Adjustment of Okada Resonator Using Composite Chambers

J. Helszajn, R. Guixa, J. Girones, E. Hoyos, and J. Garcia-Taheno

Abstract—**An important high power gyromagnetic resonator is the Okada one consisting of stacked circular metal disks between top and bottom plates on either side of which are mounted thin ferrite disks separated by a free space or dielectric region. The purpose of this paper is to describe some design features entering into the description of the quality factor of this type of junction. The quality factor of one experimental UHF Okada resonator biased above the main Kittel resonance consisting of five inner symmetrical chambers and two outer asymmetrical ones each partially filled with an inner region of ferrite tiles and an outer one of dielectric tiles is given separately.**

I. Introduction

ONE WAY to increase the power rating of a planar resonator is to have recourse to the Okada resonator [1], [2], [3], and [4]. This resonator consists of stacked circular metal plates on which are mounted ferrite disks separated by a dielectric or free space region. The schematic diagram of one possible arrangement is indicated in Fig. 1.

A means of increasing the power rating of this gyromagnetic resonator further is to use a composite structure consisting of a ferrite disk and a dielectric ring [13]. The principle of this geometry relies on the fact that the outer rim of the resonator does not to first order contribute to the gyrotropy of the junction. It may therefore be replaced by a dielectric material with a similar value of dielectric constant as that of the ferrite without unduly perturbing its operation. The basis of this technique is the fact that the thermal conductivity of a dielectric material such as alumina or berylia oxide is much higher than that of a ferrite one. It also has the merit of reducing the cross-sectional area of the magnetic circuit. If the gyromagnetic region of the resonator is assumed to reside within 0.707 of the outside radius then the number of ferrite tiles is reduced by a factor of 2.

The purpose of this paper is to establish the quality factor and radial cut-off number of an Okada resonator using ferrite disks surrounded by dielectric rings. It includes some measurements on one resonator consisting of five inner chambers using pairs of composite layers made up of ferrite and dielectric regions and two outer ones each using a single composite layer.

Some of the considerations entering into the description of this sort of resonator are average and peak power ratings, cooling provisions, magnetic and dielectric losses, gain-bandwidth or quality factor. In this sort of device, the filling factor is fixed by the quality factor of the resonator, the magnetic parameters of the ferrite material by the magnetic losses, the gap between the ferrite layers by the peak power specification, and the number of chambers by the average power rating. The radial filling factor is utilized as the independent variable.

Some related coaxial work has been described in [5], [6], [7], and [8] and some in waveguide in [9], [10], and [11].

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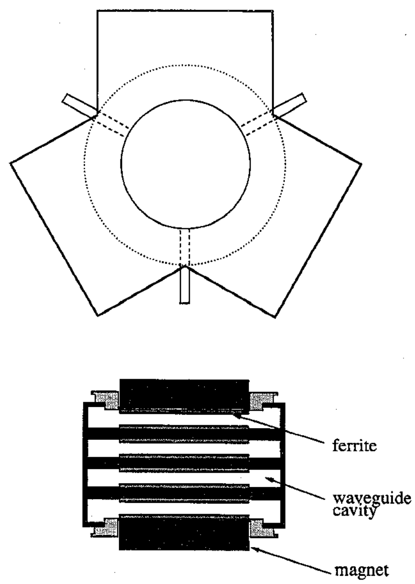


Fig. 1. Schematic diagram of Okada resonator using four double chambers.

II. Okada Resonator

The main preoccupation so far in the design of the Okada resonator has been with its operating frequency and average and peak power ratings. Such resonators have by now been described with up to six symmetrical chambers. The equivalence between any two arrangements which preserves its susceptance slope parameter is established in this section. It is accomplished by establishing a one-to-one equivalence between the capacitances of any two arrangements. Fig. 2 indicates that between a planar resonator consisting of a pair of ferrite disks and one using two pairs. The equivalence between the two is met provided the effective dielectric constants of the two geometries are equal. This condition is satisfied if the thickness of each ferrite layer $(L/2)$ in the reorganized arrangement is half that of the original structure (L). Organizing the parallel plate capacitance in this manner doubles the surface area of the resonator which is in contact

