ELLIPTIC BANDPASS FILTERS USING FOUR TM_{010} DIELECTRIC ROD RESONATORS

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ABSTRACT

Compact elliptic bandpass filters of three types are constructed by using four TM_{010} dielectric rod resonators. Filters designed have center frequencies of 3 to 5 GHz, relative bandwidths of 2 to 13 percent, insertion losses of 0.3 to 1.6 dB, and minimum stopband attenuations of 40 to 52 dB.

INTRODUCTION

Compact bandpass filters are constructed using $TE_{01\delta}$- or hybrid-mode dielectric resonators in the microwave region [1]-[3]. In so far as these modes are used, however, it is difficult to obtain the filters having relative bandwidth of 5 percent or more because of the poor separation from other resonances. Then, one of the authors has proposed maximally-flat bandpass filters using TM_{010} mode dielectric resonators [4]-[6]. They enable us to realize no spurious response in an octave band and relative bandwidth of 10 percent or more.

In order to realize sharper skirt characteristics of these filters, this paper discusses three types of elliptic bandpass filters constructed by using the same resonators. These filter designs are performed following Williams' procedure [7].

FILTER STRUCTURES

Fig. 1 shows a fundamental configuration of a TM_{010} dielectric rod resonator and its field plot. Here, a dielectric rod of relative permittivity ε_r, diameter D, and length L is placed in a conductor cavity of diameter d_0 along the axis. The resonant

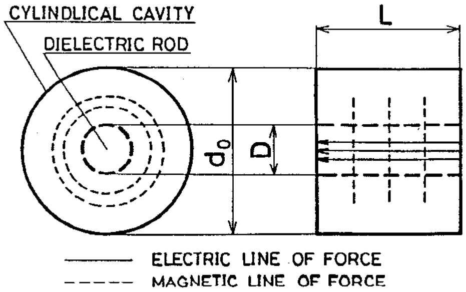

Fig. 1. A TM_{010} dielectric rod resonator and its field plots.

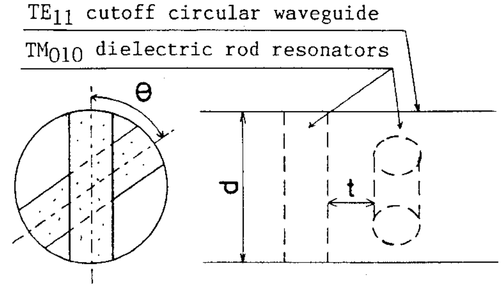

Fig. 2. Coupled TM_{010} resonators arranged transversely in a TE_{11} cutoff circular waveguide.

frequency of this dominant TM_{010} mode is independent of the length L and the oputimum dimensions can be designed to offer the best separation from the next higher order modes [5]. Fig. 2 shows coupled TM_{010} resonators arranged transversely in a TE_{11} cutoff circular waveguide of diameter d. Arbitrary cross-sectional shape of the dielectric rods and waveguide may be used except circular. Let t be the space between two rods. According as the angle θ made by two rod axes, we consider the following structures of three types:

(a) In the case of θ=0° (in-line structure), the strength of inter-resonator coupling is adjusted by d and t.

(b) In the case of θ=90° (right-angle structure), the small space t is permitted since one resonance is orthogonal to the other. But the too small space t should be avoided because the next higher order mode goes down and approaches to the TM_{010} mode. The inter-resonator coupling can be achieved by a conductor or dielectric screw positioned along an axis 45° from each of the rod axes.

(c) In the case of 0°<θ<90° (acute-angle structure) the coupling strength depends on d, t, and θ. This structure is available to realize the wider bandwidth, because its coupling is stronger than the screw coupling for the right-angle case.

On the basis of three cases described above, four-stage elliptic bandpass filters of three types were fabricated from $(Zr{\cdot}Sn)TiO_4$ ceramics of $\varepsilon_r \simeq 38$ (Murata Mfg. Co., Ltd.) and copper-plated brass. Their constructions are shown in Fig. 3. OSM connectors were used commonly for the input and output excitations. Let Ri be the i'th resonator, k_{ij} be the coupling coefficient between Ri and Rj, and t(ij) be the space between Ri and Rj.

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In-line structure

Fig. 3(a) shows the in-line structure, which is suitable for constituting canonical bandpass filters. Four circular rod resonators (R1 to R4) are positioned transversely in two parallel TE_{10} cutoff rectangular waveguides. Each of R1 and R4 is excited by a probe. Coupling between R2 and R3 is achieved by a circular hole in the waveguide side wall. Inverse coupling between R1 and R4 is realized by a S-curved loop in shape.

