# Dielectric High-Power Bandpass Filter Using Quarter-Cut $TE_{01\delta}$ Image Resonator for Cellular Base Stations

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***Abstract*—A dielectric high-power bandpass filter using "quarter-cut $TE_{01\delta}$ image resonators" has been developed. The resonator has a high unloaded $Q$ over 7000 and its construction provides a sufficient thermal diffusion path to the metal housing.**

**The insertion loss and the attenuation level of the eight-pole elliptic function type filter are 0.37 dB and 95 dB, respectively. The physical size of the dielectric filter is 280×135×65 mm, one third to one fifth the volume of conventional cavity resonator filters.**

## I. Introduction

Cellular systems operating in the 800-MHz band have been put to practical use in mobile communications systems. Transmitting high-power bandpass filters for their base stations must be compact and low in cost. The reduction in physical size of the low-power receiving bandpass filter using $TE_{01\delta}$-mode dielectric resonators is presented in [1]–[4].

$TE_{01\delta}$-mode dielectric resonators at 800 MHz have high unloaded $Q$ [5]; however, the size is not small enough for cost reduction and the required physical size reduction itself is insufficient. The most serious problem of this mode resonator is in the difficulties of the thermal design because the dielectrics are positioned separately from the metal housing.

Generally speaking, the most important problems involved in designing a high-power, small-size dielectric transmitting filter may be how to provide an effective thermal diffusion path to suppress the temperature increase of the dielectrics as well as how to construct a high-$Q$ dielectric resonator system which has low dissipation power.

In this work we propose a new dielectric resonator filter construction which solves these problems. The dielectric resonator construction of the filter comprises one quarter of an original $TE_{01\delta}$-mode dielectric ring-shaped resonator [3] and two metallized ceramic substrates for fixing the resonator. We named this the "Quarter-cut $TE_{01\delta}$ Image Resonator" (Q.T.I.R.). Using this construction we succeeded in developing an 880-MHz eight-pole elliptic function type high-power filter with a 20-MHz bandwidth. The size is reduced to about 1/3 ~ 1/5 of conventional cavity resonator filters.

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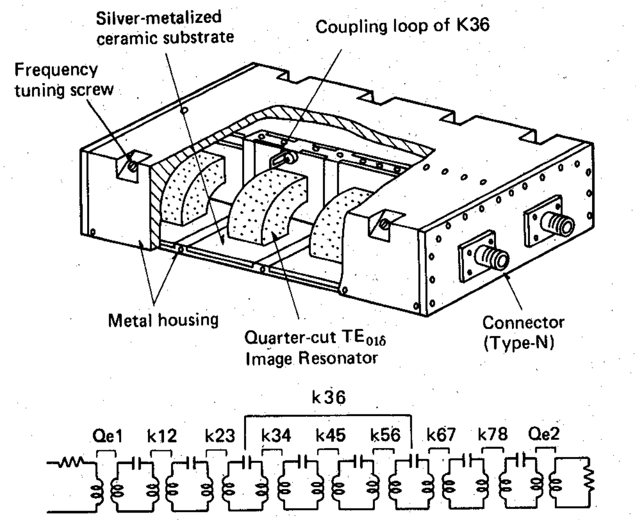


Fig. 1. Basic construction of quarter-cut $TE_{01\delta}$ image resonator filter and its equivalent circuit.

This paper describes the unloaded $Q$ estimation, the power design, and the performance of the new dielectric resonator filter.

## II. Construction

The construction of the Q.T.I.R. filter is shown in Fig. 1. A quarter-ring-shaped dielectric is fixed to the L-angle metallized ceramic substrates which work as electric walls. These substrates and the quarter-ring dielectrics make up the Q.T.I.R. construction and work as a $TE_{01\delta}$-mode image resonator.

These substrates are attached electrically and mechanically to the metal housing walls, which divide the space into one quarter that of the $TE_{01}$-mode circular cutoff waveguide. Resonators are inductively coupled to each other, and the two resonators at each end are also coupled inductively to the external load. Input and output ports are type-N connectors (female). An equivalent circuit of the direct coupled resonator filter corresponding to this construction is shown in [6, fig. 1].

