A BANDPASS FILTER USING HIGH-Q DIELECTRIC RING RESONATORS

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ABSTRACT

A Tchebyscheff bandpass filter constructed by placing high-Q $TE_{01\delta}$ dielectric ring resonators coaxially in a TE_{01} cutoff circular waveguide is designed precisely by the mode matching technique. Some discussions for design of the high-Q resonators and inter-resonator coupling are presented.

INTRODUCTION

A bandpass filter constructed by placing $TE_{01\delta}$ mode dielctric rod resonators coaxially in a TE_{01} cutoff circular waveguide has been presented by Harrison [1]. In this design, an approximate but useful formula for an inter-resonator coupling coefficient presented by Cohn [2] has been used. Furthermore, the rigorous analysis by the mode matching technique realizes more precise design of this filter [3].

In this paper, a bandpass filter constructed using high-Q dielectric ring resonators is discussed to decrease the insertion loss of the filter. Precise design of the high-Q dielectric ring resonators and inter-resonator coupling is performed by the same technique as done in the rod case.

ANALYSIS

Fig. 1 shows the geometry of coupled dielectric ring resonators to be analyzed to determine dimensions of filter structures. Two dielectric ring resonators having relative permittivity ε_r, diameter D, inner diameter D_x, and length L are supported with dielectric rings of relative permittivity ε_3 coaxially in a cutoff circular waveguide of diameter d. The space between the rings is 2M. The inter-resonator coupling coefficient k of this configuration is obtained from

$$k=2\frac{f_{sh}-f_{op}}{f_{sh}+f_{op}} \tag{1}$$

where f_{sh} is the resonant frequency when the structurally symmetric T-plane in Fig. 1 is short-circuited and f_{op} is one when the T-plane is open-circuited [3]. Thus, the analysis of k is reduced to

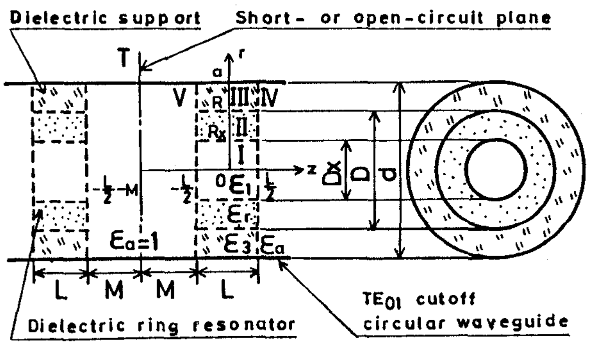

Fig. 1. Coupled dielectric ring resonators.

a problem of calculating the resonant frequencies: it is performed by the mode matching technique as described below. Choose a cylindrical coordinate system r, θ, z as in Fig. 1. According to the structural symmetry, only the region $z \geq -(L/2+M)$ is considered, which is divided into five homogenious mediums I to V. The quantities in the mediums are designated by subscripts 1 to 5, respectively.

The axial component of magnetic Hertz vector π_m in each medium is expanded in eigenmodes which satisfy the boundary conditions on the conductor surface and the T-plane; that is,

$$\begin{aligned}
\pi_{m1}&=\sum_{p=1}^{\infty}A_p I_0(k'_{1p}r)\cos(\beta_p z-\phi_p)\\
\pi_{m2}&=\sum_{p=1}^{\infty}[B_p J_0(k_{2p}r)+B'_p N_0(k_{2p}r)]\cos(\beta_p z-\phi_p)\\
\pi_{m3}&=\sum_{p=1}^{\infty}C_p T_p(k'_{3p}r)\cos(\beta_p z-\phi_p)\\
\pi_{m4}&=\sum_{q=1}^{\infty}D_q J_0(k_{4q}r)\exp(-\alpha_q z)\\
\pi_{m5}&=\sum_{q=1}^{\infty}E_q J_0(k_{4q}r)\left\{\begin{matrix}\sinh \alpha_q(z+L/2+M)\\ \cosh \alpha_q(z+L/2+M)\end{matrix}\right\}
\end{aligned} \tag{2}$$

where

$$T_n(x)=I_n(x)-\frac{I_0'(k_3'a)}{K_0'(k_3'a)}K_n(x)$$

$$\beta_p^2= k_0^2\varepsilon_1+ k_{1p}'^2= k_0^2\varepsilon_r- k_{2p}^2= k_0^2\varepsilon_3+ k_{3p}'^2 \quad (3)$$