Right-angle structure

Fig. 3(b) shows the right-angle structure, which is shorter in length than the in-line one. Square rod resonators R2 and R3 are positioned perpendicularly to similar ones R1 and R4. Each of R1 and R4 is excited by a dipole. A conductor screw for k_{12} and another one for k_{34} are at right angles to each other to realize the negative value k_{14}. The magnitudes of k_{23} and k_{14} can be determined independently by designing t(23), t(14), and width W_1 and height W_2 of the cutoff waveguide.

Acute-angle structure

Fig. 3(c) shows the acute-angle structure. Each of R1 and R4 is excited by a probe. The R2 axis is positioned clockwise at θ° to the R1 axis, the R3 axis is similarly at 90°−θ° to the R2 axis, and the R4 axis is moreover at θ° to the R3 axis. Then, $k_{13}=k_{24}=0$, because the R1 and R3 axes as well as the R2 and R4 axes are at right angles to each other. The negative value k_{14} can be realized automatically, since the R1 and R4 axes make an angle of 90°+θ°.

In this structure, k_{12}, k_{23}, and k_{14} depend on θ one another; so they can not be determined independently. Then, we shall determine the necessary values θ, t(12), and t(23) from simultaneous equations for k_{12}, k_{23}, and k_{14}. At first, two separate resonant frequencies f_1 and f_2 versus t were measured for the coupled resonators as shown in Fig. 2 for θ=0. The coupling coefficient can be obtained from

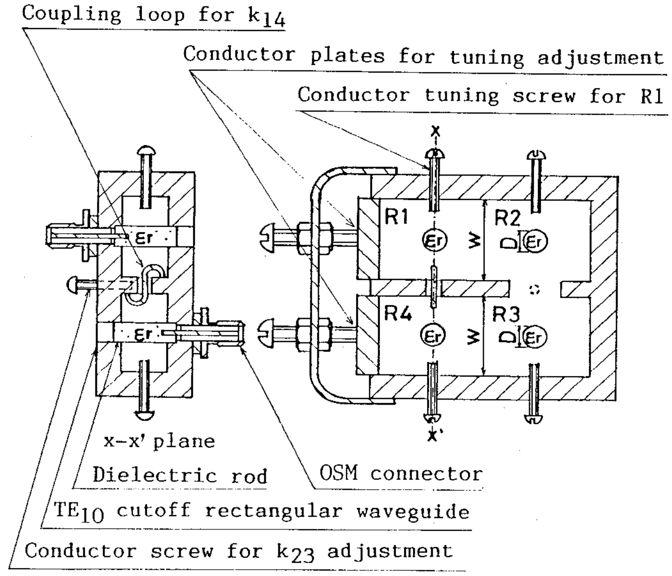
$$k=2(f_1-f_2)/(f_1+f_2). \quad (1)$$

These results are shown in Fig. 4(a) by the open dots. Then, we assume that the following exponential relationship between k and t holds:

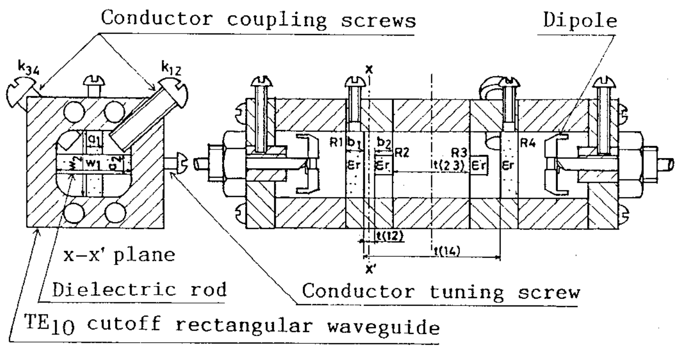
$$k=A10^{-Bt} \quad (2)$$

where A=0.344 and B=0.113, which are determined from the measured values in Fig. 4(a) by the least squares method. Equation (2) is illustrated in Fig. 4(a) by the solid line A. In addition, when R2 is placed perpendicularly between R1 and R4, a similar result are indicated in Fig. 4(a) by the solid line B. In this case, we replace t in (2) by t=t(14)−Δt where Δt=1.0 mm. Furthermore, the experimental results of the normalized coupling coefficient k_θ/k versus θ with t constant are shown in Fig. 4(b) by the open dots. Then we assume that the cosine relationship between k and θ holds. Thus, the coupling coefficients are given by