The elliptic function type filter design we used is the same as the method presented by Atia *et al.* [7], and an

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TABLE I
OUTLINE OF REQUIRED CHARACTERISTICS

| | |
|---|---|
| Center frequency ($f_0$) | 880MHz |
| Bandwidth (BW) | 20 MHz |
| Attenuation ($f_0$-35MHz) | 90 dB min |
| Insertion loss (BW) | 0.45 dB max |
| Input power | 500 watts max |
| VSWR (BW) | 1.5 max |
| Volume | 3000cc max |

TABLE II
CERAMIC MATERIALS

| | Resonator | Substrate |
|---|---|---|
| Material system | (Zr, Sn)$TiO_4$ | $2MgO \cdot SiO_2 - ZrSiO_4$ |
| Dielectric permittivity ($\epsilon r$) | 37.5 | 8.5 |
| Dissipation factor ($\tan\delta$) | $2.5 \times 10^{-5}$ at 800 MHz | |
| $\frac{1}{\tan\delta} \cdot \frac{\Delta\tan\delta}{\Delta T}$ | 2% / 10°C | |
| Temperature coefficient ($\eta_{f_0}$) | 2ppm / °C | |
| Thermal expansion coefficient ($\alpha$) | 6.5ppm / °C | 6.5ppm / °C |
| Thermal conductivity (K) | 0.02 Joule/cm·deg·sec | |

optimal coupling K36 for the attenuation pole is obtained by inductive loops.

## III. ELECTRICAL DESIGN

### A. Outline of Required Characteristics

The required characteristics for the bandpass filter used for mobile communications systems in the 800-MHz band are listed in Table I. High attenuation of 90 dB at the receiving side and low insertion loss of 0.45 dB at the passband frequency are required under 500-W power operation for this transmitting filter.

### B. Dielectric Materials

Dielectric materials of the Q.T.I.R. are listed in Table II. The frequency dependence of the dissipation factor and the other characteristics of this high-$Q$ ceramic material were reported by Wakino [8]. The dissipation factor ($\tan\delta$) of the material at 800 MHz is about $2.5 \times 10^{-5}$ ($Q_0 =$ 40,000). In order to avoid mechanical distortion by the temperature of the Q.T.I.R., the thermal expansion coefficient of the ceramic substrate is selected to be the same [9] as that of dielectric high-$Q$ material.

### C. Resonant Frequency and Coupling Coefficient

The electromagnetic field distribution of the Q.T.I.R. filter is exactly the same as that in the filter using axially coupled original $TE_{01\delta}$-mode resonators. An accurate design method of the filter was reported by Kobayashi *et al.* [4]. So both the resonant frequency and the coupling coefficient of the newly designed filter can be analytically obtained with high accuracy using this method.

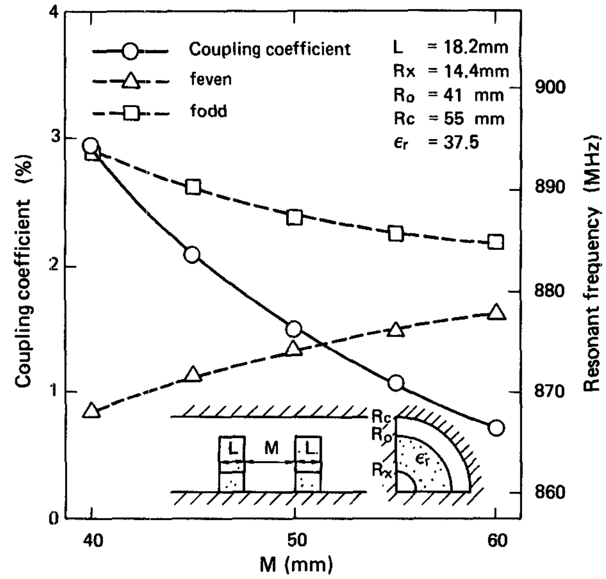


Fig. 2. Coupling coefficient and resonant frequency of quarter-cut $TE_{01\delta}$ image resonator.