$$\alpha_q^2= k_{4q}^2- k_0^2= (j_{1q}/a)^2- k_0^2$$

$$J_1(j_{1q})=0, \quad k_0=2\pi f_0/c$$

In the above, the first and second expressions in { } correspond to the short- and open-circuited T-plane modes, respectively. Jn(x) and Nn(x) are the Bessel functions of the first and second kinds. In(x) and Kn(x) are the modified Bessel functions of the first and second kinds. The prime on a cylinder function denotes differentiation with respect to the argument. k_0 and c are the wave number and light velocity in vacuum, and f_0 is the resonant frequency. Ap, Bp, Bp', Cp, Dq, Eq, and Φp are expansion coefficients to be determined from the boundary conditions. For the present case the TE_{01} mode in the circular waveguide is supposed to be the evanescent mode; that is,

$$d < \frac{c}{\pi f_0} j_{11} \;;\quad j_{11}=3.832 \quad (4)$$

so that α_q is real for any q.

The field components in each medium are given by substituting (2) into the following equations:

$$H_z=k^2\pi_m+ \frac{\partial^2\pi_m}{\partial z^2}, \quad H_r= \frac{\partial^2\pi_m}{\partial r\partial z}, \quad E_\theta=j\omega\mu_0\frac{\partial\pi_m}{\partial r} \quad (5)$$

where k is the wave number of each medium. Then imposing the boundary conditions at the interfaces of the mediums and applying the orthogonality of the Bessel functions, we get homogeneous equations for the expansion coefficients. The resonant frequencies are determined by the condition that the determinant of the coefficient matrix vanishes:

$$\det H\,(f_0;\ \varepsilon_r,\ d,\ D,\ D_x,\ L,\ M,\ \varepsilon_1,\ \varepsilon_3)=0 \quad (6)$$

where the matrix elements are given elsewhere [4].

Putting M=∞ in (6), we can calculate resonant frequencies for a single resonator. Furthermore, the unloaded Q (Q_u) of the $TE_{01\delta}$ mode is given by

$$1/Q_u=1/Q_d+1/Q_{d3}+1/Q_c \quad (7)$$

where Q_d and Q_{d3} are ones due to the dielectric ring and support losses, respectively, and Q_c is one due to the conductor loss. They are calculated from (6) by the perturbation technique [5]. The temperature coefficients of the resonant frequencies also can be calculated in a similar way [5].

DESIGN OF $TE_{01\delta}$ DIELECTRIC RING RESONATOR

The $TE_{01\delta}$ dielectric ring resonators used in this filter structure were fabricated from low loss ceramic $Ba(SnMgTa)O_3$ rings (ε_r=24.3, tan $\delta=5\times10^{-5}$ at 12 GHz), polystyrene foam supports (ε_3=1.031, tan $\delta_3= 4\times10^{-5}$), and copper-plated brass tubes (the conductivity $\sigma=\bar{\sigma}\sigma_0$; $\bar{\sigma}$=0.9, $\sigma_0=58\times10^6$ S/m). High Q design of these resonators was performed at f_0= 11.958 GHz, as shown below.

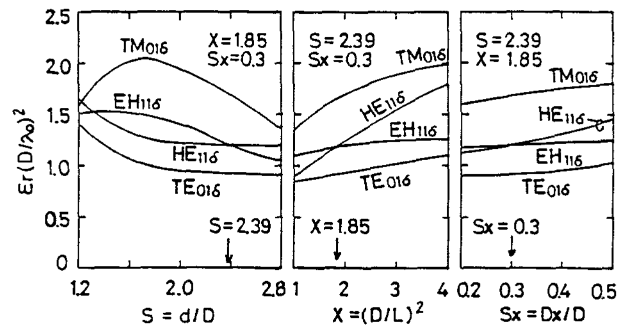

Fig. 2. Mode charts for a dielectric ring resonator placed coaxially in a cutoff circular waveguide in the case of ε_r=24.

Define the resonant frequency ratio F_r by $F_r= f_r/f_0$, where f_0 and f_r are ones of the $TE_{01\delta}$ mode and of the next higher-frequency mode. For a dielectric rod resonator (D_x=0), at first, the dimension ratios S=d/D and X=$(D/L)^2$ were calculated for obtaining the maximum value of F_r, F_{rmax}. The design process is the same as described in [6]. The result is F_{rmax}=1.14 when S=1.9 and X=3.1. Then for the ring resonator the values of S, $S_x=D_x/D$, and X were calculated for obtaining the maximum Q_u value, as F_r=1.14 and f_0=11.958 GHz were kept constant. The result is S=2.39, S_x=0.30, and X=1.85. Fig. 2 shows mode charts calculated around these values indicated by arrows.

Table 1. Calculated Q_u values for the dielectric ring and rod resonators with F_r=1.14 when f_0=11.958 GHz.

