Precise Design of a Bandpass Filter Using High-Q Dielectric Ring Resonators

YOSHIO KOBAYASHI, MEMBER, IEEE, AND MASAHIKO MINEGISHI

***Abstract*—A precise design is presented for a bandpass filter constructed by placing $TE_{01\delta}$ dielectric ring resonators coaxially in a TE_{01} cutoff circular waveguide. On the basis of a rigorous analysis by the mode-matching technique, the interresonator coupling coefficients are determined accurately from the calculation of two resonant frequencies f_{sh} and f_{op} when the structurally symmetric plane is short- and open-circuited. For the $TE_{01\delta}$ ring resonator, the resonant frequency f_0, the temperature coefficient τ_f, the unloaded $Q(Q_u)$, and the other resonances are also calculated accurately in a similar way. From the calculations, the optimum dimensions are determined to obtain the maximum Q_u, as $F_r = f_r/f_0$ is kept constant, where f_r is the next higher resonant frequency; the ring resonator using low-loss ceramics ($\epsilon_r = 24.3$, $\tan\delta = 5\times10^{-5}$) has $Q_u = 16800$ at 12 GHz and $\tau_f = 0.1 \pm 0.5$ ppm/°C, while the rod one has $Q_u = 14700$. A four-stage Chebyshev filter having ripple of 0.04 dB and equiripple bandwidth of 27.3 MHz at $f_0 = 11.958$ GHz is fabricated using these resonators; the measured frequency responses agree well with theory. The insertion loss is 0.9 dB, which corresponds to $Q_u = 9800$.**

I. Introduction

A BANDPASS filter constructed by placing $TE_{01\delta}$ mode dielectric rod resonators coaxially in a TE_{01} cutoff circular waveguide has been presented by Harrison [1]. In this design, the approximate but useful formula for an interresonator coupling coefficient presented by Cohn [2] has been used. For a similar filter structure, a more precise design has been performed on the basis of a rigorous analysis by the mode-matching technique [3]. Recently, dielectric resonators with high unloaded $Q(Q_u)$ have been needed to decrease the insertion loss of filters. $TE_{01\delta}$ ring resonators have a possibility of realizing higher Q_u values than the rod-shaped ones.

This paper discusses a precise design of a bandpass filter constructed using these ring resonators. The resonant frequency, its temperature coefficient, the Q_u value, the other resonances, and the interresonator coupling coefficient are analyzed rigorously by the same technique as used in the rod case. A precise design of the high-Q_u ring resonators and the interresonator coupling coefficients is performed from these calculations, and a four-stage Chebyshev filter is fabricated.

II. Analysis

A. Interresonator Coupling Coefficient

Fig. 1 shows the geometry of the coupled dielectric ring resonators to be analyzed, and the cylindrical coordinate system r, θ, z. 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 relative permeability in each medium is $\mu_r = 1$. The conductor and dielectric are supposed to be lossless first.

The interresonator coupling coefficient k of this configuration is obtained from

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

where f_{sh} and f_{op} are the resonant frequencies when the structurally symmetric plane (T plane in Fig. 1) is short- and open-circuited, respectively [3]. The error of the second equation in (1) is below 0.01 percent when $k < 2\times10^{-2}$. Thus, the derivation of k is reduced to the problem of calculating the resonant frequencies, and is performed by the mode-matching technique described below. According to the structural symmetry, only the region $z \geqslant -(L/2 + M)$ is considered, and this is divided into five homogeneous media I to V. The quantities in the media are designated by subscripts 1 to 5, respectively. The axial component of the 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, i.e.,

$$\begin{aligned}
\pi_{m1} &= \sum_{p=1}^{\infty} A_p I_0(k'_{1p} r)\cos(\beta_p z - \phi_p)\\
\pi_{m2} &= \sum_{p=1}^{\infty} \left[B_p J_0(k_{2p} r) + B'_p N_0(k_{2p} r)\right]\cos(\beta_p z - \phi_p)\\
\pi_{m3} &= \sum_{p=1}^{\infty} C_p T_0(k'_{3p} r)\cos(\beta_p z - \phi_p)\\
\pi_{m4} &= \sum_{q=1}^{\infty} D_q J_0(k_{4q} r)\exp(-\alpha_q z)\\
\pi_{m5} &= \sum_{q=1}^{\infty} E_q J_0(k_{4q} r)\begin{Bmatrix}\sinh\alpha_q(z + L/2 + M)\\ \cosh\alpha_q(z + L/2 + M)\end{Bmatrix}
\end{aligned} \tag{2}$$