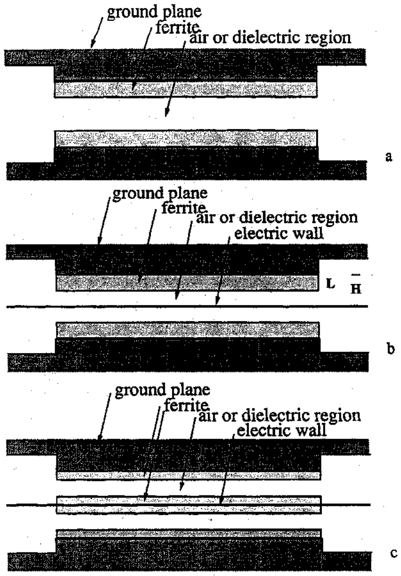


Fig. 2. Equivalence between one and two Okada chambers.

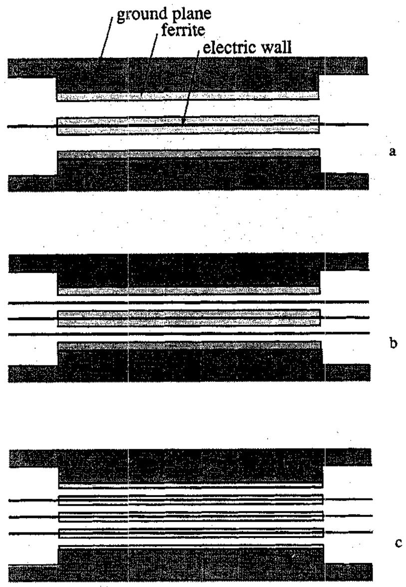


Fig. 3. Equivalence between two and four Okada chambers.

with the heat sink and halves its thickness. The power rating of the device is therefore increased by a factor of four. The mapping between the two arrangements starts by introducing an electric wall at the symmetry plane of the original circuit. Since the electric field is perpendicular to this wall it is unaffected by it. (The magnetic field in such a resonator is parallel to it and so it is also unaffected by the introduction of such a wall.) The derivation is completed by noting that the effective dielectric constant and consequently the capacitance of the circuit is unaltered if the ferrite disks on the top and bottom walls of the original circuit are equally divided between the original walls and the surfaces revealed by the electric wall. Fig. 3 depicts the mapping between a two-layered structure and a four-layered one. The power rating of the device is in this instance increased by a factor of 16 compared to that of the original prototype. The power rating of this sort of circuit is therefore in general increased by a factor of n^2. In a practical arrangement, the infinitely thin dielectric walls are replaced by conducting plates which are water cooled.

III. Okada Resonator Using Composite Resonators

One means of increasing the mean power of the Okada resonator still further is to employ a composite arrangement. One geometry is indicated in Fig. 4. Its adjustment forms the main endeavor of this paper. Still another possibility that may have some value, is to embody magnetic tiles between the inner gyromagnetic ones and the outer dielectric ones in order to focus the direct magnetic field. The magnetic tiles may be constructed from a similar material to that of the gyromagnetic ones except for its magnetization. The value of this quantity is then chosen such that its Kittel line resides at a lower direct magnetic field at the operating frequency of the resonator from that of the gyromagnetic region. This geometry is shown in Fig. 5. The size of the planar circular or hexagonal plates required for the fabrication of planar resonators at UHF frequencies poses, in practice, a manufacturing problem in that it is not possible to fire such large ferrite assemblies. Another difficulty, in the design of high mean power devices is that large ferrite surfaces bounded to ground planes are likely to shutter under thermal shock. One way to avoid both difficulties is to replace the ferrite substract by a number of circular or hexagonal tiles [3]. This approach has also the merit that tiles may be replaced if damaged. The use of a planar disk resonator in the design of a junction circulator is not unique. Another possibility is a regular hexagonal shape, still other possibilities are irregular hexagonal and triangular ones. Fig. 6(a) illustrates a regular hexagonal arrangement and Fig. 6(b) one using a composite substrate. Rubber-based adhesive is usually employed in the design of high power devices to bond the ferrite tiles to metal surfaces.