	Qd	Qd3	Qc	Qu
Ring	20,790	1,020,000	96,700	16,800
Rod	20,530	1,740,000	52,800	14,700

Table 1 shows the Q_u values calculated for these resonators. The ring resonator realizes higher Q_u than one of the rod case. Furthermore, the Q_u value of the ring resonator is 1.7 times higher than the value Q_u=9840 calculated for an $EH_{11\delta}$ dielectric rod resonator [7].

The calculated temperature coefficient of this resonator is τ_f=0.1±0.5 ppm/°C while the measured result is τ_f=-0.5±0.1 ppm/°C.

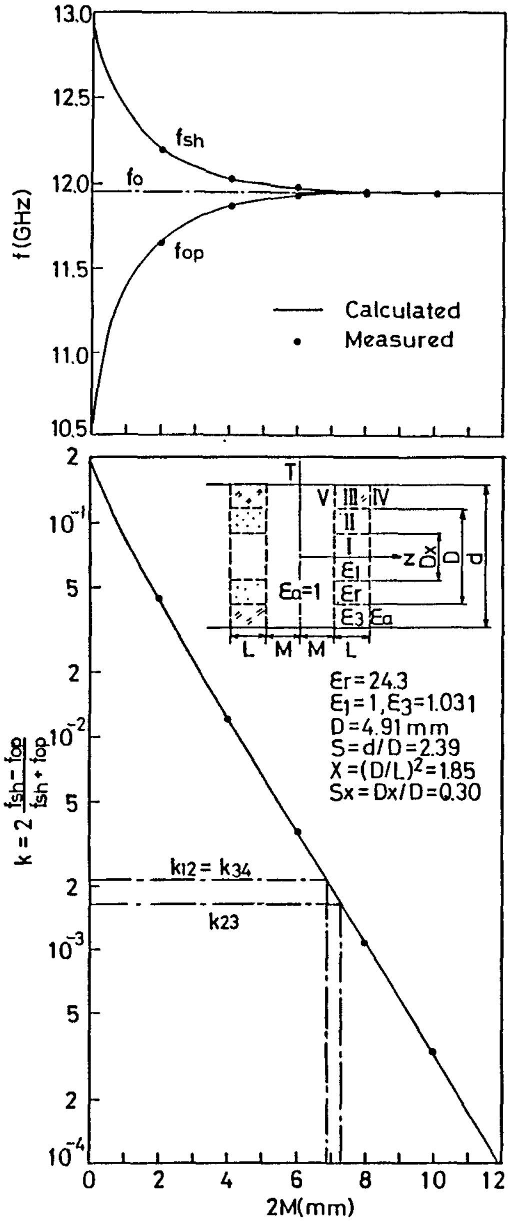

Fig. 3. Calculated and measured results of f_{sh}, f_{op}, and k versus 2M for coupled $TE_{01\delta}$ ring resonators.

INTER-RESONATOR COUPLING COEFFICIENT

When the ring resonators designed are coupled, the calculated and measured results of f_{sh}, f_{op}, and k, are shown in Fig. 3. These measured values agree with the theoretical curves to within 0.1, 0.1, and 1 %, respectively. The difference between the center frequency $f_{0k}=\sqrt{f_{sh}\cdot f_{op}}$ and f_0 is within 0.02 % when k<0.01; it can be neglected in filter design. To investigate the effect of ring in shape, the k values for the rod (D_x=0) were calculated using the same technique [3] and Cohn's formula [1], [2], where the rod length was shortened so as to make the resonant frequency equal to the ring case. These results are summarized in Table 2. The k values for the ring are 4 % smaller than ones for the rod. The results by Cohn's theory are 13 to 19 % smaller than ones by this theory, as k increases.

DESIGN OF FILTER

Fig. 4 shows a structure of a 4-stage Tchebyscheff bandpass filter designed. Three brass rings are machined with the precise dimensions designed, copper plated, and mounted in a filter housing; the precision of the resonator attachment eliminates the need for k adjustment screws. Each of the first and fourth resonators is excited by a coupling aperture located at the end of a WR-90 rectangular waveguide with an external Q (Q_e) adjustment screw. The resonant frequency for each resonator is adjusted with a tuning screw.

In consideration of the application to a Japanese broadcasting satellite [8], the specifications of this filter are as follows: center frequency f_0= 11.958 GHz (13 ch.), 15 dB bandwidth Δf_{15dB}=49.7 MHz, RW bandwidth Δf_{RW}=27.3 MHz, and ripple width RW=0.04 dB. Then, we obtain the necessary values $k_{12}=k_{34}=2.14\times10^{-3}$, $k_{23}=1.64\times10^{-3}$, and Q_e=395; the 2M values required are determined from Fig. 3. The size of this filter is also indicated in Fig. 4.

