BANDPASS FILTERS USING TM_{010} DIELECTRIC ROD RESONATORS

Yoshio Kobayashi and Shinichiro Yoshida
Department of Electrical Engineering
Saitama University
Urawa, Saitama 338, Japan

ABSTRACT

New types of miniaturized bandpass filters have been constructed by using TM_{010} dominant mode of a shielded dielectric rod resonator. The next higher order mode exists at an octave frequency band above the TM_{010} mode. It is shown that no spurious response in the octave band, relative bandwidth of 6 % or more, and frequency stability of 10 ppm/°c or less can be realized for these filters. The insertion loss corresponding to the measured unloaded Q of 2800 at 6 GHz is expected.

Introduction

Recently dielectric resonators have been widely used to miniaturize microwave bandpass and bandrejection filters. For such resonators only $TE_{01\delta}$ mode has been considered.[1,2,3] The higher order modes exist at approximately $1.5f_o$, where f_o is the resonant frequency for the dominant mode. These modes have unwanted influences to the $TE_{01\delta}$ mode when the strong coupling is wanted. Therefore, so far as this mode is used, it is difficult to obtain the filter having the bandwidth wider than 3 % or the second passband frequency higher than $1.5f_o$.

New types of bandpass filters using TM_{010} mode of a shielded dielectric rod resonator are proposed in this paper. The characteristics of the TM_{010} resonator are described theoretically and experimentally. Two kinds of maximally-flat response bandpass filters were constructed at the frequency region of 6 GHz. No spurious response in an octave band, relative bandwidth of 6 %, and frequency stability of 10 ppm/°c were obtained. The insertion loss corresponding to the measured unloaded Q of 2800 at 6 GHz is expected.

Resonant Modes

A fundamental configuration of a shielded dielectric rod resonator is shown in Fig. 1(a). This resonator consists of a dielectric rod of relative permittivity ε_r, relative permeability $\mu_r = 1$, diameter D, and length L placed in the cylindrical metallic cavity of diameter d along the axis.

The mode chart for this resonator can be calculated numerically using the following equations.[4]

$$\left[\frac{1}{u}\frac{J_n'(u)}{J_n(u)}-\frac{1}{v}\frac{J_n'(v)\,N_n'(w)-N_n'(v)\,J_n'(w)}{J_n(v)\,N_n'(w)-N_n(v)\,J_n'(w)}\right]$$

$$\cdot\left[\frac{k_1^2}{u}\frac{J_n'(u)}{J_n(u)}-\frac{k_2^2}{v}\frac{J_n'(v)\,N_n(w)-N_n'(v)\,J_n(w)}{J_n(v)\,N_n(w)-N_n(v)\,J_n(w)}\right]$$

$$= n^2h^2\left(\frac{1}{u^2}-\frac{1}{v^2}\right)^2 , \qquad (1)$$

where

$$u=\frac{D}{2}\sqrt{k_1^2-h^2} , \quad v=\frac{D}{2}\sqrt{k_2^2-h^2} , \quad w=vS , \qquad (2)$$

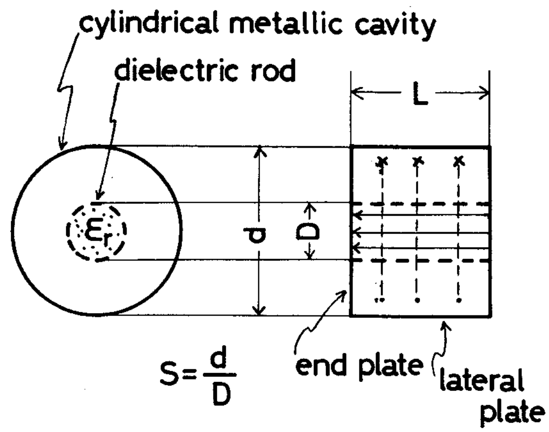
$$k_1=\frac{2\pi}{\lambda_0}\sqrt{\varepsilon_r}, \quad k_2=\frac{2\pi}{\lambda_0} , \quad h=\frac{\pi l}{L} , \quad l=0,1,2\ldots \qquad (3)$$

In above equations, $S=d/D$ is the diameter ratio, λ_0 is the resonant wavelength, and $J_n(x)$ and $N_n(x)$ are the Bessel functions of the first kind and the second kind respectively. The prime above a cylinder function denotes differentiation with respect to the argument x.

