DISTRIBUTED COUPLING IN A CIRCULAR DIELECTRIC DISK RESONATOR AND ITS APPLICATION TO A SQUARE DIELECTRIC DISK RESONATOR TO FABRICATE A LOW-PROFILE DUAL-MODE BPF

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Abstract

A novel method is proposed to calculate the distributed coupling of a circular disk resonator. New theoretical expressions are devised to calculate it and its validity is justified by FD-TD analysis and experiments. This coupling concept is applied to a square disk resonator to calculate its resonant frequency. We have fabricated two types of low-profile dual-mode bandpass filter using square dielectric disk resonator.

Introduction

Dual-mode disk and ring resonators are widely used to fabricate bandpass filters for communication systems and many papers have been published on the subject [1]-[2]. In these papers, coupling between the orthogonal dual-modes is provided by adding perturbation at the edge of the symmetry plane with respect to the electromagnetic field distribution at the resonance. But there is no further explanation about coupling.

This paper presents a new concept about mode coupling in a circular disk resonator, which we named distributed coupling. A circular disk resonator can be easily represented by a branch line model [3]. Thus perturbation to the dual-degenerate mode of a circular disk resonator can be analyzed based on this model. The effect of the perturbation will vary with respect to its position. Using this concept, we have calculated the property of a square disk resonator. If the metal pattern on the top plate of the square disk resonator is triangularly removed, it causes coupling between the orthogonal modes. The coupling is calculated by distributed coupling concept and compared with experiment and FD-TD analytical data.

Finally, we have designed and fabricated a low-profile dual-mode square dielectric disk resonator BPF using high dielectric constant material (ε_r=93) having a dimension of 5×5×1 (mm). Low profile design is possible since the resonant frequency has a little dependence on the height of the resonator. We find that the unloaded quality factor of the resonator becomes maximum (≅250) when it's height is only 1 mm, which we have considered here [4]. Attenuation poles at the both sides of the passband appear or disappear according to the position of perturbation.

Dual-mode circular disk resonator and its resonant frequency

The distribution of dual-mode electric current at the top plate of a circular disk resonator is shown in Fig. 1, naming TM_{110}(x-mode) and TM_{110}(y-mode) [1].In the circular disk resonator the orthogonal degenerate resonance mode can be described by two oppositely travelling wave resonance modes. Based on this travelling wave model the schematic diagram of the branch line model can be easily shown [3]. Fig. 2 shows the configuration of a circular disk resonator. If we substitute the total electric energy (W_e) and effective value of excitation voltage (V) of the resonator in Foster reactance theorem [5], we obtain:

$$\frac{\partial B}{\partial \omega}=\frac{4W_e}{|V|^2}=C_0\left[1-\frac{J_0(k_c a)J_2(k_c a)}{J_1^2(k_c a)}\right] \quad (1)$$

where a= radius, h= height, k_c= cutoff wave number, and $C_0=(\varepsilon_0\varepsilon_r \pi a^2)/h$, capacitance of the disk resonator respectively. Using the resonance condition at the edge of the circular disk resonator and eq.(1) we can write :

$$y_a=\frac{\omega_r C_0}{2\pi}\left[1-\frac{J_0^2(k_c a)}{J_1^2(k_c a)}\right], \quad (2)$$

where ω_r = angular resonant frequency and y_a=

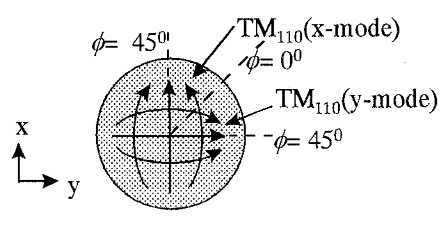

Fig. 1 Electric current distribution at the top surface of a circular disk resonator for dual-degenerate modes.