The transmission and reflection responses are shown in Fig. 5. The agreement between experiment and theory is good. The measured value Q_u=14000 gives the midband insertion loss of 0.64 dB, while the measured insertion loss of 0.9 dB corresponds to Q_u=9800. This Q_u degradation is due to the conductor loss of the coupling apertures and tuning screws. The wideband response is shown in Fig. 6. The resonant modes for the single resonator are indicated on the top of the figure. It is seen that the higher order mode couplings due to the apertures are considerably strong.

Table 2. Comparison of three cases of k values calculated when f_0=11.958 GHz, ε_r=24.3, and ε_3=1.031.

2M (mm)		0	2	4	6	8	10	12
Ring*1	This theory	1.74×10^{-1}	4.51×10^{-2}	1.24×10^{-2}	3.63×10^{-3}	1.08×10^{-3}	3.22×10^{-4}	9.62×10^{-5}
Rod*2	This theory	1.84×10^{-1}	4.71×10^{-2}	1.29×10^{-2}	3.77×10^{-3}	1.12×10^{-3}	3.33×10^{-4}	9.96×10^{-5}
	S.B.Cohn	1.41×10^{-1}	3.82×10^{-2}	1.10×10^{-2}	3.26×10^{-3}	0.97×10^{-3}	2.90×10^{-4}	8.68×10^{-5}

*1 D=4.91mm, Dx=1.47mm, L=3.61mm, d=11.73mm
*2 D=4.91mm, Dx=0 mm, L=3.42mm, d=11.73mm

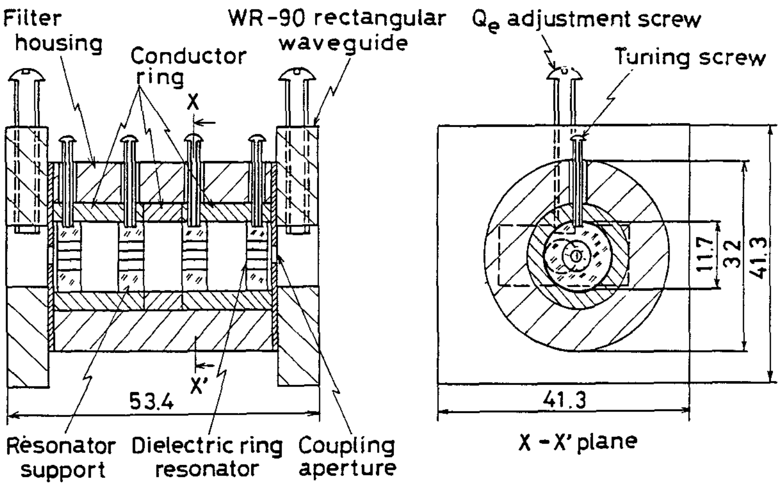

Fig. 4. Structure of a 4-stage dielectric ring resonator filter.

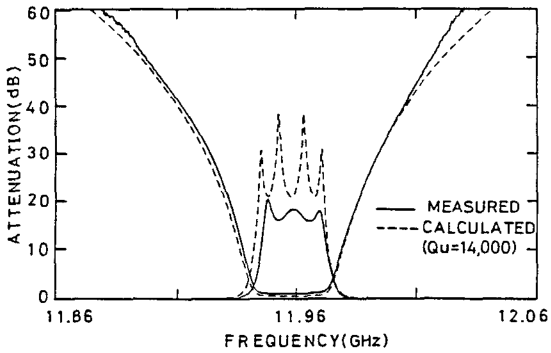

Fig. 5. Transmission and reflection responses of the 4-stage Tchebyscheff bandpass filter.

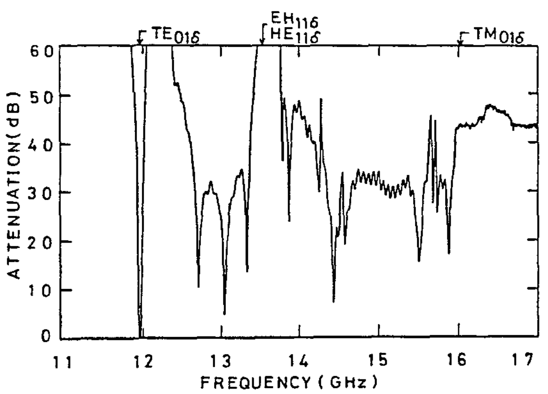

Fig. 6. Wideband response of the filter.

CONCLUSION

In conclusion, the filter structure presented allows us to realize precise filter design and ease of fabrication because of its simple configuration.

ACKNOWLEDGMENT

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