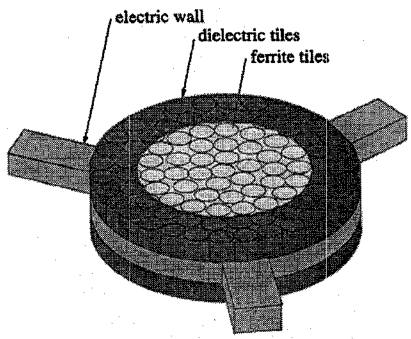


Fig. 4. Schematic diagram of composite resonator using ferrite and dielectric tiles.

IV. Fabrication of Planar Resonators

In this type of device, the filling factor is fixed by the quality factor of the resonator and its magnetic parameters, the gap between the ferrites by the peak power specification and the number of chambers by the average power rating. The resonator investigated in this paper consisted of five inner chambers using pairs of composite resonators and two outer

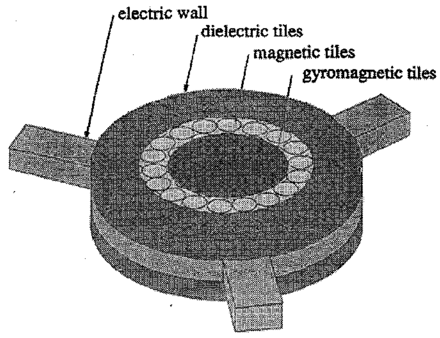
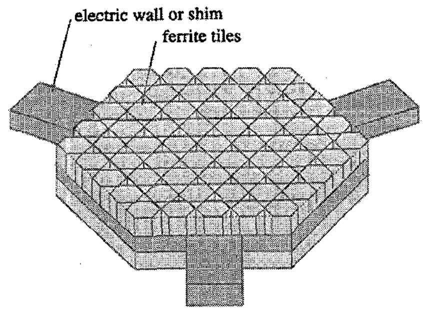
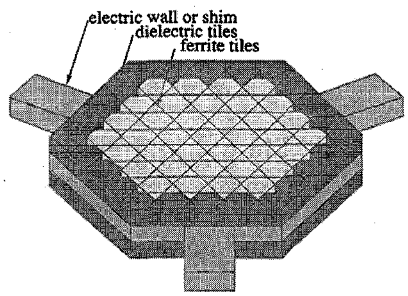


Fig. 5. Schematic diagram of composite resonator with focusing ferrite tiles.



(a)



(b)

Fig. 6. (a) Okada geometry using hexagonal resonator. (b) Okada geometry using hexagonal composite resonator.

ones using single ones. The filling factor employed in this paper is

$$k = 0.35.$$

The thickness (L_r) of each divided ferrite geometry is

$$L_r = 3.5 \text{ mm}$$

and the thickness (H_r) of each divided half-chamber is

$$H_r = 10.0 \text{ mm}.$$

The thickness (t) of each strut is

$$t = 15.0 \text{ mm}.$$

The overall height of the resonator used in this work is obtained by adding these quantities together. This gives

$$12H_r + 6t = 210 \text{ mm}.$$

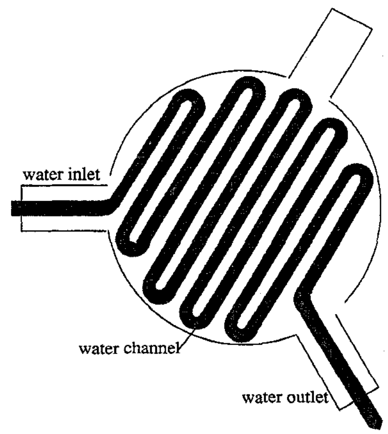


Fig. 7. Cooling geometry of struts.

The narrow dimension (b) and the wide one (a) of the WR2300 waveguide used in this work are

$$b = 292.1 \text{ mm}$$

$$a = 584.2 \text{ mm}$$

respectively.

The struts in a high-power Okada resonator are usually water cooled. One cooling arrangement is schematically shown in Fig. 7.