where

$$\begin{aligned}
T_n(x) &= I_n(x) + (-1)^n \frac{I_1(k'_{3p} a)}{K_1(k'_{3p} a)} K_n(x)\\
\beta_p^2 &= k_0^2\epsilon_1 + k'^2_{1p} = k_0^2\epsilon_r - k_{2p}^2 = k_0^2\epsilon_3 + k'^2_{3p}\\
\alpha_q^2 &= k_{4q}^2 - k_0^2 = (j_{1q}/a)^2 - k_0^2\\
J_1(j_{1q}) &= 0 \qquad k_0 = 2\pi f_0/c.
\end{aligned} \tag{3}$$

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The authors are with the Department of Electrical Engineering, Saitama University, Urawa, Saitama 338, Japan.

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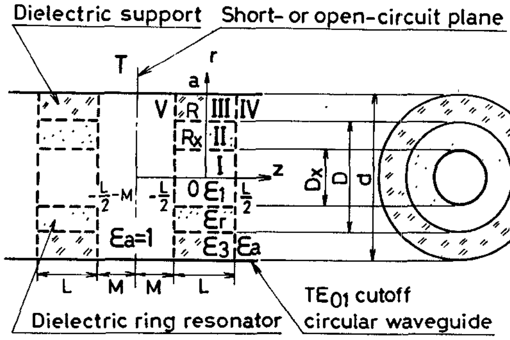

Fig. 1. Coupled dielectric ring resonators.

Also, the upper and lower expressions in the braces $\{\ \}$ correspond to the short- and open-circuited T-plane modes, respectively. $J_n(x)$ and $N_n(x)$ are the Bessel functions of the first and second kinds. $I_n(x)$ and $K_n(x)$ are the modified Bessel functions of the first and second kinds. A time factor $e^{j\omega t}$ $(\omega = 2\pi f_0)$ is tacitly assumed, and f_0 is the resonant frequency. The quantities k_0 and c are the wavenumber and the light velocity in vacuum. A_p, B_p, B'_p, C_p, D_q, E_q, and ϕ_p 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, i.e.,

$$d < \frac{c}{\pi f_0} j_{11}, \qquad j_{11} = 3.832 \tag{4}$$

so that α_q is real for any q.

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

$$H_z = k_i^2 \pi_{mi} + \frac{\partial^2 \pi_{mi}}{\partial z^2} \qquad H_r = \frac{\partial^2 \pi_{mi}}{\partial r \partial z} \qquad E_\theta = j\omega\mu_0 \frac{\partial \pi_{mi}}{\partial r} \tag{5}$$

where $i = 1, 2, \cdots, 5$, and k_i is the wavenumber of the ith medium.

In the media I, II, and III, at first, the requirements that the pth components of H_z and E_θ be continuous at the interfaces $r = R_x$ and $r = R$ lead to

$$\begin{aligned}&\left[u_{xp} N_0(u_{xp}) I_1(w'_p) - w'_p N_1(u_{xp}) I_0(w'_p)\right]\\ &\quad\times\left[u_p J_0(u_p) T_1(v'_p) - v'_p J_1(u_p) T_0(v'_p)\right]\\ &= \left[u_{xp} J_0(u_{xp}) I_1(w'_p) - w'_p J_1(u_{xp}) I_0(w'_p)\right]\\ &\quad\times\left[u_p N_0(u_p) T_1(v'_p) - v'_p N_1(u_p) T_0(v'_p)\right]\end{aligned} \tag{6}$$

where

$$\begin{aligned}u_p &= k_{2p} R\\ u_{xp} &= k_{2p} R_x = \frac{D_x}{D} u_p\\ w'_p &= k'_{1p} R_x = R_x \sqrt{k_0^2(\epsilon_r - \epsilon_1) - (u_p/R)^2}\\ v'_p &= k'_{3p} R = R\sqrt{k_0^2(\epsilon_r - \epsilon_3) - (u_p/R)^2}.\end{aligned} \tag{7}$$

