A Direct-Coupled $\lambda/4$-Coaxial Resonator Bandpass Filter for Land Mobile Communications

KAZUNORI HANO, HIROAKI KOHRIYAMA, AND KEN-ICHI SAWAMOTO

***Abstract*—A bandpass filter operating at 870 MHz was constructed using $\lambda/4$-coaxial resonators. The resonators were made of metallized high-Q dielectric ceramic ($Q \geqslant 10\,000$, $\epsilon_r = 37$), and were directly coupled to each other through apertures which were formed on the outer side surface of the resonators. In order to couple the input and output resonators to the external circuit, a rectangular metal film was deposited on the open-circuit end. The resonant frequency of each resonator, coupling coefficients between adjacent resonators, and external Q's at both ends were adjusted before assembly. The resonators were then assembled in a housing with no further adjustment. The measured response was in excellent agreement with the theory.**

I. Introduction

SIZE REDUCTION OF electronic circuits is in progress with the development of recent semiconductor technologies. Microwave filters occupy a large volume in radio equipment, especially in land mobile communication. Surface acoustic wave (SAW) filters can be used to reduce the size, although power handling and insertion loss may limit their practical use. In another approach, high-Q dielectric ceramics resonators with high-dielectric constant and small temperature coefficient may be used [1].

A compact bandpass filter was constructed by Fukazawa [2], by arranging resonant elements in a housing with narrow air spaces between the elements. In a bandpass filter which was constructed by Sugawara *et al.* [3], coupling capacitors fabricated on a dielectric substrate were used as coupling elements between the adjacent resonators.

As described in this paper, a bandpass filter operating at 870 MHz was constructed utilizing $\lambda/4$-coaxial resonators made of high-Q dielectric ceramics ($Q \geqslant 10\,000$, $\epsilon_r = 37$). The design method used here is based on one for mechanical filters [4]. Coupling between adjacent resonators was obtained via apertures which are formed on the outer side surfaces of the resonators. For the input or output coupling, a rectangular metal film was deposited on the open-circuit end of the $\lambda/4$-resonator. The resonant frequency of each resonator, coupling coefficients between adjacent resonators, and external Q's at input and output stages were adjusted so as to produce the desired filter response before assembly. It is sufficient to assemble these resonators in a housing with no further adjustment. This method may be appropriate to mass production of bandpass filters.

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II. Coupling of Two Resonators and of a Resonator to External Circuit

A bandpass filter can be designed using coupling coefficients $k_{i,i+1}$ and external Q (Q_e). They are given as

$$k_{i,i+1} = (\mathrm{BW}/f_0)/\sqrt{g_i g_{i+1}} \tag{1}$$

$$Q_e = (f_0/\mathrm{BW}) \cdot g_0 g_1 \tag{2}$$

where f_0 and BW are the center frequency and the 3-dB bandwidth of the bandpass filter, respectively, and g_i ($i = 0, 1, 2, \cdots$) are the prototype elements, and are prescribed for a desired filter response [5]. In the following discussion, the unloaded quality factor Q_u of the resonators is assumed to be infinite.

A. Coupling Between Two Resonators

Each resonator was constructed from a cylindrical ring made of high-Q dielectric ceramic ($Q \geqslant 10\,000$, dielectric constant $\epsilon_r = 37$), with outer and inner diameters of 10 mm and 2.6 mm, respectively, and length of about $\lambda/4$ at frequency f_0, where λ is a wavelength of electromagnetic plane waves in the medium. Two flat and parallel sides were formed by shaving the outer side surface of the cylindrical ring. By metallizing all surfaces of the shaved ring except one end surface, a $\lambda/4$-coaxial resonator was produced. This end surface is an open-circuit surface, and the opposite end surface is a short-circuit surface. The resonant frequency of the $\lambda/4$-resonator was turned to f_{r0} ($= f_0$). On one of the two flat sides, an aperture ($w \times l$: w = width, l = length measured from the short-circuit surface or open-circuit surface) was formed by removing metal with selective etching techniques. Resonators with matching apertures were coupled by making one resonator come into contact with the other as shown in Fig. 1. The coupling methods in Fig. 1 (a) and (b) are referred to as L-coupling and C-coupling, respectively.