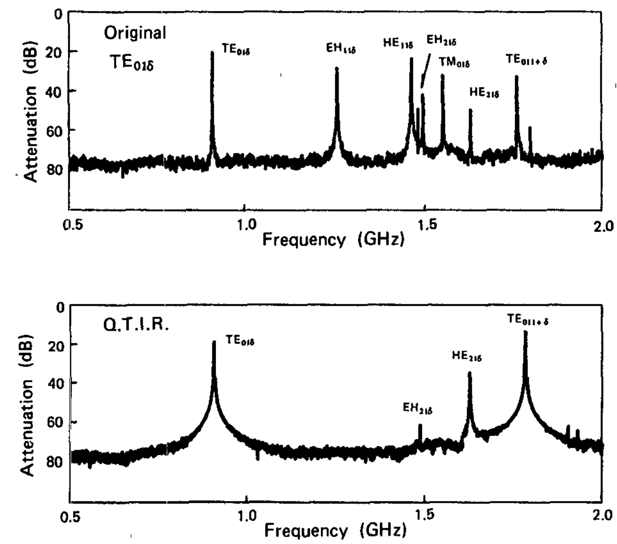


Fig. 3. Measured resonant characteristics of original $TE_{01\delta}$ mode resonator and quarter-cut $TE_{01\delta}$ image resonator.

Fig. 2 shows the calculated resonant frequency and the coupling coefficient ($k$) of the Q.T.I.R., where $k$ is defined by the following equation:

$$k = \frac{2(f_{odd} - f_{even})}{(f_{odd} + f_{even})}. \quad (1)$$

Unlike the complete resonators, the field distributions of the higher order modes of this resonator construction are strongly distorted from that of the original ring-shaped resonator because of the existence of the two electric walls. $TM_{01\delta}$, $HE_{11\delta}$, and $EH_{11\delta}$ modes are not excited [10], and degenerated dual modes such as $HE_2$ and $EH_2$ should be single resonance modes as shown in Fig. 3. The spurious response of the Q.T.I.R. filter, therefore, can be expected to be far superior to the original $TE_{01\delta}$-mode filter.

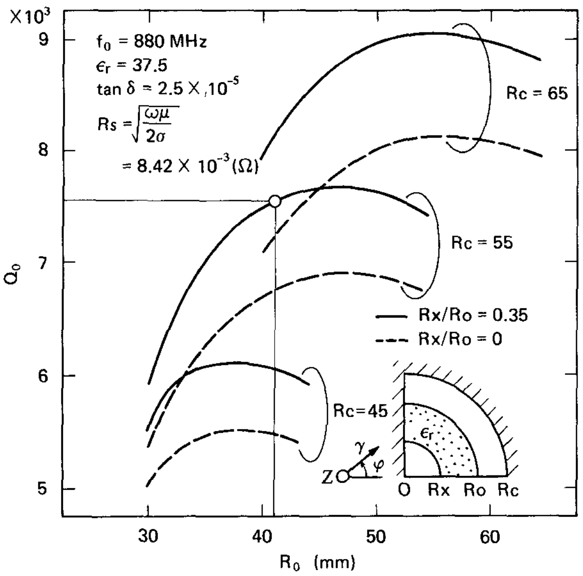


Fig. 4. Unloaded $Q$ of quarter-cut $TE_{01\delta}$ image resonator.

### D. Unloaded Q of Q.T.I.R.

The unloaded $Q$ analysis of the original $TE_{01\delta}$-mode resonator was also reported by Kobayashi [11]. However, in order to estimate the unloaded $Q$ of the Q.T.I.R., we must calculate the additional conductor losses on the two electric walls. The unloaded $Q$ of the Q.T.I.R. ($Q_0$) is given using the additional conductor losses ($1/Q'$) and the unloaded $Q$ of original $TE_{01\delta}$-mode resonator ($Q_{0\,\text{original}}$) as follows:

$$Q' = \frac{\pi \mu_0 \omega}{4Rs} \cdot \langle r \rangle \tag{2}$$

$$\frac{1}{Q_0} = \frac{1}{Q'} + \frac{1}{Q_{0\,\text{original}}} \tag{3}$$

where

$$\langle r \rangle = \frac{\int r H^2 \, dr \, dz}{\int H^2 \, dr \, dz}. \tag{4}$$

All construction parameters of the Q.T.I.R. are shown in Fig. 4.