In the above, a set of the values u_p, u_{xp}, v'_p, and w'_p is the pth solution for (6), where $u_p < u_{p+1}$ $(p = 1, 2, \cdots)$. Then, imposing the boundary conditions that H_r and E_θ be continuous at $z = L/2$ and $z = -L/2$ and applying the orthogonality of the Bessel functions, we obtain homogeneous equations for the expansion coefficients. The resonant frequencies are determined by the condition that the determinant of the coefficient matrix vanish, i.e.,

$$\det H(f_0; \epsilon_r, \epsilon_1, \epsilon_3, d, D, D_x, L, M) = 0 \tag{8}$$

where elements of the $N \times N$ square matrix $(p, q = 1, 2, \cdots, N/2)$ are given by

$$\begin{aligned}H_{2p-1,2q-1} &= T_{pq}\left(\frac{\beta_p}{\alpha_q}\tan\frac{\beta_p L}{2} - 1\right)\\ H_{2p-1,2q} &= -T_{pq}\left(\frac{1}{\alpha_q L} + \frac{1}{\beta_p L}\tan\frac{\beta_p L}{2}\right)\\ H_{2p,2q-1} &= T_{pq}\left(\frac{\beta_p}{\alpha_q}\begin{Bmatrix}\tanh\alpha_q M\\ \coth\alpha_q M\end{Bmatrix}\tan\frac{\beta_p L}{2} - 1\right)\\ H_{2p,2q} &= T_{pq}\left(\frac{1}{\alpha_q L}\begin{Bmatrix}\tanh\alpha_q M\\ \coth\alpha_q M\end{Bmatrix} + \frac{1}{\beta_p L}\tan\frac{\beta_p L}{2}\right)\end{aligned} \tag{9}$$

and also

$$\begin{aligned}T_{pq} &= -\frac{1}{a^2}\left(\frac{A_p}{B_p}\frac{w'_p}{u_{xp}}P_{pq} + Q_{pq} + \frac{C_p}{B_p}\frac{v'_p}{u_p}R_{pq}\right)\\ P_{pq} &= \int_0^{R_x} r I_1(k'_{1p} r) J_1(k_{4q} r)\, dr\\ Q_{pq} &= -\int_{R_x}^{R} r\left[J_1(k_{2p} r) + \frac{B'_p}{B_p} N_1(k_{2p} r)\right] J_1(k_{4q} r)\, dr\\ R_{pq} &= \int_R^a r T_1(k'_{3p} r) J_1(k_{4q} r)\, dr\\ \frac{A_p}{B_p} &= -\frac{u_{xp}^2}{w_p'^2}\frac{J_0(u_{xp}) + (B'_p/B_p) N_0(u_{xp})}{I_0(w'_p)}\\ \frac{C_p}{B_p} &= -\frac{u_p^2}{v_p'^2}\frac{J_0(u_p) + (B'_p/B_p) N_0(u_p)}{T_0(v'_p)}\\ \frac{B'_p}{B_p} &= -\frac{J_0(u_{xp})}{N_0(u_{xp})}\left[\frac{I_1(w'_p)}{w'_p I_0(w'_p)} - \frac{J_1(u_{xp})}{u_{xp} J_0(u_{xp})}\right]\\ &\quad\bigg/\left[\frac{I_1(w'_p)}{w'_p I_0(w'_p)} - \frac{N_1(u_{xp})}{u_{xp} N_0(u_{xp})}\right].\end{aligned} \tag{10}$$

In the practical calculations, N is chosen to be a value for which the solution converges to the desired accuracy.