In the over-coupled state (very light input and output coupling), the two observed resonant frequencies f_1 and f_2, coupling coefficient k, midfrequency f_m between f_1 and f_2, and frequency shift η_k of midfrequency are de-

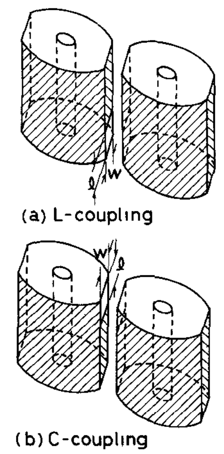


Fig. 1. Two λ/4-coaxial resonators coupled through apertures. The inner and outer side surfaces and the bottom surface of each resonator are metallized. The aperture ($w \times l$) is located near (a) the short-circuit surface or (b) the open-circuit surface. $w = 5.0 \pm .02$ [mm].

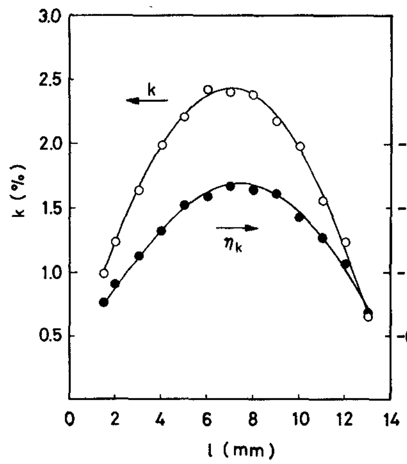


Fig. 2. Relationship between coupling coefficient k or frequency shift η_k and aperture length l (L-coupling).

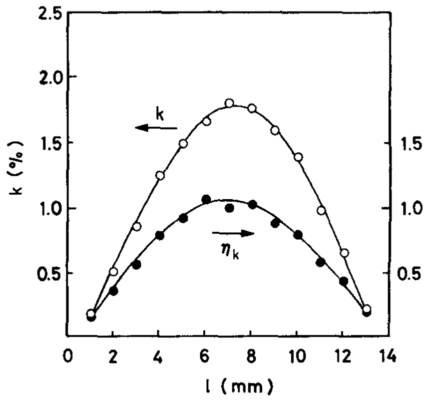


Fig. 3. Relationship between coupling coefficient k of frequency shift η_k and aperture length l (C-coupling).

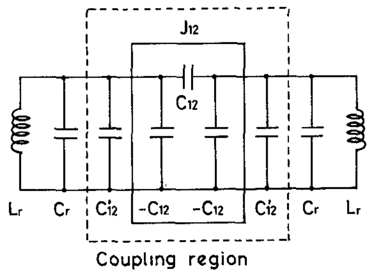


Fig. 4. Equivalent circuit of two resonators coupled through apertures. A parallel circuit of L_r and C_r represents a λ/4-resonator. J_{12} $(=\omega C_{12})$ stands for an admittance inverter. C_{12}' is a representative of mid-frequency shift. The area bounded by broken lines indicates the coupling region of two resonators.

fined as follows:

$$k = |f_2 - f_1| / f_m \tag{3}$$

$$f_m = (f_1 + f_2)/2 \tag{4}$$

$$\eta_k = (f_m - f_{r0})/f_{r0}. \tag{5}$$

The frequencies f_1 and f_2 were measured for various aperture lengths with a network analyzer (HP 8410). Fig. 2 shows the relationship between k or η_k and l for L-coupling. k and the magnitude of η_k take a maximum for $l = L/2$ (L = length of the λ/4-resonator), and are negligibly small for $l = 0$ and $l = L$: The configuration with $l = L/2$ is equivalent to commensurate combline with electrical length $\theta = 45°$. For small aperture length, the coupling is mainly magnetic. Fig. 3 shows a similar relationship for C-coupling. In this case, the coupling is mostly electric for small l. In the figure, the sign of η_k is opposite to the one in Fig. 2. The behavior of k and η_k can be explained by the fact that a cancelling between electric and magnetic coupling effects takes place [6]. The equivalent circuit of the two-coupled resonators is shown in Fig. 4. In that circuit, L_r and C_r are equivalent inductive and capacitive elements of the λ/4-resonator, respectively, and the resonant frequency is equal to f_{r0}. J_{12} represents an admittance inverter. C_{12}' is an equivalent capacitor which accounts for the resonant frequency shift required when the coupling between the two resonators is represented by an admittance inverter. C_{12}' may be positive or negative according to the sign of η_k. The area bounded by broken lines represents the coupling region of the coupled resonators. If $J_{12} = \omega C_{12}$ is assumed as shown in the figure, k, f_m, and η_k are expressed as follows:

$$k = C_{12}/(C_r + C_{12}') \doteqdot C_{12}/C_r \tag{6}$$

$$f_m = f_{r0}/\sqrt{1 + (C_{12}'/C_r)} \doteqdot f_{r0}[1 - (C_{12}'/2C_r)] \tag{7}$$

$$\eta_k = -C_{12}'/2C_r \tag{8}$$

where

$$C_{12}'/C_r \ll 1 \tag{9}$$

is assumed. From (6), k is equal to the coupling coefficient achieved when two resonators are coupled by means of an admittance inverter. Therefore, condition (9) is necessary for (1) to be used. The condition is satisfied in the present coupling methods if $k \ll 1$. The frequency f_m in (7) is the resonant frequency of one resonator with the other detuned. Equation (8) results from (5) and (7).