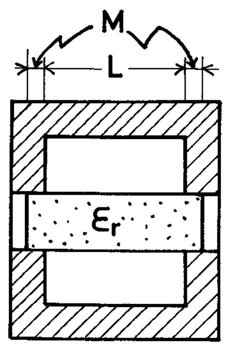
In the case of $n \neq 0$ and $l \neq 0$, the solutions of (1) are for the hybrid modes.

In the case of n=0 or l=0, (1) reduces to the two equations for TE_{0ml} and TM_{0ml} (n=0) modes, or TE_{nm0} and TM_{nm0} (l=0) modes,respectively. In addition, TE_{nm0} mode disappears because of the short-circuit boundary condition at each end of this resonator.

The mode chart is shown in Fig. 2 when ε_r=10 and 36, and S= 3.5. For HE_{111} mode, the following property is known: that is, if $\varepsilon_r > \varepsilon_p$, this mode haz Hz=0 at $R=(D/L)^2=0$, while if $\varepsilon_r < \varepsilon_p$, this mode has Ez=0 at R=0,



(a) Fundamental configuration and field lines for TM_{010} mode.
——— electric field line,
- - - - - magnetic field line.



(b) Temperature-stable configuration.

Fig. 1 Configuration of shielded dielectric rod resonators.

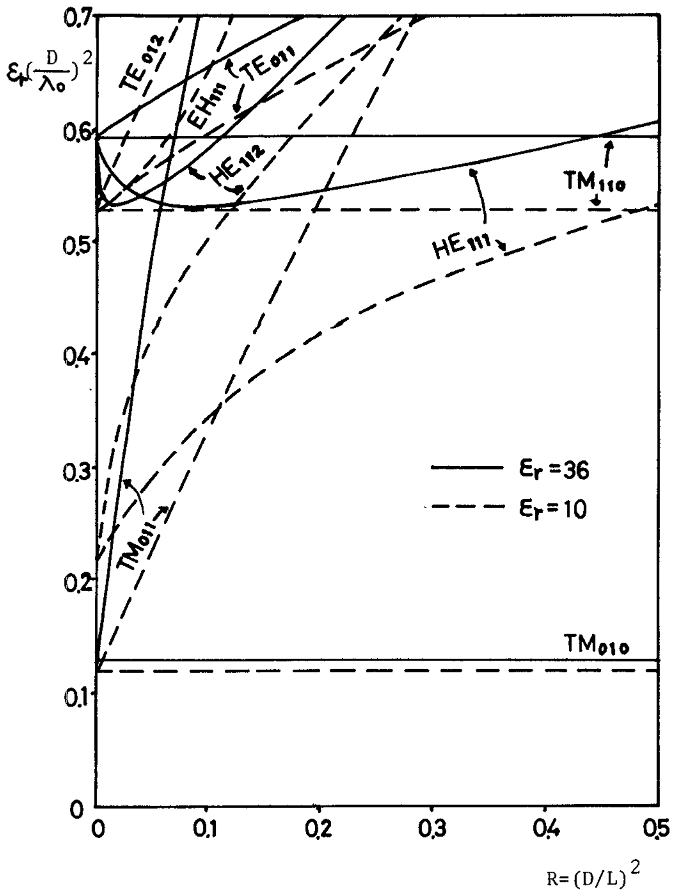


Fig. 2 A mode chart for a shielded dielectric rod resonator in the case of S=3.5.

where ε_r=25 in the case of S=3.5.(See Fig. 2 in the reference 4.) The first resonant mode is TM_{010}, whose field lines are indicated in Fig. 1(a). In the case of R>0.45, the next higher order mode TM_{110} exists at about $2.1f_0$. Therefore, TM_{010} mode can be utilized for fabricating the bandpass filter with no spurious response in an octave band.

Furthermore, since the unloaded quality factor Qu for the TM_{010} mode is higher with increasing L as given in (6) later, higher Qu is obtained by smaller R. In the case of R=0.065 for this example, the next higher order mode HE_{111} for ε_r=36 appears at $2.03f_0$, while for ε_r=10 the TM_{011} mode appears at $1.47f_0$. As a result, the TM_{010} resonator having the second resonant frequency of $2f_0$ and high value of Qu could be achieved by using high-ε_r and low loss materials.