The average extent $\langle r \rangle$ of the magnetic field ($H$) is calculated by the finite element method (F.E.M.) according to the definition in (4). The effect of the small inner radius ($Rx$) is to expand the $\langle r \rangle$, and the unloaded $Q$ ($Q_0$) increases as shown in Fig. 4. When the construction parameters are given, for example, as in the same figure, the theoretical and measured values of the unloaded $Q$ are 7500 and 7100, respectively.

## IV. Power Design

The most sensitive characteristics of the dielectric filter under high-power operation seem to be the temperature rise of the resonator and the third-order intermodulation. The dielectrics of the Q.T.I.R. are paraelectric material, and the polarization of this material has an almost linear response to the applied weak field. But the unharmonic

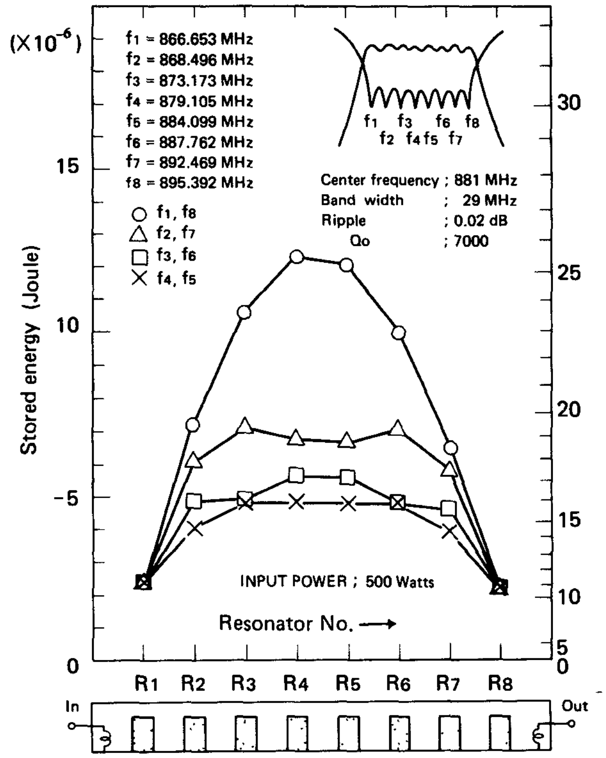


Fig. 5. Calculated stored energy and electric field intensity of each resonator.

characteristics of this material at the high-power microwave frequency have not been studied yet. Then the calculation of the maximum field intensity in the dielectrics of the resonator and the evaluation of the harmonic distortion are required for the design of Q.T.I.R. construction parameters.

### A. Stored Energy and Field Intensity

The electromagnetic energy stored in each resonator under high-power operation, as shown in Fig. 5, is obtained from the equivalent circuit. The F.E.M field analysis of the $TE_{01\delta}$-mode resonator gives electric field strength in the dielectrics of the resonator when the stored energy is known, as shown in the same figure.

The maximum value is calculated to be about 26 V/mm under 500-W operation when the input frequencies are $f_1$ and $f_8$ (band-edge frequencies) and the resonator numbers are the fourth and fifth (center positioned resonators).

### B. Intermodulation by Harmonic Distortion of the Q.T.I.R.

We developed an effective measurement system which evaluates the distortion level of the Q.T.I.R. using two relatively small RF power sources, as shown in Fig. 6(b). The coupled three-resonator system has three independent resonance modes, and each mode has a corresponding resonant frequency [12]. The theoretical field distribution of each mode of the Q.T.I.R. is shown in Fig. 6(a). Adjusting the coupling coefficient between resonators, the relation of these resonant frequencies becomes