characteristic admittance of the equivalent transmission line. Normalized susceptance of the circular disk, $b=(\omega_r C_p)/y_a$,where C_p= perturbation capacitance. Resonant frequency of a circular disk resonator is [6]:

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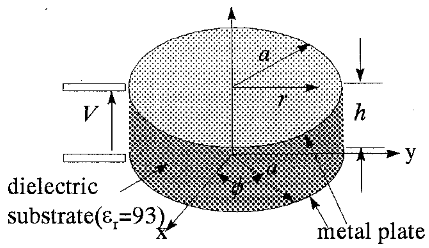

Fig. 2 Configuration of a circular disk resonator.

$$f_r = X\frac{30}{2\pi a\sqrt{\varepsilon_r}} \quad (3),\qquad \text{For } TM_{110} \text{ mode, } X=1.84118.$$

Calculation of even and odd mode resonant frequency of a circular disk resonator

Along the symmetry plane of the circular disk resonator (Fig. 3), let us consider a perfect magnetic wall (PMW) and perfect electric wall (PEW) for calculation of even and odd mode resonant frequency respectively. The equivalent transmission line ckt. for even mode becomes as of Fig. 4. For odd mode equivalent ckt. the open ends of Fig. 4 will be shorted. Let L be the total length of the resonator and l be the distance of perturbation from ϕ=0. Hence the total electrical length of the circular disk resonator $\theta = \beta L$. Then the electrical length of a partial line of length l is given by $\theta' = \beta l = \phi\theta/(2\pi)$. Applying resonance condition Y_1+Y_2=0(Fig. 4)we get the following relation

$$b + \tan\theta\left(\frac{1}{2}-\frac{\phi}{2\pi}\right) + \tan\theta\frac{\phi}{2\pi} = 0 \qquad (4)$$

Let us suppose that $\theta = 2\pi + \Delta\theta$. In other words, the frequency is shifted a little from the original resonance condition. By using Taylor expansion and doing some manipulation we can get the following relation for the even mode resonant frequency (f_e):

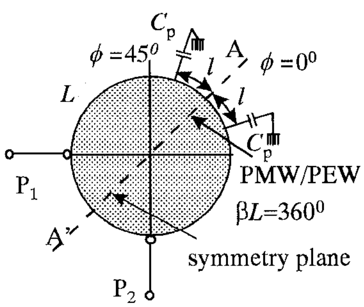

Fig. 3 Configuration for calculation of even and odd mode resonant frequencies of a circular disk resonator.

$$f_e = f_r\left(1-\frac{b\cos^2\phi}{2\pi}\right) \qquad (5)$$

Similarly for odd mode resonant frequency (f_o):

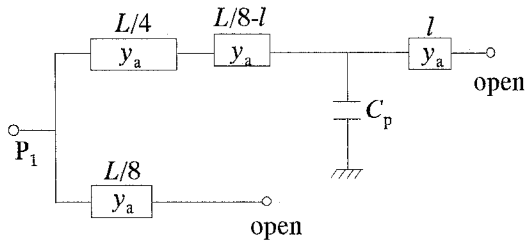

Fig. 4 Equivalent ckt. for calculation of even mode resonant frequency.

$$f_o = f_r\left(1-\frac{b\sin^2\phi}{2\pi}\right) \qquad (6)$$

Thus the coupling constant k becomes:

$$k = \frac{2|f_e - f_o|}{f_e + f_o} = \frac{2b|\cos 2\phi|}{4\pi - b} \qquad (7)$$

For a capacitive perturbation of 0.25 pF the variation of k from $\phi = 0$ to $\phi = 45^0$ is shown in Fig. 5. The figure shows that for the same amount of perturbation, the coupling constant varies sinusoidally as a function of the position of perturbation. At $\phi = 0$ the coupling constant is maximum and at $\phi = 45^0$ it is minimum (zero) in agreement with our expectation.