B. Coupling between a Resonator and External Circuit

On the open-circuit surface of a λ/4-resonator, a copper metal film was deposited using RF sputtering equipment.

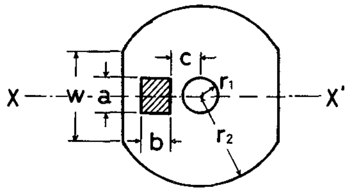


Fig. 5. Configuration of open-circuit surface of $\lambda/4$-coaxial resonator having terminal electrode. The configuration is symmetrical with respect to $X-X'$ axis. The electrode $(a\times b)$ is positioned close to the inner conducting cylinder in order to couple the resonator to external circuit. $r_1=1.3$, $r_2=5.0$, $w=5.0\pm.02$, $b=1.7\pm.03$, $c=1.63\pm.03$ [mm].

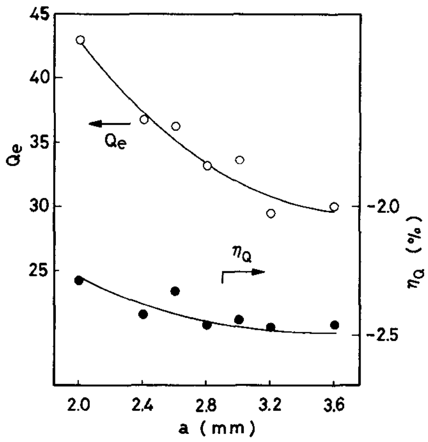


Fig. 6. External Q (Q_e) and frequency shift η_Q versus terminal electrode width a.

Selective etching techniques were used to create a rectangular electrode $(a\times b)$ for the input or output terminal of a bandpass filter, at a distance c from the center axis of the inner conducting cylinder. Fig. 5 indicates the configuration of the open-circuit surface. The resonator couples to the external circuit by the capacitance formed between the terminal electrode and the inner conducting cylinder.

The external Q (Q_e) of a resonator coupled to an external circuit is defined as

$$Q_e = f_{rL}/\delta f \tag{10}$$

where f_{rL} and δf are the resonant frequency and the half-power bandwidth, respectively. The frequency f_{rL} is shifted from the resonant frequency f_{r0} of the resonator before loading. The frequency shift η_Q is defined as

$$\eta_Q = (f_{rL}-f_{r0})/f_{r0}. \tag{11}$$

The dependence of Q_e and η_Q on the electrode width a is shown in Fig. 6. Low Q_e, which is require for a practical bandpass filter, is easily obtained by bringing the electrode close to the inner conducting cylinder.

The equivalent circuit of the resonator loaded by the external circuit is shown in Fig. 7. A parallel connection of L_r and C_r represents the unloaded resonator with a resonant frequency of f_{r0}. R_0 and C_0 represent a source (or load) resistance and a stray capacitance, respectively. C_{01} is the coupling capacitor. R_e and C_e are the equivalent resistive and capacitive elements of the source (or load) appearing across the L_r-C_r circuit. The resonant frequency and external Q are expressed as

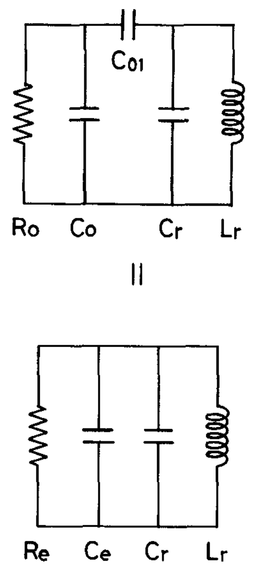
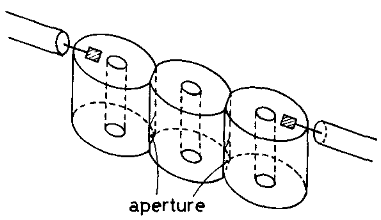
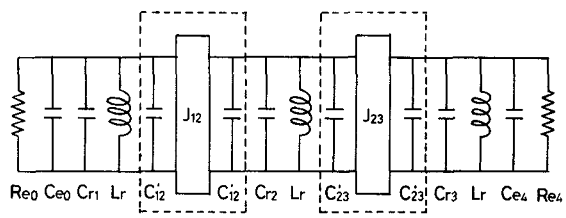