Resonator Excitation

It is known[5] that the energy loss by radiation occurs for the TM_{010} mode, if the lateral plate of the resonator is removed. Therefore, the bandwidth wider than that for the $TE_{01\delta}$ filter can be realized easily, because the TM_{010} mode can be coupled strongly to either coaxial line or waveguide. The bandwidth of 6 % is verified by the experiment described later.

Resonator Size

It is shown by calculation for ε_r=36 that the volume of the dielectric material for the TM_{010} resonator is below a half times that for the $TE_{01\delta}$ resonator. Therefore, the TM_{010} resonator can be made smaller than the $TE_{01\delta}$ resonator in volume. Paticularly, this resonator will find many applications in lower region of microwave frequency.

Temperature-Stable Configuration of Resonator

For the structure in Fig. 1(a), the resonant frequency of the TM_{010} mode is sensitive to small change of the air-gap length. This was improved by using the structure shown in Fig. 1(b): that is, both ends of the rod were fitted in the holes drilled in the end plates. Since these holes operate as circular cutoff waveguides of TM_{01} mode, the fields decay exponentially with depth of the hole. Thus, the air-gap effect can be remarkably reduced. For example, when a brass cavity and TiO_2-B_aO ceramics material(ε_r=36) are used, the measured value of $\eta_f=(\Delta f/\Delta T)/f_0$ is about 130 ppm/°c for the structure in Fig. 1(a). On the other hand, the measured value of 10 ppm/°c is obtained for the structure in Fig. 1(b), though this value is not optimum.

Estimation of Qu

Since the TM_{010} resonator corresponds to air-filled TEM coaxial line resonator having the length of a half wavelength if the dielectric rod is replaced by the conductor, it is of interest to compare the values of Qu between both resonators having the same resonant frequency and volume.

The Qu for the TM_{010} resonator is given by the following equations:

$$\frac{1}{Qu}=\frac{1}{Qc}+\frac{1}{Qd}=\frac{1}{Qlat}+\frac{1}{Qend}+\frac{1}{Qd}\ , \tag{4}$$

where

$$Qlat=\frac{\lambda_0}{\delta_c}\frac{w}{2\pi}\left[\ 1+\left(\frac{G_1(v)}{SG_1(w)}\right)^2\left(\frac{G_0(v)G_2(v)}{G_1^2(v)}-\frac{J_0(u)J_2(u)}{J_1^2(u)}\right)\right] \quad \text{..........(5)}$$

$$Qend=\frac{L}{\delta_c}\ ,\qquad \delta_c=\sqrt{\frac{2}{\omega\mu\sigma}}\ , \tag{6}$$

$$Qd=\frac{1}{\tan\delta}\left[1+\frac{1}{\varepsilon_r}\frac{J_1^2(u)}{J_0^2(u)+J_1^2(u)}\ \frac{S^2G_1^2(w)-G_0^2(v)-G_1^2(v)}{G_1^2(v)}\right] \tag{7}$$

$$G_n(x)=J_n(x)-\frac{J_0(w)}{N_0(w)}N_n(x)\ . \tag{8}$$

In above equations, Qc, Qlat, Qend, and Qd are the Q's relating to the conductor loss, the lateral plate loss, the end plates loss, and the dielectric loss, respectively. σ is the conductivity of the conductor. While, for the TEM resonator the following relations hold:

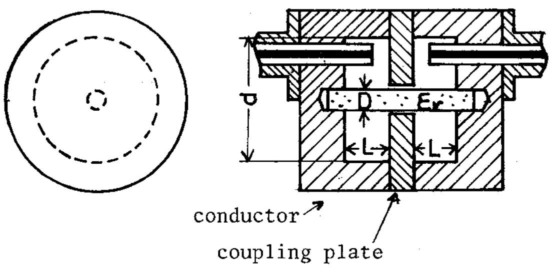
$$Qlat=\frac{d}{\delta_c}\frac{\ln S}{1+S}\ ,\qquad Qend=L/2\delta_c\ ,\ Qd=\infty\ . \tag{9}$$

