A Bandpass Filter Using Electrically Coupled $TM_{01\delta}$ Dielctric Rod Resonators

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ABSTRACT

A compact bandpass filter having Chebyshev, low-loss and good spurious response is constructed by placing high-Q $TM_{01\delta}$ dielectric rod resonators coaxially in a TM_{01} cutoff circular waveguide. A precise design of the high-Q resonators and interresonator coupling is performed by the mode matching technique. The interresonator coupling is equivalently expressed by a capacitively coupled LC resonant circuit.

INTRODUCTION

Dielectric resonators with various resonant modes are used to construct compact filters. However, investigations for filters using only the $TM_{01\delta}$ mode of dielectric resonators are little presented so far [1][2].

In this paper a design and characteristics are discussed about a Chebyshev bandpass filter constructed by placing $TM_{01\delta}$ dielectric rod resonators coaxially in a TM_{01} cutoff circular waveguide. A rigorous analysis of the interresonator coupling and a precise design of the high-Q $TM_{01\delta}$ resonators are performed by the mode matching technique in a similar way to the $TE_{01\delta}$ case [3]. Some discussions verify that the interresonator coupling for this case is equivalently expressed by a capacitively coupled LC resonant circuit. This is in contrast with the inductively coupled case for the $TE_{01\delta}$ mode [3][4]. A four-stage Chebyshev filter having ripple of 0.035dB and equiripple bandwidth of 27 MHz at the center frequency of 11.958 GHz is fabricated using these resonators. This filter has lowloss and good spurious characteristics.

ANALYSIS

The geometry of coupled resonators to be analyzed is shown in Fig. 1. Two dielectric rod resonators having relative permittivity ε_r, diameter D, and length L are supported coaxially in a cutoff circular waveguide of diameter D with dielectric rings of relative permittivity $\varepsilon_b(<\varepsilon_r)$. The space between the rods is 2M. It is assumed that TM_{01} mode in the circular waveguide is evanescent; that is, $\pi f_0 d/c < 2.405$, where c is the light velocity in vacuum. As discussed later, the coupling coefficient of coupled $TM_{01\delta}$ dielectric resonators k is given by

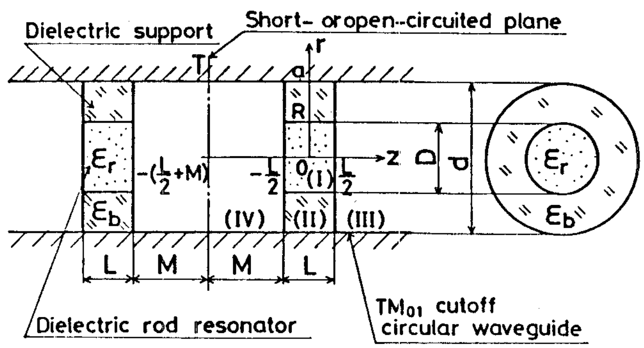

Fig. 1. Coupled dielectric rod resonators.

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

where f_{op} and f_{sh} correspond to the resonant frequencies when the structurally symmetric plane T shown in Fig.1 is open- and short-circuited, respectively. As the analysis by the mode matching technique, these resonant frequencies are calculated from the roots of the following equation:

$$\det H\ (f;\ \varepsilon_r,\ \varepsilon_b,\ d,\ D,\ L,\ M)=0 \tag{2}$$

where the matrix elements are omitted. Putting $M=\infty$ in (2), we can calculate resonant frequencies for a single resonator. Furthermore, the unloaded Q (Q_u) of the $TM_{01\delta}$ mode is given by

$$\frac{1}{Q_u}=\frac{1}{Q_d}+\frac{1}{Q_{db}}+\frac{1}{Q_c} \tag{3}$$

where Q_d and Q_{db} are Q-factors due to the dielectric rod and support loss, respectively, and can be calculated from (2) by the frequency perturbation technique [5]. Also, Q_c is one due to the conductor loss, and can be calculated from the stored energy and the conductor loss for the structure shown in Fig.2 [6]. In a similar way to

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the $TE_{01\delta}$ case [3], we can also calculate the temperature coefficient of the resonant frequency τ_f.

DESIGN OF $TM_{01\delta}$ DIELECTRIC ROD RESONATOR

The $TM_{01\delta}$ resonators used in this filter structure were fabricated from low-loss ceramics $Ba(SnMgTa)O_3$ (ε_r=24, tan δ=4×10^{-5} at 12 GHz, Ube Industries, Ltd.), polystyrene foam supports (ε_b= 1.031, tan δ_b=4×10^{-5}), and copper-plated brass (the conductivity $\sigma=\bar{\sigma}\sigma_0$; $\bar{\sigma}$=0.9, σ_0=58×10^6 S/m). High Q design of these resonators was performed as described below.

