results are sammarized in Table 1.

Consider the No. 1 resonator to discuss the temperature stability of the resonant frequency. In this case, τ_f is given by

$$\tau_f = -0.486\tau_r - 0.880\tau_\alpha - 0.119\tau_c. \qquad (9)$$

In (9), the effect of τ_c on τ_f is only -2.4 ppm/°C even if τ_c=20 ppm/°C, because it is weakened due to the effect of energy concentration in the dielectric; while it is -20 ppm/°C for an empty cavity. Thus, temperature stable resonators are realized by offsetting the effects of both the temperature dependence of ε_r and the thermal expansion of dielectric and conductor; that is, τ_ε should be negative since τ_α and τ_c are positive.

Furthermore, it follows that $Q_u \simeq 1/\tan\delta$ when $\tan\delta > 10^{-4}$, because Q_c is much higher than Q_d; however, both Q_d and Q_c should be considered in the Q_u estimation when $\tan\delta < 10^{-4}$ [5].

The measured results for the No. 1 resonator were f_0=6.341 GHz, F_{rmax}=1.27, τ_f=0.2±0.2 ppm/°C, and Q_u=21000±2000. They agree well with the calculated values in Table 1. Thus, validity of these charts is confirmed.

At 48 GHZ, three resonators were constructed using the same Nos. 1, 2, and 3 ceramics as shown above. The resonator dimensions are D≃1.37 mm, L≃0.6 mm, d≃3.1 mm, and h≃1.7 mm. The measured Q_u values are 4100, 4300, and 4500, respectively. They are comparable to ones for conductor cavities. In addition to this, their temperature properties are much better than ones for the cavities. Thus, these ceramics also have great capabilities of being used in the millimeter wave circuits.

CONCLUSION

It was shown that some charts presented are available for designing precisely shielded dielectric rod and ring resonators. The resonant properties were discussed for $TE_{01\delta}$ dielectric rod resonators fabricated using new low-loss BMT ceramics at 6, 9, 12, and 48 GHz. From these results, it is concluded that these ceramics have capability of realizing compact, temperature-stable resonators having high unloaded Q values comparable to ones for conventional conductor cavities.

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