Fig. 7. Equivalent circuit of $\lambda/4$-resonator loaded by external circuit. A parallel connection of L_r and C_r stands for the unloaded $\lambda/4$-resonator. R_0 and C_0 represent a source (or load) resistance and stray capacitance, respectively. C_{01} is the coupling capacitor. R_e and C_e are the equivalent resistive and capacitive elements appearing across the L_r-C_r circuit.



(a)



(b)

Fig. 8 Three-resonator bandpass filter with (a) input and output coaxial lines and (b) the equivalent circuit.

$$f_{rL} = f_{r0}/\sqrt{1+(C_e/C_r)}$$
$$Q_e = 2\pi f_{rL}(C_r+C_e)R_e. \tag{12}$$

From (11) and (12), η_Q is given as

$$\eta_Q = -\left[1-\frac{1}{\sqrt{1+(C_e/C_r)}}\right]. \tag{13}$$

III. Three-Resonator Bandpass Filter

Fig. 8(a) shows a direct-coupled bandpass filter which consists of three $\lambda/4$-coaxial resonators with input and output coaxial lines. To couple the resonators to each other, apertures are formed on both flat sides of the center resonator and on one flat side of both end resonators. The equivalent circuit is shown in Fig. 8(b) using circuit considerations in Section II.

A bandpass filter with center frequency f_0 can be composed by coupling identical resonant circuits, each at a resonant frequency of f_0, using admittance inverters. The following relations must then be satisfied in Fig. 8(b):

$$f_0 = 1/2\pi\sqrt{L_r(C_{r1}+C_{e0}+C'_{12})} = 1/2\pi\sqrt{L_r(C_{r2}+C'_{12}+C'_{23})} = 1/2\pi\sqrt{L_r(C_{r3}+C'_{23}+C_{e4})}. \quad (14)$$

Equation (14) can be satisfied when

$$C_{r1} = C_r - C_{e0} - C'_{12}$$
$$C_{r2} = C_r - C'_{12} - C'_{23}$$
$$C_{r3} = C_r - C'_{23} - C_{e4}. \quad (15)$$

From (15), the resonant frequency $f_{ri} = 1/2\pi\sqrt{L_rC_{ri}}$ ($i = 1,2,3$) of each resonator is determined as

$$f_{r1} = f_0(1-\eta_{01}-\eta_{12})$$
$$f_{r2} = f_0(1-\eta_{12}-\eta_{23})$$
$$f_{r3} = f_0(1-\eta_{23}-\eta_{34}) \quad (16)$$

where

$$\eta_{01} = -\left[1-\frac{1}{\sqrt{1+(C_{e0}/C_r)}}\right]$$
$$\eta_{34} = -\left[1-\frac{1}{\sqrt{1+(C_{e4}/C_r)}}\right]$$
$$\eta_{12} = -C'_{12}/C_r \quad \eta_{23} = -C'_{23}/C_r. \quad (17)$$

η_{01} and η_{34} correspond to η_Q, and η_{12} and η_{23} to η_k in Section II. η_{12} and η_{23} are assumed to be small compared with 1.

IV. Construction of a Bandpass Filter

The specifications of a bandpass filter to be designed are as follows:

Filter response: Chebyshev type, 0.01-dB ripple,
Center frequency: $f_0 = 870$ MHz,
3-dB Bandwidth: BW = 25 MHz,
Number of resonators: 5.

The λ/4-resonators used have an unloaded Q (Q_u) of 700 (measured).