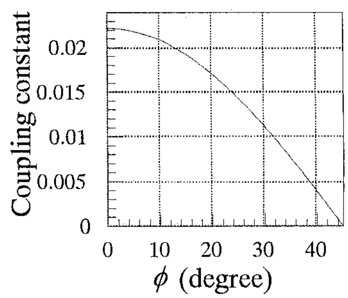

Fig. 5 Variation of coupling constant with respect to the position of capacitive perturbation (C=0.25 pF).

Distributed perturbation of a circular disk resonator and its application to determine the resonant frequency of a square disk resonator

A square disk resonator could be expressed by a perturbed circular disk resonator as shown in Fig. 6. Here the exterior part of the circular disk resonator act as capacitive perturbation. Hence the resonant frequency of square disk becomes lower than that of circular disk. For the same diagonal elements, the perturbation effects at the opposite ends are additive but they have opposite sign to that of other diagonal elements. As a result, the total perturbation effect is nullified. The perturbation of each corner can be calculated in the following method. As shown in Fig.7(for simplicity, only a quarter of the square

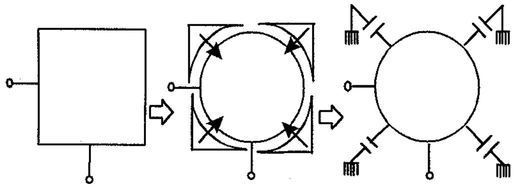

Fig. 6 Equivalence of a square and circular disk .

disk resonator is shown), the elementary area *cdef* can be expressed in terms of ϕ by the following expression:

$$cdef = \frac{1}{2} a^2 \tan^2\left(\frac{\pi}{4} - \phi\right) \Delta\phi \qquad (8)$$

Thus the total change of even mode resonant frequency due to perturbations at the four corners of the circular disk resonator can be expressed by the following relations, substituting eq.(8) into eq.(5) and integrating between 0 and π/4.

$$\Delta f_{e(total)} = -2\int_0^{\pi/4} \frac{f_r^2 \varepsilon_0 \varepsilon_r a^2 \tan^2(\pi/4-\phi)\cos^2\phi}{y_a h} d\phi \qquad (9)$$

The odd mode frequency change is also given by

$$\Delta f_{o(total)} = -2\int_0^{\pi/4} \frac{f_r^2 \varepsilon_0 \varepsilon_r a^2 \tan^2(\pi/4-\phi)\sin^2\phi}{y_a h} d\phi \qquad (10)$$

So the even $(f_e^\diamond)$ & odd mode resonant $(f_e^\diamond)$ frequencies of the square disk resonator becomes

$$f_o^\diamond = f_e^\diamond = f_r + \frac{[\Delta f_{e(total)} + \Delta f_{o(total)}]}{2} = f_r^\diamond \qquad (11)$$

Under the above condition no coupling exists inside the disk resonator. Thus $f_r^\diamond$ is considered the resonant frequency of the square disk resonator. Now, the resonant frequency calculated by the above procedure and that of experimental value are: $f_{r(experimental)}^\diamond$)=3.40 GHz & $f_{r(theoretical)}^\diamond$=3.3 GHz. In spite of rather brave assumptions there is little discrepancy between measured & calculated values.

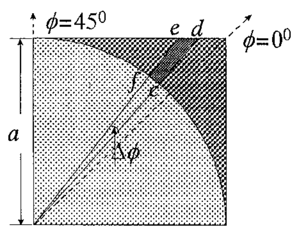

Fig. 7 Configuration for calculation of distributed coupling constant for variable perturbation.