B. Resonant Frequencies for a Single Resonator

Putting $M = \infty$ in (8), we can calculate resonant frequencies for a single resonator. In this case, elements of the $N \times N$ square matrix $(p, q = 1, 2, \cdots, N)$ are given by

$$H_{p,q} = T_{pq}\left(\frac{\beta_p}{\alpha_q}\tan\frac{\beta_p L}{2} - 1\right). \tag{11}$$

C. Temperature Coefficient of the Resonant Frequency

The temperature coefficient of the resonant frequency τ_f can be expressed as follows [4]:

$$\tau_f = A_r\tau_r + A_3\tau_3 + (A_D + A_x + A_L)\tau_\alpha + A_c\tau_c \quad (12)$$

where

$$\tau_f = \frac{\Delta f_0}{f_0 \Delta T} \quad \tau_r = \frac{\Delta \epsilon_r}{\epsilon_r \Delta T} \quad \tau_3 = \frac{\Delta \epsilon_3}{\epsilon_3 \Delta T}$$

$$\tau_\alpha = \frac{\Delta D}{D \Delta T} = \frac{\Delta D_x}{D_x \Delta T} = \frac{\Delta L}{L \Delta T} \quad \tau_c = \frac{\Delta d}{d \Delta T}$$

$$A_r = \frac{\epsilon_r}{f_0}\frac{\Delta f_0}{\Delta \epsilon_r} \quad A_3 = \frac{\epsilon_3}{f_0}\frac{\Delta f_0}{\Delta \epsilon_3} \quad A_D = \frac{D}{f_0}\frac{\Delta f_0}{\Delta D}$$

$$A_x = \frac{D_x}{f_0}\frac{\Delta f_0}{\Delta D_x} \quad A_L = \frac{L}{f_0}\frac{\Delta f_0}{\Delta L} \quad A_c = \frac{d}{f_0}\frac{\Delta f_0}{\Delta d}. \quad (13)$$

In the above, τ_r and τ_3 are the temperature coefficients of ϵ_r and ϵ_3, and τ_α and τ_c are the coefficients of thermal linear expansion of the dielectric and conductor, respectively. Also, the constants A_r, A_3, A_D, A_x, A_L, and A_c can be determined accurately by calculating the small resonant frequency shifts Δf_0 caused by the small changes $\Delta\epsilon_r$, $\Delta\epsilon_3$, ΔD, ΔD_x, ΔL, or Δd, respectively.

D. Unloaded Q

The unloaded $Q(Q_u)$ of the $TE_{01\delta}$ mode can be expressed as follows [5]:

$$1/Q_u = 1/Q_d + 1/Q_{d3} + 1/Q_c \quad (14)$$

where

$$Q_d = \frac{-1}{2A_r}\frac{1}{\tan\delta} \quad Q_{d3} = \frac{-1}{2A_3}\frac{1}{\tan\delta_3} \quad Q_c = \frac{-1}{2A_c}\frac{d}{\delta_s} \quad (15)$$

and

$$\delta_s = (\pi f_0 \mu \bar{\sigma} \sigma_0)^{-1/2} \quad \bar{\sigma} = \sigma/\sigma_0 \quad \sigma_0 = 58\times 10^6 \text{ [S/m]}. \quad (16)$$

In the above, Q_d, Q_{d3}, and Q_c are due to the ring, support, and conductor losses, respectively. The quantities $\tan\delta$ and $\tan\delta_3$ are the loss tangents of the dielectric for the ring and support, respectively, δ_s is the skin depth of the conductor, σ is the conductivity, $\bar{\sigma}$ is the relative conductivity, and σ_0 is the conductivity of the international standard annealed copper.

III. Design of $TE_{01\delta}$ Dielectric Ring Resonator

$TE_{01\delta}$ dielectric ring resonators used in this filter structure were fabricated from the low-loss ceramics $Ba(SnMgTa)O_3$ ($\epsilon_r = 24.3$, $\tan\delta = 5\times10^{-5}$ at 12 GHz; Murata Mfg. Co., Ltd.), polystyrene foam supports ($\epsilon_3 = 1.031$, $\tan\delta_3 = 4\times10^{-5}$), and copper-plated brass cylinders ($\bar{\sigma} = 0.9$). High-Q design of these resonators were performed at $f_0 = 11.958$ GHz, as described below.