$$f_C = 2f_B - f_A \qquad (f_C > f_B > f_A). \tag{5}$$

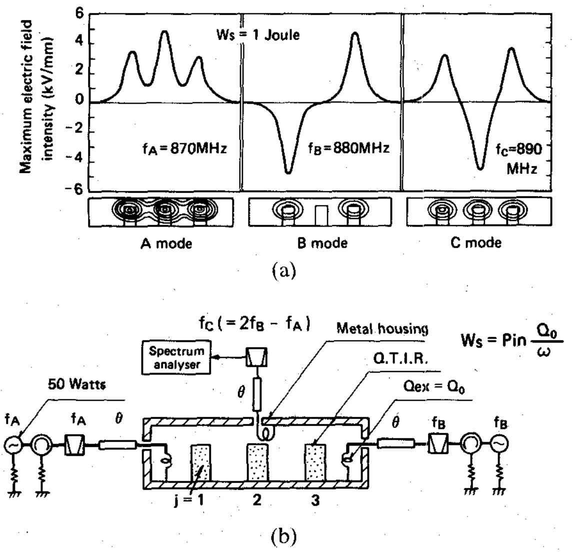


Fig. 6. The measurement method of the third-order intermodulation. (a) Calculated electromagnetic distribution of each mode. (b) Measurement system.

Then if the frequencies of the input power are $f_A$ (870 MHz) and $f_B$ (880 MHz), the third-order intermodulation power occurred in the first ($j=1$) and the third ($j=3$) resonators, and it is stored as a c-mode resonance field energy at the frequency of $f_C$ (890 MHz). The impedance matching between the RF power sources and the resonator system is easily obtained by the critical coupling method ($Q_0 = Q_{ex}$) at each frequency.

The stored energies in the three resonators are given by the following equation:

$$W_s^j = \frac{Q_0}{\omega} P_{\text{input}} \cdot \begin{bmatrix} 1/4 \\ 2/4 \end{bmatrix} \quad \begin{matrix} j=1,3 \\ j=2 \end{matrix} \tag{6}$$

where $j$ is the resonator number of the three-resonator system.

The field intensity in the dielectrics obtained by this measurement system is calculated to be 44 V/mm, which is equivalent to when the filter input power is 1.45 kW. This intensity is low enough for the Q.T.I.R. because the available field intensity of the paraelectric material is generally about a few kV/mm. The measured distortion level of the new dielectric resonator at the field intensity of 44 V/mm is less than −120 dB, as shown in Fig. 7.

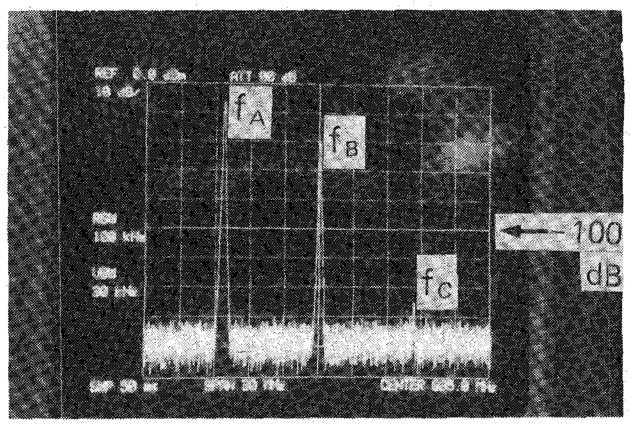


Fig. 7. The third-order intermodulation of Q.T.I.R.

### C. Temperature Rise of Q.T.I.R.

The thermal energy, which was caused by the dissipation factor of the dielectrics, flows to the electric walls, which work as heat sinks. Assuming that the thermal diffusion is due only to the thermal conductivity ($K$) of the ceramic dielectrics and assuming a magnetic wall model of the dielectric resonator, the stationary temperature is given by two-dimensional analysis. Thermal source $q(r_0, \varphi_0)$ is expressed by total RF loss power ($P_{\text{DLOSS}}$) and electric field distribution as follows:

$$q(r_0, \varphi_0) \simeq \frac{2 P_{\text{DLOSS}} J_1^2\left(u_{01} \dfrac{r_0}{R_0}\right)}{\pi L \displaystyle\int_{Rx}^{R_0} r J_1^2\left(u_{01} \dfrac{r}{R_0}\right) dr}, \qquad (u_{01} = 2.401). \tag{7}$$