Coupling constant of a square disk resonator based on circular disk resonator concept

For triangular perturbation at the corner of a square disk resonator, the angular limit ϕ' for integration in terms of the dimension Δa (Fig. 9) of triangular perturbation, can be easily calculated. The area of the triangularly removed metal pattern contributing in negative capacitive perturbation can be easily calculated. Hence the change of even & odd mode resonant frequencies can be presented by the following expressions:

$$\Delta f_e^\nabla = -2\int_0^{\phi'} \frac{f_r^2 \varepsilon_0 \varepsilon_r \cos^2\phi \times s}{h y_a} d\phi \qquad (12)$$

and

$$\Delta f_o^\nabla = -2\int_0^{\phi'} \frac{f_r^2 \varepsilon_0 \varepsilon_r \sin^2\phi \times s}{h y_a} d\phi \qquad (13)$$

where

$$s = \frac{1}{2}\left[a^2 \sec^2(\pi/4-\phi) - \frac{(2a-\Delta a)^2 \sec^2(\pi/4-\phi)}{\{1+\tan(\pi/4-\phi)\}^2}\right]$$

Thus the even & odd mode resonant frequencies of the square disk resonator can be expressed as follows:

$$f_e^\diamond = f_r^\circ + \left[\left(\Delta f_{e(total)} + \Delta f_{o(total)}\right)/2 - \Delta f_e^\nabla\right] \qquad (14)$$

$$f_o^\diamond = f_r^\circ + \left[\left(\Delta f_{e(total)} + \Delta f_{o(total)}\right)/2 - \Delta f_o^\nabla\right] \qquad (15)$$

where Δf_e^∇ and Δf_o^∇ are the change of even and odd mode resonant frequency of the square disk resonator.

If we assume that the total perturbation is acting as a lumped perturbation at $\phi = 0$, the perturbation capacitance can be expressed as below:

$$C_p = -\frac{\varepsilon_0 \varepsilon_r \Delta a^2}{2h} \quad \therefore \quad b = -\frac{\omega_r \varepsilon_0 \varepsilon_r \Delta a^2}{2h y_a} \qquad (16)$$

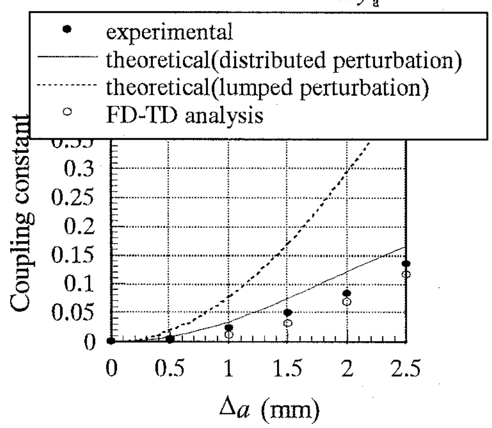

Fig. 8 Coupling constant vs. dimension of removed metal pattern from top of the dielectric disk resonator.

Hence the even and odd mode resonant frequencies of the square disk resonator becomes as follows:

$$f_e^\diamond = f_r^\diamond - \frac{f_r^\circ b}{2\pi} \quad (17) \quad \text{and} \quad f_o^\diamond = f_r^\diamond \quad (18)$$

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Now the coupling constant calculated by the lumped and distributed approach is compared with the experimental results, as shown in Fig. 8. The resonator dimension is taken as 5× 5× 1 (mm) and ε_r=93. We found that the coupling constant calculated by distributed approach shows a good agreement with experimental and FD-TD analytical values.

Design and fabrication of a dual-mode BPF

The filter configuration having a dimension of 5× 5× 1(mm) is shown in Fig. 9, the top and bottom plate of which is directly silver-coated. Here the bottom silver plate is grounded and that of top is floating. Capacitive excitation is done at the floating plate. The x-mode and y-mode frequency tuning are done by making a very narrow slit at the center of the corresponding rim of the floating surface [7]. So it does not affect the internal coupling of the resonator, as we have proved before. The filter characteristics are shown in Figs.10 (a) & (b). The attenuation poles appear at the both sides of the passband, when coupling is provided at the corner P and /or P' and it disappears when it is provided at corner Q and Q'.