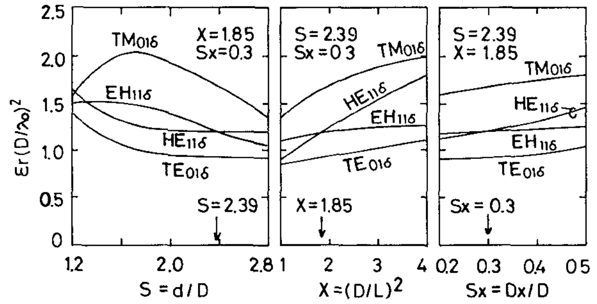

Fig. 2. Mode charts for a dielectric ring resonator placed coaxially in a cutoff circular waveguide in the case of $\epsilon_r = 24$.

TABLE I
Calculated Q_u Values for the Dielectric Ring and Rod Resonators with $F_r = 1.14$ when $f_0 = 11.958$ GHz, $\epsilon_r = 24.3$, $\tan\delta = 5\times10^{-5}$, $\epsilon_3 = 1.031$, $\tan\delta_3 = 4\times10^{-5}$, and $\bar{\sigma} = 0.9$

	Q d	Q d3	Q c	Q u
Ring*1	20,790	1,020,000	96,700	16,800
Rod *2	20,530	1,740,000	52,800	14,700

*1 $D = 4.91$ mm, $D_x = 1.47$ mm, $L = 3.61$ mm, $d = 11.73$ mm.
*2 $D = 5.25$ mm, $D_x = 0$, $L = 2.98$ mm, $d = 9.98$ mm.

Define the resonant frequency ratio F_r by $F_r = f_r/f_0$, where f_0 and f_r are the resonant frequencies for the $TE_{01\delta}$ mode and the next higher frequency mode. For a dielectric rod resonator ($D_x = 0$), initially, optimum dimension ratios $S = d/D$ and $X = (D/L)^2$ were calculated for obtaining the maximum value of $F_r(F_{r\max})$. The design process is the same as that described in [6]. The result is $F_{r\max} = 1.14$ when $S = 1.9$ and $X = 3.1$. For the ring resonator, the optimum values of S, $S_x = D_x/D$, and X were calculated for obtaining the maximum Q_u value, where $F_r = 1.14$ 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 optimum values indicated by arrows. Table I shows the Q_u values calculated for these resonators. The ring resonator realizes higher Q_u than that of the rod case. The development of lower loss material will increase the Q_u difference between the ring and rod resonators. 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 τ_f value for the ring resonator calculated from (12) is

$$\tau_f = -0.481\tau_r - 0.0123\tau_3 - 0.963\tau_\alpha - 0.0950\tau_c$$

$$= 0.1 \pm 0.5 \text{ ppm/°C}$$

where $\tau_r = -24\pm0.3$ ppm/°C, $\tau_3 = -8.4\pm0.5$ ppm/°C, $\tau_\alpha = 10\pm0.5$ ppm/°C, and $\tau_c = 20\pm0.03$ ppm/°C. The coefficient τ_f mainly depends on the terms τ_r and τ_α, while the τ_c effect on τ_f is only -1.9 ppm/°C because of energy concentration into the ring. Also, the measured result is $\tau_f = -0.5\pm0.1$ ppm/°C.