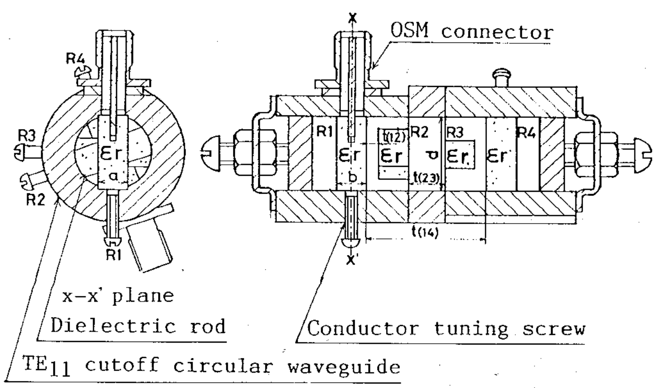
$$k_{12}=k_{34}= A\ 10^{-Bt(12)}\cos\theta \quad (3)$$



(a) In-line structure

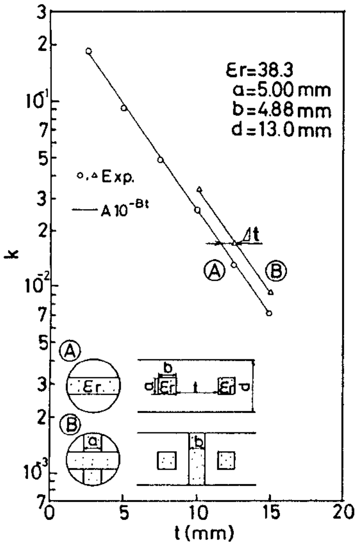


(b) Right-angle structure

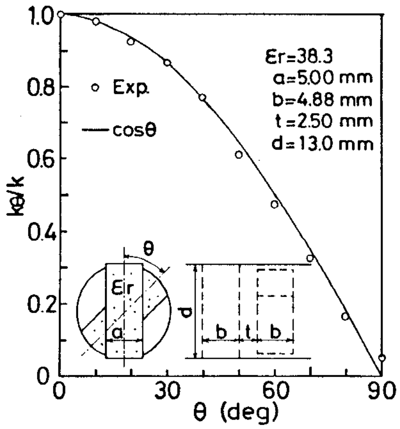


(c) Acute-angle structure

Fig. 3. Three structures of elliptic bandpass filters using four TM_{010} dielectric rod resonators.

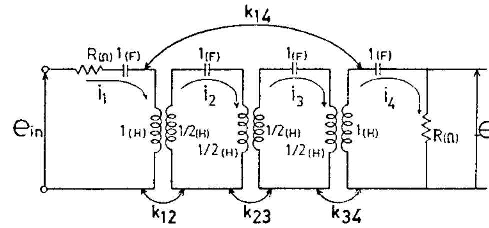


(a) k versus t.

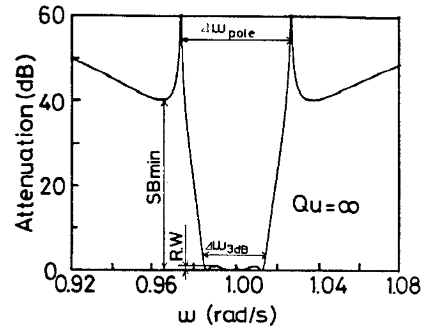


(b) k versus θ.

Fig. 4. Experimental results of coupling coefficient between coupled resonators in a circular cutoff waveguide.



(a) Equivalant circuit.



(b) Frequency response.

Fig. 5. The equivalent circuit and its frequency response.

$$k_{23} = A\ 10^{-Bt(23)}\cos(90-\theta)$$
$$= A\ 10^{-Bt(23)}\sin\theta \qquad (4)$$

$$k_{14} = A\ 10^{-Bt(14)'}\cos(90+\theta)$$
$$= -A\ 10^{-Bt(14)'}\sin\theta \qquad (5)$$

where $t(14)' = t(14) - 2\Delta t = 2t(12) + 2b + t(23) - 2\Delta t$ since R2 and R3 are placed between R1 and R4. Then we solve the simultaneous equations (3), (4), and (5) for three unknowns θ, $t(12)$, and $t(23)$; that is,

$$\theta = \cos^{-1}\left(\frac{k_{12}}{A}\sqrt{\frac{k_{23}}{-k_{14}}}\ 10^{-B(b-\Delta t)}\right)$$

$$t(12) = \frac{1}{B}\log\left(\frac{A\cos\theta}{k_{12}}\right) \qquad (6)$$

$$t(23) = \frac{1}{B}\log\left(\frac{A\sin\theta}{k_{23}}\right)$$

Thus, giving the design values k_{12}, k_{23}, and k_{14}, we can determine the necessary values θ, $t(12)$, and $t(23)$ from (6).