In the following, only the L-coupling method is employed, although the C-coupling method may also be used. The calculated values of $k_{i,i+1}$ and Q_e using (1) and (2) are given in the second column of Table I. With the help of Figs. 2 and 6, the aperture length l and terminal electrode width a can be determined as in the third column of the table. The frequency shifts which correspond to $k_{i,i+1}$ and Q_e are listed in the $\eta_{i,i+1}$ column. Taking these frequency shifts into account, the resonant frequency of each resonator was adjusted to

$$f_{ri} = f_0(1-\eta_{i-1,i}-\eta_{i,i+1}) \qquad (i = 1,2,\cdots,5). \quad (18)$$

The adjustment of these resonant frequencies was performed by shortening the length of resonators. The shortening was achieved by lapping the open-circuit surface of the resonators. Then, the aperture(s) of each resonator and the terminal electrode of the first and fifth resonators were formed as described in Section II. These resonators were arranged in a housing so that each aperture contacts an aperture on an adjacent resonator as shown in Fig. 9. The housing was made from brass plates (1.0-mm thickness). There is an air space between the upper plate of the housing and the open-circuit surfaces of the resonators so that the resonant frequencies are not perturbed by the housing. The contacts between resonators and resonator outer diameter to external housing were obtained by mechanical pressing.

TABLE I
Data for Bandpass Filter

resonator i - $i+1$	$k_{i,i+1}$ or Q_e	l or a [mm]	$\eta_{i,i+1}$ [%]
0 - 1	34	2.7	-2.44
1 - 2	2.17 %	4.7	-1.45
2 - 3	1.50 %	2.6	-1.04
3 - 4	1.50 %	2.6	-1.04
4 - 5	2.17 %	4.7	-1.45
5 - 6	34	2.7	-2.44

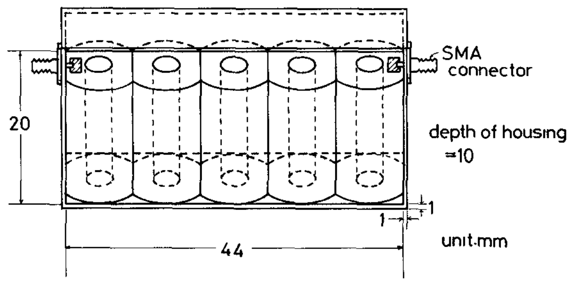


Fig. 9. Configuration of constructed bandpass filter. There is an air space between the upper plate of housing and the open-circuit surfaces of the resonators.

The measured response of the bandpass filter is shown in Fig. 10. In the passband region, the following results were obtained:

$f_0 = 870.4$ MHz,
BW = 25.0 MHz,
Passband ripple = 0.2 dB,
Insertion loss (IL) = 1.90 dB.

The center frequency is 0.05% higher than the specification; the deviation might be due to a tolerance error on the fabricated electrodes, for a precise measurement of resonant frequency and external Q of a heavily loaded resonator is difficult. The 3-dB bandwidth is exact. The insertion loss is slightly higher than the theoretical value of 1.68

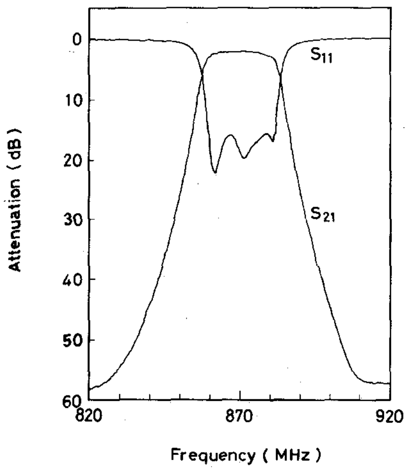


Fig. 10. Measured response of bandpass filter. The transmission and return losses are shown versus swept frequency.

dB, which is given by [7] as

$$\mathrm{IL} = \frac{4.343}{\mathrm{BW}/f_0} \frac{1}{Q_u} \sum_i g_i. \tag{19}$$

The attenuation in the stopband was more than 55 dB, the noise level of the network analyzer. Spurious responses were not observed up to 2 GHz.

V. Conclusions

A bandpass filter requiring no tuning screws was constructed by adjusting the resonant frequencies, the coupling coefficients, and the external Q's before assembly. The methods of coupling between the resonators and resonator to external circuits prescribed here would be suitable for reducing the size of bandpass filters. For adequate contact between the resonators and the external housing, high-frequency soldering techniques, for example, are recommended so as not to increase the insertion loss. By combining both L-coupling and C-coupling apertures between the same two resonators, it may be possible to achieve an elliptic and pseudo-elliptic bandpass filter response.

Acknowledgment

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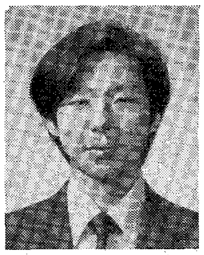

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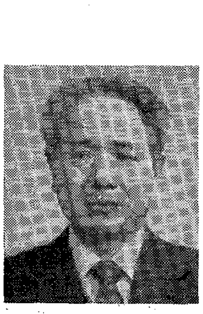

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