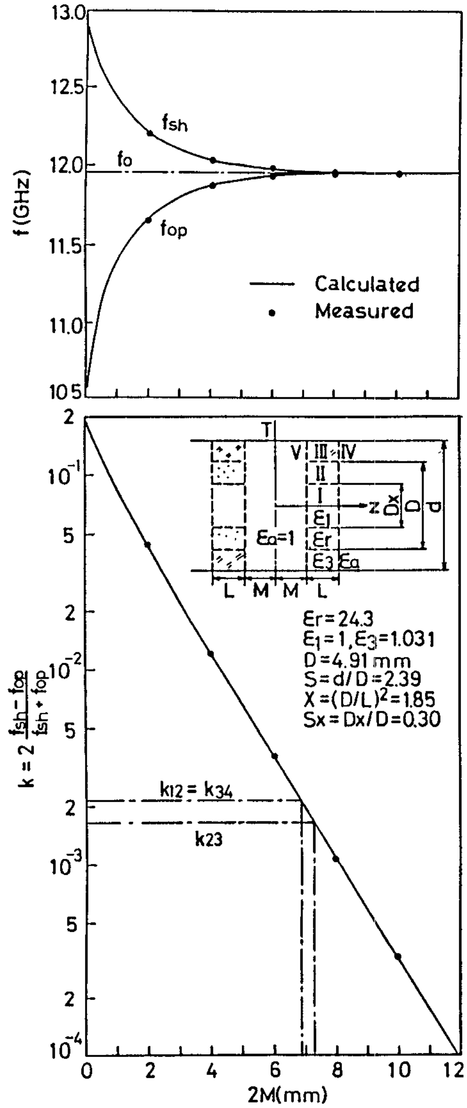

Fig. 3. Calculated and measured results of f_{sh}, f_{op}, and k versus $2M$ for coupled $TE_{01\delta}$ ring resonators.

TABLE II
COMPARISON OF THREE CASES OF k VALUES CALCULATED WHEN $f_0 = 11.958$ GHz, $\epsilon_r = 24.3$, AND $\epsilon_3 = 1.031$

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

*1 $D = 4.91$ mm, $D_x = 1.47$ mm, $L = 3.61$ mm, $d = 11.73$ mm.
*2 $D = 4.91$ mm, $D_x = 0$, $L = 3.42$ mm, $d = 11.73$ mm.

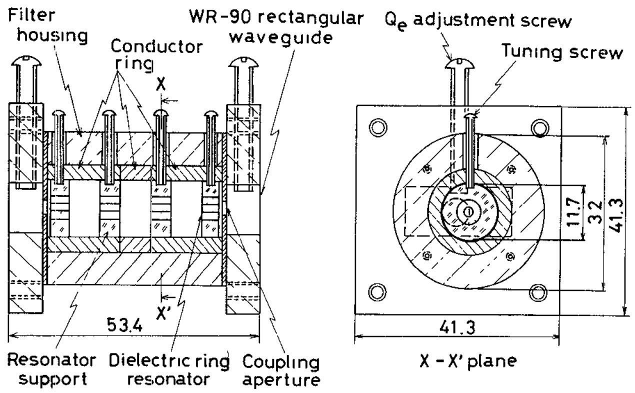

Fig. 4. Cross-sectional view of a four-stage dielectric ring resonator filter.

IV. INTERRESONATOR COUPLING COEFFICIENT

For coupled ring resonators with the same dimensions as those described above, 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 percent, respectively. The difference between the center frequency $f_{0k} = \sqrt{f_{sh}\cdot f_{op}}$ and f_0 is within 0.02 percent when $k < 0.01$; it can be neglected in filter design. To compare these k values with the rod case, the k values for the rod ($D_x = 0$) were calculated using the same mode-matching technique as the present one [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 II. The k values for the ring are 4 percent smaller than those for the rod. The results by Cohn's formula are 13 to 19 percent smaller than the ones by the present theory, as k increases; the discrepancy is approximately equal to the case of $\epsilon_r = 97.6$ given in [2].

V. DESIGN OF THE FILTER

Fig. 4 shows the cross-sectional view of a four-stage Chebyshev bandpass filter actually constructed. Three brass rings are precisely machined with the desired dimensions, copper-plated, and mounted in a filter housing. This structure ensures precise spacing of resonators and eliminates the need for k adjustment screws. The first and fourth resonators are each excited by a coupling aperture located at the end of a WR-90 rectangular waveguide. The external $Q(Q_e)$ values at the input and output ports are adjusted with conducting screws mounted in the waveguide flanges [8]. The resonant frequencies for the resonators are each adjusted with tuning screws.

In consideration of the application to a Japanese broadcasting satellite [9], the specifications of this filter are as follows: center frequency f_0 of 11.958 GHz (ch. 13), 15 dB bandwidth of 49.7 MHz, equiripple bandwidth of 27.3 MHz, and ripple of 0.04 dB. We obtain the values $k_{12} = k_{34} = 2.14\times10^{-3}$, $k_{23} = 1.64\times10^{-3}$, and $Q_e = 395$ [10], and the values of $2M$ are determined from Fig. 3. The size of this filter is also indicated in Fig. 4.