For example, when f_0=3 GHz, ε_r=36, S=3.6 and R=0.1 the calculated dimensions for the TM_{010} resonator are D=6.0 mm, d=21.4 mm,and L=12.0 mm. While, the dimensions for the TEM resonator having the same volume are D=3.6 mm, d=12.8 mm, and L=50 mm. The next higher order resonance occurs at $2f_0$ for each resonator. In the case of copper conductor, Qc=9200 and 2500 are obtained for the TM_{010} and TEM resonators, respectively. Furthermore, considering the dielectric loss of $\tan\delta=1\times10^{-4}$, the value of Qu becomes 4700 for the TM_{010} resonator. For the $TE_{01\delta}$ resonator, Qu=7000 is obtained. As a result, the Qu for the TM_{010} resonator is lower than that for the $TE_{01\delta}$ resonator because of the increased conductor wall loss, but is higher than that for the TEM resonator. The measured value at 6 GHz was Qu=2800 against the theoretical value of 3000.

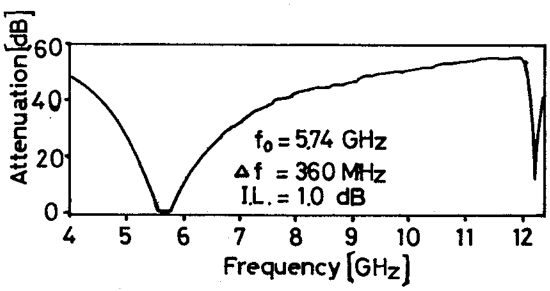
Bandpass Filters

The direct-coupled bandpass filters having maximally-flat response are constructed by using the brass cavity and the dielectric rods of ε_r=36 and D=3 mm at 6 GHz.

The configuration in Fig. 3(a) shows a longitudinal type of the filter in which the inter-resonator coupling is carried out at the end of the rod by the electric field. The coupling strength can be adjusted by means of changing either size of the hole or the thickness of the coupling plate. The structure shown in the figure has a merit that the filter of desired stages can be constructed easily by using conductor plates, but a demerit that the lower value of Qu results from the increased loss by current flow between the lateral and end plates. The filter has 30 mm in diameter and 33 mm in length, excluding the both connectors. The experimental result is shown in Fig. 3(b).



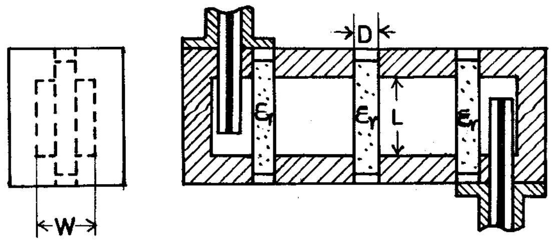
(a) Configuration



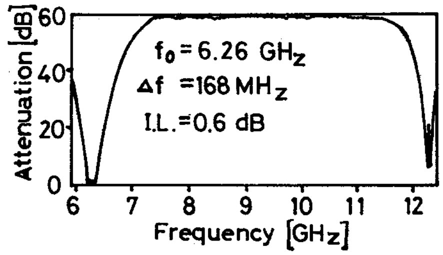
(b) Frequency response

Fig. 3 Two TM_{010} resonator dielect-coupled bandpass filter of a longitudinal type.

Fig. 4(a) shows the configuration of a transverse type of the filter in which the inter-resonator coupling is carried out at the lateral plane of the rod by the magnetic field. The width W shown in the figure is adjusted so that the rectangular cutoff waveguide of TE_{10} mode is constructed. The coupling strength can be adjusted by changing the width W or the space between two rods. This configuration is suitable to construct the waveguide filters. The filter has 20×25×50 mm^3 in size, excluding the both connectors. The experimental result is shown in Fig. 4(b). The filter performances of two example described above are excellent. The spurious response does not appear in an octave band for each case as expected. The relative bandwidth of



(a) Configuration



(b) Frequency response

Fig. 4 Three TM_{010} resonator direct-coupled bandpass filter of a transverse type.

6 % was obtained in Fig. 4.

Conclusion

New types of bandpass filters using TM_{010} mode of a shielded dielectric rod resonator have been proposed. The characteristics of the TM_{010} resonator have been described in detail. This resonator will also find many applications in microwave frequency, paticularly in lower region of it.

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