Define the resonant frequency ratio F_r by F_r=f_r/f_0, where f_0 is one of the interested mode and f_r of the neibouring mode. The design of the $TE_{01\delta}$ ring resonator has been already performed to obtain the highest Q_u value as F_r=1.14 is kept constant [3], which is the maximum F_r value calculated for the $TE_{01\delta}$ rod resonator when ε_r = 24. A similar design was performed for the $TM_{01\delta}$ rod resonator. Fig.3 shows the mode charts calculated around the optimum values S^0=1.5 and X^0=1.8

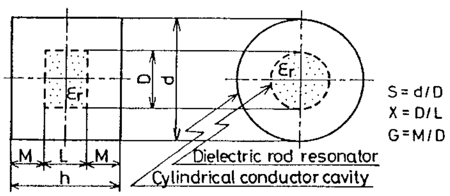

Fig. 2. Dielectric rod resonator in cavity

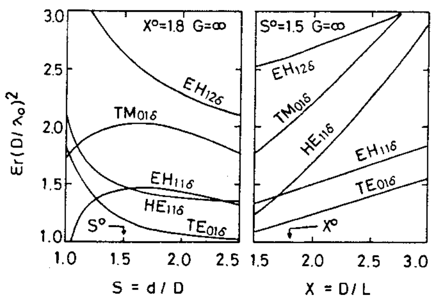

Fig. 3. Mode charts for a dielectric rod resonator in the case of ε_r=24.

Table 1. Calculated Q_u values of the $TM_{01\delta}$ rod and $TE_{01\delta}$ ring resonators with F_r = 1.14 when f_0=11.958GHz, ε_r=24, tanδ=4×10^{-5}, ε_b=1.031, tanδ_b=4×10^{-5}, and $\bar{\sigma}$=0.9.

Mode	Q d	Q db	Q c	Q u
$TM_{01\delta}$ Rod*1	31,000	610,000	100,000	23,000
$TE_{01\delta}$ Ring*2	26,000	1,000,000	97,000	20,000

*1 D=7.27mm, Dx=0mm, L=4.04mm, d=10.90mm

*2 D=4.94mm, Dx=1.48mm, L=3.63mm, d=11.80mm

indicated by arrows. Table 1 shows the comparison of the results calculated at f_0=11.958 GHz. The Q_d value for the $TM_{01\delta}$ resonator is higher than the $TE_{01\delta}$ case because the electric field energy stored inside the dielectric is less than the $TE_{01\delta}$ case. The measured results are Q_u = 21000 for the $TM_{01\delta}$ resonator and Q_u=18000 for the $TE_{01\delta}$ resonator. As a result, the $TM_{01\delta}$ resonator realizes a higher Q_u value compared with the $TE_{01\delta}$ resonator.

In addition, the temperature characteristic of the resonant frequency for this $TM_{01\delta}$ resonator is excellent: that is, the calculated τ_f value is τ_f= -0.2±0.4 ppm/°C while the measured results is τ_f= 0.3±0.3 ppm/°C.

INTERRESONATOR COUPLING COEFFICIENT

For the coupled $TM_{01\delta}$ resonators, the calculated and measured results of f_{sh}, f_{op}, and k are shown in Fig. 4. These measured values agree with the theoretical curves to within 0.4, 0.4, and 2 percents, respectively. The calculated

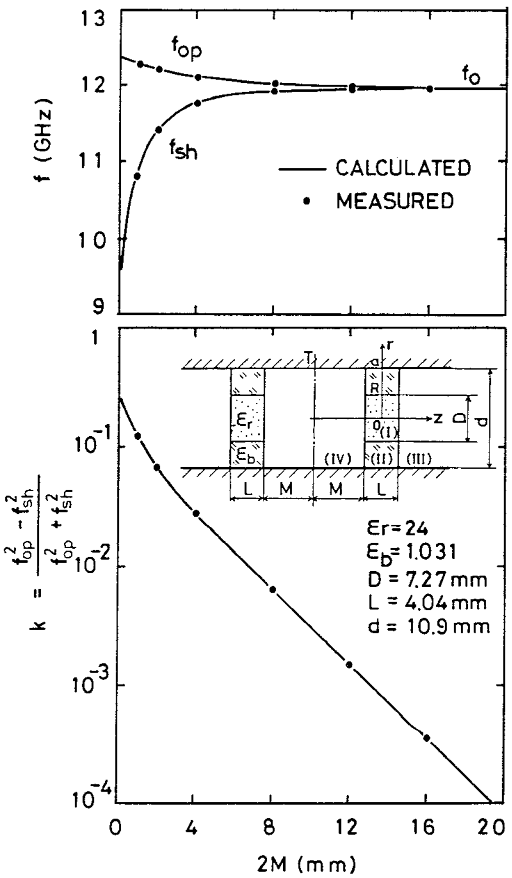

Fig. 4. Calculated and measured results of f_{sh}, f_{op}, and k versus 2M for coupled $TM_{01\delta}$ rod resonators.