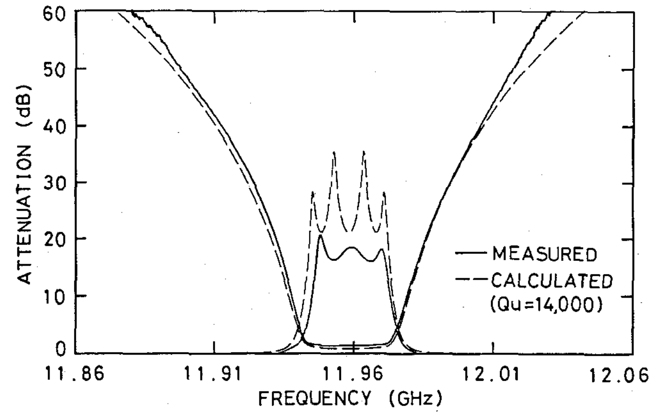

Fig. 5. Transmission and reflection responses of the four-stage Chebyshev bandpass filter.

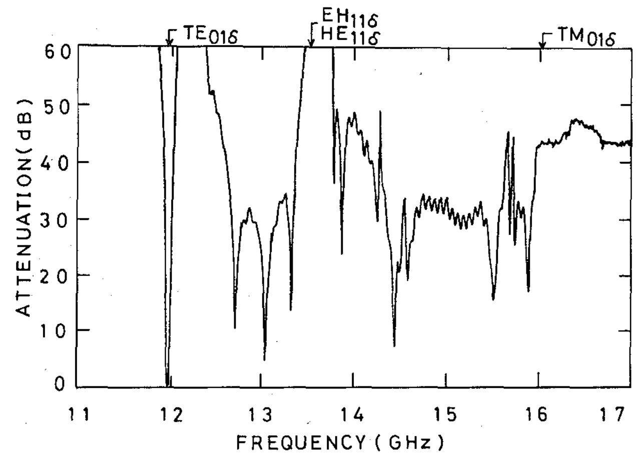

Fig. 6. Wide-band response of the filter.

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 a midband insertion loss of 0.64 dB [10], 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 wide-band response measured is shown in Fig. 6. The resonant modes for the single resonator calculated from Fig. 2 are indicated on the top of the figure. It is seen that strong couplings between the higher order modes worsen the spurious characteristics of the filter.

VI. Conclusions

For a $TE_{01\delta}$ dielectric ring resonator placed coaxially in a TE_{01} cutoff circular waveguide, the resonant frequency, its temperature coefficient, the unloaded Q, the other resonances, and the interresonator coupling coefficient were calculated accurately on the basis of a rigorous analysis by a mode-matching technique. The filter structure presented allows us to realize precise filter design and ensures ease of fabrication because of its simple configuration.

Acknowledgment

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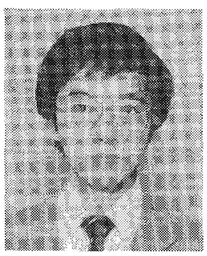
Yoshio Kobayashi (M'74) was born in Gumma, Japan, on July 4, 1939. He received the B.E., M.E., and D. Eng. degrees in electrical engineering from Tokyo Metropolitan University in 1963, 1965, and 1982, respectively.

He was a Research Assistant from 1965 to 1968, and a Lecturer from 1968 to 1982 in the Department of Electrical Engineering, Saitama University, Urawa, Saitama, Japan. He is now an Associate Professor at the same university. His current research interests are in dielectric waveguides and resonators, dielectric resonator filters, and the measurement of dielectric materials in the microwave and millimeter-wave regions.

Dr. Kobayashi is a member of the Institute of Electronics, Information and Communication Engineers of Japan, and the Institute of Electrical Engineers of Japan.



Masahiko Minegishi was born in Tokyo, Japan, on January 30, 1963. He received the B.E. degree in electrical engineering from Saitama University, Saitama, Japan, in 1986. Currently, he is studying toward the M.E. degree at Saitama University. His research activities have been concerned with dielectric resonator filters in the microwave region.

Mr. Minegishi is an associate member of the Institute of Electronics, Information and Communication Engineers of Japan.