The temperature distribution is given using the two-dimensional Green's function as follows:

$$\underset{(r<r_0)}{G^I(r,\varphi; r_0, \varphi_0)} = \frac{2}{K\pi} \sum_{n=1} \frac{\left[1+\left(\dfrac{r_0}{R_0}\right)^{4n}\right] \sin 2n\varphi \cdot \sin 2n\varphi_0}{n\left[1+\left(\dfrac{Rx}{r_0}\right)^{4n}\right]\left[2-\left(\dfrac{r_0}{R_0}\right)^{4n}-\left(\dfrac{Rx}{r_0}\right)^{4n}\right]} \cdot \left[\left(\frac{r}{r_0}\right)^{2n} + \left(\frac{Rx}{r_0}\right)^{4n}\left(\frac{r_0}{r}\right)^{2n}\right] \tag{8}$$

$$\underset{(r>r_0)}{G^{II}(r,\varphi; r_0, \varphi_0)} = \frac{2}{K\pi} \sum_{n=1} \frac{\sin 2n\varphi \cdot \sin 2n\varphi_0}{n\left[2-\left(\dfrac{r_0}{R_0}\right)^{4n}-\left(\dfrac{Rx}{r_0}\right)^{4n}\right]} \cdot \left[\left(\frac{r_0}{r}\right)^{2n} + \left(\frac{r_0}{R_0}\right)^{4n}\left(\frac{r}{r_0}\right)^{2n}\right] \tag{9}$$

$$\theta(r,\varphi) = \int_0^{\frac{\pi}{2}} \int_{Rx}^{r} G^{II}(r,\varphi; r_0,\varphi_0) q(r_0,\varphi_0) r_0 \, dr_0 \, d\varphi_0 + \int_0^{\frac{\pi}{2}} \int_r^{R_0} G^{I}(r,\varphi; r_0,\varphi_0) q(r_0,\varphi_0) r_0 \, dr_0 \, d\varphi_0. \tag{10}$$

The highest temperature point in the dielectrics is the center of the outer circumference; its calculation and experimental value are, respectively, 16 degrees and 20 degrees centigrade higher than the heat sink, as shown in Fig. 8. The insertion loss increase due to the temperature

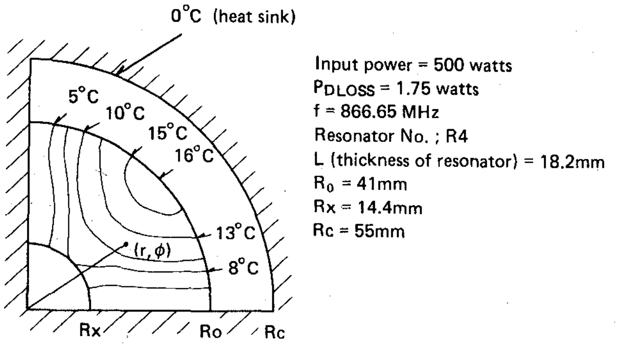


Fig. 8. Temperature distribution of quarter-cut $TE_{01\delta}$ image resonator.

TABLE III
PERFORMANCE OF THE FILTER

| | |
|---|---|
| Center frequency ($f_0$) | 880 MHz |
| Bandwidth (BW) | 20 MHz |
| Attenuation ($f_0$- 35MHz) | 95 dB |
| Insertion loss (BW) | 0.37 dB |
| VSWR | 1.37 |
| Size | 280 X 135 X 65mm (2460cc) |

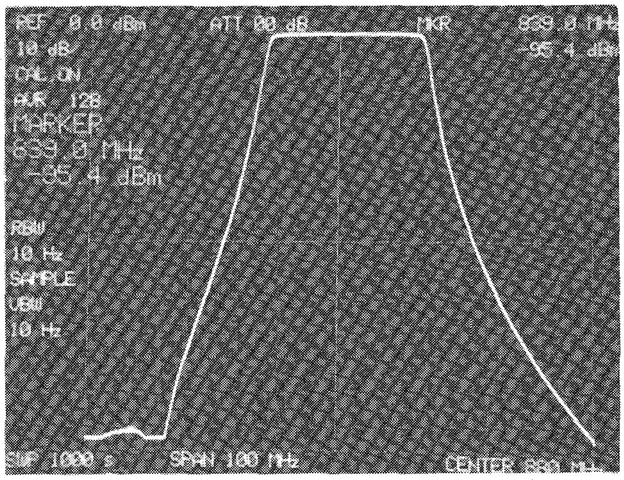


Fig. 9. Attenuation characteristics.

rise of the dielectrics of the filter under 500-W RF power operation should be about 0.03 dB.