result shows $f_{op} > f_{sh}$, which is in contrast with the usual inductively coupled case for the $TE_{01\delta}$ mode; namely, $f_{sh} > f_{op}$. This fact is not considered in the paper presented by Zaki and Chen [4]. Then we consider a capacitively coupled LC resonant circuit shown in Fig.5(a). Fig.5(b) shows this equivalent circuit, where f_{op} and f_{sh} are the resonant frequencies when the symmetric plane T is open- and short-circuited, respectively. Fig.5(c) shows the result calculated from Fig.5(b). It is seen from Fig.5(c) that $f_{op} > f_{sh}$, which is in accordance with the case of the coupled $TM_{01\delta}$ resonators. But, this circuit is still incomplete because $f_{op} > f_0$ for the coupled resonators. In order to improve this, we modify this circuit into one shown in Fig.6(a). This equivalent circuit is shown in Fig.6(b). The constant a is determined so that the f_{op} and f_{sh} values of the equivalent circuit fit with ones for the coupled dielectric $TM_{01\delta}$ resonators. Fig.6(c) shows the calculated results for a=0.6; thus, this equivalent circuit is more suitable than the one given in Fig.5.

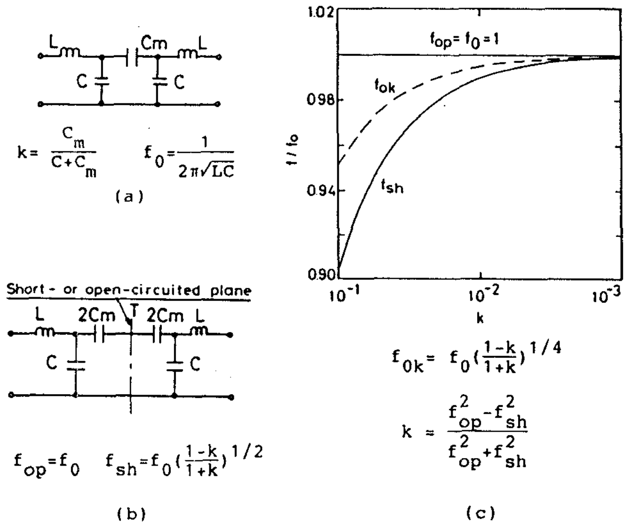

Fig. 5. Capacitively coupled LC resonant circuit.

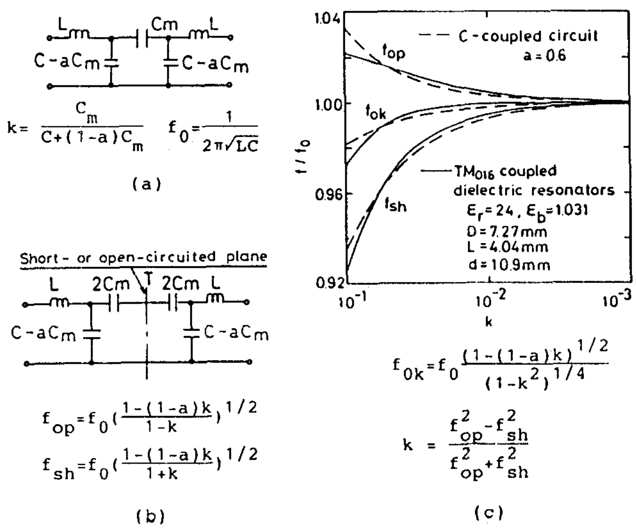

Fig. 6. Modified C-coupled LC resonant circuit.

As a result, two dielectric resonators placed in a cutoff waveguide couple electrically each other when the dominant evanescent waveguide mode is the TM mode, while they couple magnetically when the dominant evanescent mode is the TE mode.

The difference between the center frequency $f_{0k} = \sqrt{f_{sh} \cdot f_{op}}$ and f_0 is within 0.02 percent when $k < 6\times10^{-3}$, so that it can be neglected in narrow bandwidth filter design as the present case. But f_{0k} should be considered for wide bandwidth filter design.