Conclusion

To the best of our knowledge, the present paper successfully describe the distributed coupling concept of a circular disk resonator for the first time. The calculated coupling constant shows a good agreement with experimental values. We have also calculated the resonant frequency of the square disk resonator with the help of distributed coupling concept. Two types of low-profile high *Q* BPFs are fabricated using high dielectric material for having or without attenuation poles at the both sides of the passband.

References

[1] Ishikawa, S. Hidaka, T. Ise and N. Matsui , "Low-Profile Filter Using Open Disk Dual Mode Dielectric Resonators, " *IEICE Trans. Electron.*, Vol. J78-C-I No. 12 pp. 687-694, Dec. 1995 (in Japanese).

[2] Curits and S. J. Fiedziuszko, " Miniature Dual Mode Microstrip Filters, "*IEEE MTT-S Digest*, pp. 443-446, 1991.

[3] I. Awai and T. Yamashita, " Theory on Rotated Excitation of a Circular Dual-Mode Resonator and Filter, "*IEEE MTT-S Digest*, pp.781-784, 1997.

[4] A. C. Kundu and Ikuo Awai, "Low-Profile Dual-Mode BPF Using Square Dielectric Disk Resonator, " 1997 Autumn Electronics Society Conference of IEICE. pp. 273 (Oct. 1997).

[5] R. E. Collin, " Foundations For Microwave Eng., " McGraw-Hill, Inc., pp.230-232, 1992.

[6] Y. Konishi, "Design and Application of Filter Circuits for Communication, " Sohgoh Denshi Pub. Co., pp. 168, Tokyo, 1994 (in Japanese).

[7] L. Accatino, G. Bertin, and M. Mongirado, "A Four-Pole Dual Mode Elliptic Filter Realized in a Circular Cavity Without Screws, " *IEEE Trans. Microwave Theory Tech.*, Vol. 44, pp. 2680-2686, Dec. 1996.

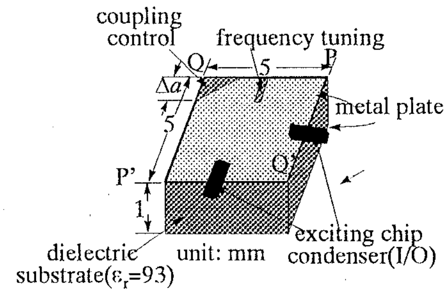
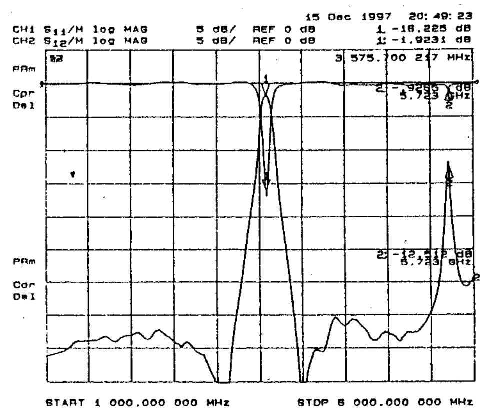
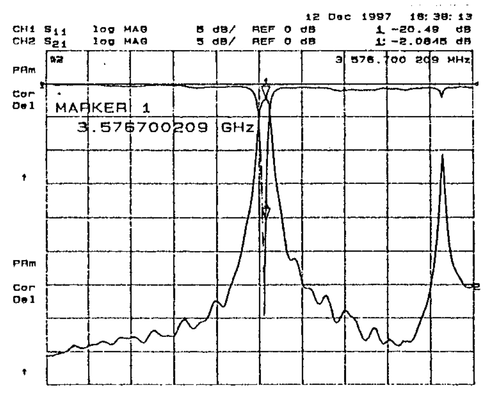


Fig. 9 Configuration of the filter.



(a) With attenuation poles.



(b) Without attenuation poles

Fig. 10 Measured response of a dual- mode dielectric disk resonator bandpass filter.