## V. Performance

The performance of this filter is shown in Table III. This performance sufficiently satisfies the required characteristics shown in Table I. Measured value of insertion loss at the center frequency is 0.28 dB. Of this, 0.03 dB is due to the two type-N female connectors. The resultant 0.25 dB loss corresponds to the unloaded $Q$ of the Q.T.I.R. Then the mean value of the unloaded $Q$ ($Q_0 = 7000$) is estimated by Cohn's formula [13]. High attenuation of about 95 dB at the receiving side is obtained by the elliptic function type filter design shown in Fig. 9. The spurious response of the Q.T.I.R. filter is shown in Fig. 10. $TM_{01\delta}$, $HE_{11\delta}$, and $EH_{11\delta}$ modes are completely suppressed, as we expected.

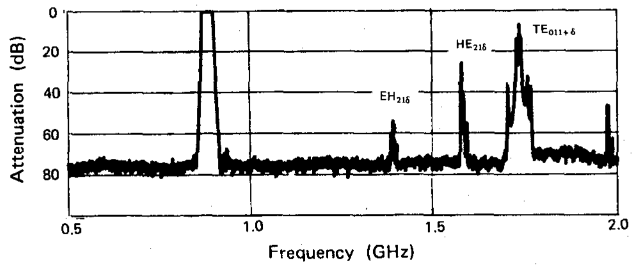


Fig. 10. Spurious response characteristics.

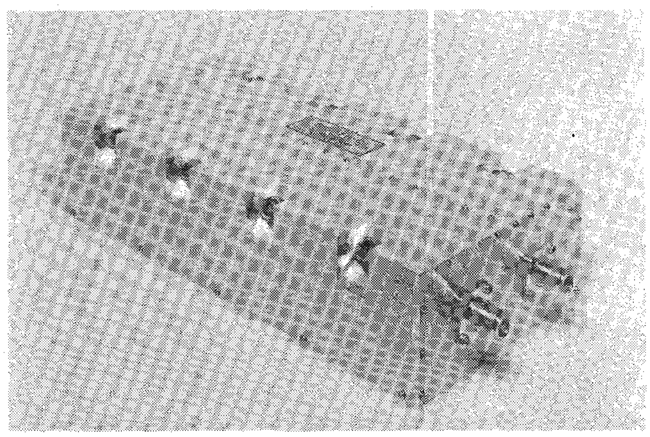

Fig. 11. Outside view of quarter-cut $TE_{01\delta}$ image resonator filter.

## VI. Conclusions

An 800-MHz-band dielectric high-power bandpass filter with 20-MHz bandwidth using quarter-cut $TE_{01}\delta$ image resonators has been developed. Low insertion loss of 0.37 dB is obtained by a high unloaded $Q$ of 7100, and high attenuation of 95 dB is obtained by an eight-pole elliptic function type filter design. Stable power characteristics of the filter are guaranteed by the new measurement method for evaluating the harmonic distortion (under $-120$ dB) of the dielectric resonator and by the thermal design of the dielectric resonator construction. The temperature rise of dielectrics from the metal housing at 500-W power operation is suppressed under 20 degrees centigrade because of the existence of a good thermal diffusion path of the Q.T.I.R. The dimensions of the filter are $280 \times 135 \times 65$ mm, about one third to one fifth the size of conventional cavity resonator filters. This is expected to be applicable to 800-MHz use in cellular base stations.

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Dr. Wakino received the Award of Invention from the Japan Institute of Invention and Innovation in 1971, the Award of Engineering from the Japanese Ceramic Society in 1978, and the Award of Engineering Progress from the Japan Society of Powder and Powder Metallurgy in 1984. Holder of 10 U.S. patents, he has written over 86 technical papers. Dr. Wakino is a fellow of the American Ceramic Society and a member of Institute of Electronics, Information and Communication Engineers, and the Institute of Electrical Engineers of Japan.

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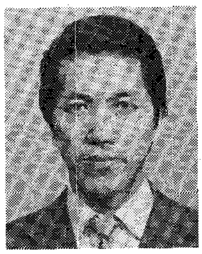

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