FILTER DESIGN

Fig. 7 shows a structure of a four-stage band-pass filter actually constructed. Three brass rings are precisely machined with the designed dimensions and are copper-plated. This structure eliminates the need for k adjustment screws, because the 2M values can be determined precisely from the calculation. The resonant frequencies for the resonators are each adjusted with tuning dielectric-screws. The first and fourth resonators are each excited by monopole antennas. Fig. 8 shows the measured results for the resonant frequency f_{0e} and the external Q (Q_e) versus the distance between the monopole and the resonator l_d in three cases of the monopole length l_p. The case of l_p=6.6mm is the most suitable for the filter design, because we can adjust Q_e value as the resonant frequency is invariant at $f_{0e}=f_0$.

In consideration of the application to a Japanese broadcasting satellite [7], the specifications of the Chebyshev filter are as follows: center frequency of 11.958 GHz (ch. 13), 15 dB bandwidth of 50 MHz, equiripple bandwidth of 27 MHz, and ripple of 0.035 dB. Following to the reference [8], we obtain the design values $k_{12}=k_{34}=2.1\times10^{-3}$, $k_{23}=1.6\times10^{-3}$, and Q_e=390.

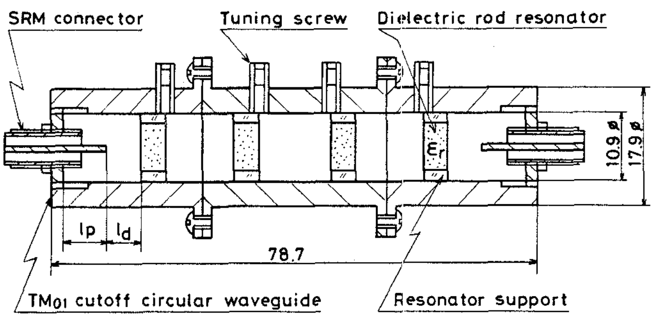

Fig. 7. Cross-sectional view of a four-stage dielectric rod resonator filter.

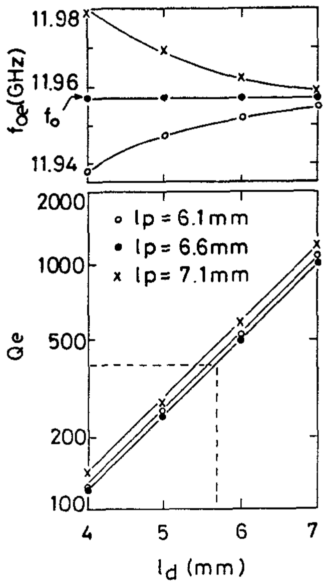

Fig. 8. Measured result for the resonator excited by monopole antenna in Fig.7

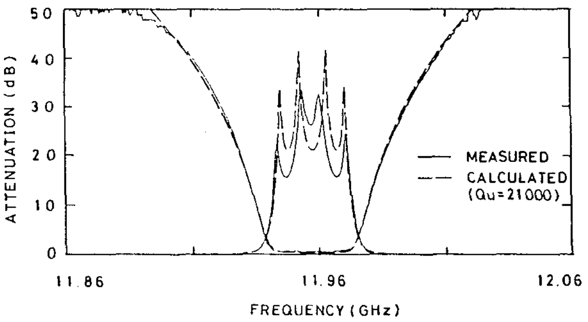

Fig. 9. Transmission and reflection responses of the four-stage Chebyschev bandpass filter.

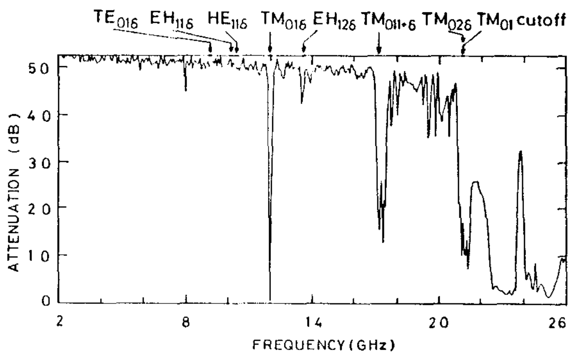

Fig. 10. Wideband response of the filter.

The transmission and reflection responses are shown in Fig. 9. The agreement between experiment and theory is good. The measured value Q_u = 21000 gives a midband insertion loss of 0.4 dB, while the measured insertion loss of 0.5 dB corresponds to Q_u =18000. This Q_u degradation is due to the conductor loss of the coupling structure. The measured wideband response is shown in Fig. 10. The resonant modes for the single resonator calculated are indicated on the top of the figure. The good spurious response was obtained because the excitation of the resonant modes except the TM_0 modes were suppressed by the present monopole antennas exitation.

CONCLUSIONS

In conclusion, a compact bandpass filter having lowloss and good spurious characteristics was realized using high Q $TM_{01\delta}$ dielectric rod resonators. Filters of this kind are also useful as waveguide filters.

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