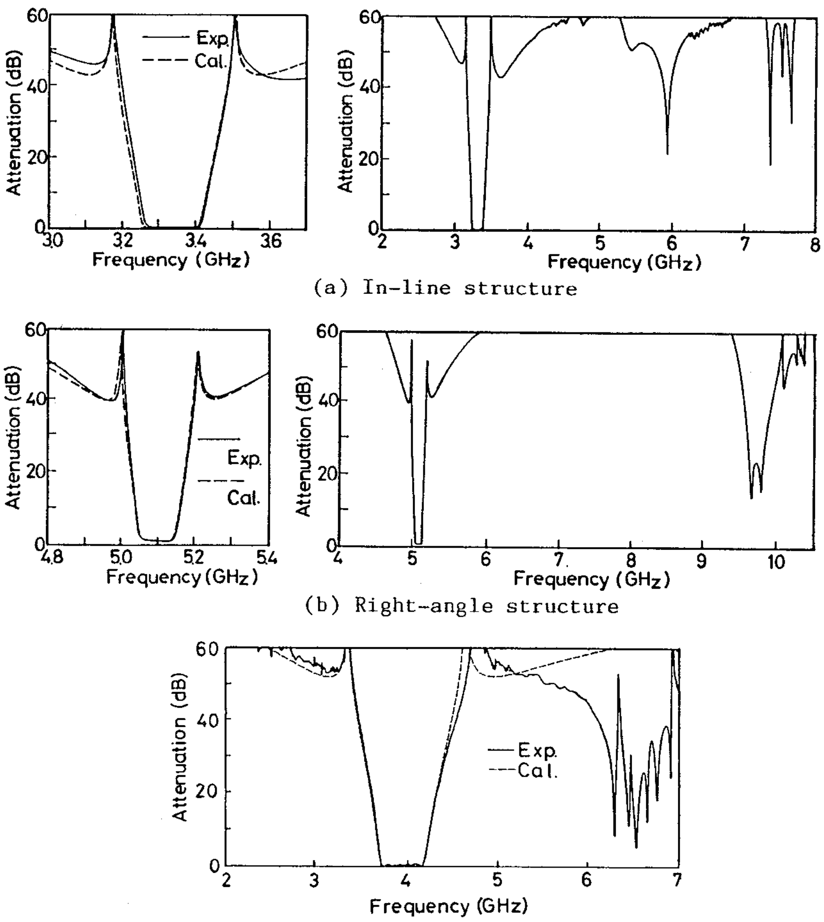
EXPERIMENTAL RESULTS

Fig. 5 shows an equivalent circuit of a four stage elliptic bandpass filter and its frequency response. Following Williams' procedure for the filter design [7], we can determine the necessary values of k and Q_e (external Q) from given values of center frequency f_0, 3 dB bandwidth Δf_{3dB}, pole bandwidth Δf_{pole}, and minimum stopband attenuation SB_{min} (or ripple width RW). The design specification of three filters described above is shown in Table 1.

Table 1. Design specifications.

Filter structures	In-line structure	Right-angle structure	Acute-angle structure
f_0 (GHz)	3.33	5.10	3.94
$\Delta f_{3dB}/f_0$ (%)	4.87	2.00	12.7
$\Delta f_{pole}/f_0$ (%)	9.93	4.00	33.0
SBmin (dB)	43.0	40.0	52.0
RW (dB)	0.03	0.08	0.23
$k_{12}=k_{34}$ ($\times 10^{-2}$)	3.20	1.41	8.45
k_{23} ($\times 10^{-2}$)	3.01	1.21	7.45
k_{14} ($\times 10^{-3}$)	-3.44	-1.65	-5.23
Qe [=1/R]	26.8	55.6	10.0

The experimental results of frequency response for these filters are shown in Fig. 6 by the solid lines; the calculated values are indicated by the broken lines. The experimental results agree very well with the calculated ones. The measured insertion losses for Fig. 6 (a), (b), and (c) are 0.6, 1.6, and 0.3 dB, respectively, which correpond to the unloaded Q about 900. The spurious responses, which appear near 7.5, 9.8, and 6.4 GHz for Fig. 6(a), (b), and (c), respectively, are due to the next higher order modes TM_{120} and TM_{210} in the Cartesian coordinate. It was verified experimentally that another spurious response near 6 GHz in Fig. 6(a) is due to a half-wavelength resonance of the S-curved loop shown in Fig. 3(a).



(c) Acute-angle structure

Fig. 6. Calculated and experimental results of frequency response for three structures of the elliptic bandpass filters.

CONCLUSION

In conclusion, elliptic bandpass filters using TM_{010} dielectric rod resonators permit us to realize sharp skirt characteristics and relative bandwidth of 10 percent or more because of the good separation from other resonances. It is anticipated that the frequency responses of the filters constructed are affected remarkably by temperature, because of variation of air gap at dielectric-to-conductor interface with temperature. This problem will be overcome by fabricating filters from materials with the same thermal expansion coefficients, as proposed by Nishikawa, et al. [8].

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