V. Effective Constitutive Parameters

In order to proceed with the design of a planar resonator using one or two ferrite regions it is necessary to replace the constitutive parameters by effective ones. The relationship between the actual and effective parameters are summarized below [7]

$$\epsilon_f(\text{eff}) = \frac{\epsilon_f}{\epsilon_f - k(\epsilon_f - 1)} \tag{1}$$

$$\mu_e(\text{eff}) = 1 + k(\mu_e - 1) \tag{2}$$

where

$$\mu_e = \frac{\mu^2 - \kappa^2}{\mu} \tag{3}$$

μ and κ are the actual diagonal and off diagonal elements of the tensor permeability. The filling factor (k) is defined in terms of the dimensions entering into the description of one half of the symmetrical chamber in Fig. 2(a)

$$k = \frac{L}{H}. \tag{4}$$

The relationship between (1) and (2) satisfies the duality derived in [12].

The form of the effective diagonal element $\kappa(\text{eff})$ differs from that of μ in that κ is zero outside the ferrite region whereas μ is unity there. The required quantities are given by

$$\mu(\text{eff}) = 1 + k(\mu - 1) \tag{5}$$

$$\kappa(\text{eff}) = k\kappa \tag{6}$$

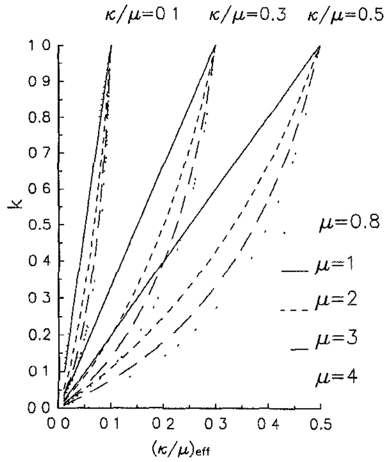


Fig. 8. Relationship between actual and effective gyrotropies.

and the gyrotropy by

$$\left(\frac{\kappa}{\mu}\right)_{\text{eff}} = \frac{k\mu}{1+k(\mu-1)}\left(\frac{\kappa}{\mu}\right). \tag{7}$$

In a below resonance device μ is usually not very different from unity and

$$\left(\frac{\kappa}{\mu}\right)_{\text{eff}} = k\left(\frac{\kappa}{\mu}\right). \tag{8}$$

Values of (κ/μ) between

$$0.10 \le \left(\frac{\kappa}{\mu}\right) \le 0.70 \tag{9}$$

are realizable without any difficulty in below resonance devices.

In an above resonance device μ is usually greater than unity. For $\mu = 2$ (7) gives

$$\left(\frac{\kappa}{\mu}\right)_{\text{eff}} = \frac{2k}{1+k}\left(\frac{\kappa}{\mu}\right). \tag{10}$$

For $\mu = 3$

$$\left(\frac{\kappa}{\mu}\right)_{\text{eff}} = \frac{3k}{1+2k}\left(\frac{\kappa}{\mu}\right). \tag{11}$$

Scrutiny of these two situations indicates that for a given value of the effective gyrotropy, a large value of μ is compatible with a small filling factor.

A definition of the gyrotropy κ/μ above resonance is usually a more subjective matter. It requires definitions of the linewidth and the skirt characteristics of the main Kittel resonance which are not always readily available. Values of κ/μ between

$$0.10 \le \frac{\kappa}{\mu} \le 0.30 \tag{12}$$

are realizable with narrow linewidth materials. Once μ and κ/μ are specified κ is given without ado.

Fig. 8 depicts the relationship between the effective gyrotropy of the resonator and the filling factor for different choices of μ and κ. This illustration suggests that for given values of κ/μ and $(\kappa/\mu)_{\text{eff}}$ it is possible to employ a smaller filling factor above resonance than is possible below it.

If μ and κ are fixed then one relationship between k and $(\kappa/\mu)_{\text{eff}}$ is

$$k = \frac{\left(\frac{\kappa}{\mu}\right)_{\text{eff}}}{\kappa - \left(\frac{\kappa}{\mu}\right)_{\text{eff}}(\mu-1)}. \tag{13}$$

If $(\kappa/\mu)_{\text{eff}}$, (κ/μ) and k are fixed then

$$\mu = \frac{\left(\frac{\kappa}{\mu}\right)_{\text{eff}}(1-k)}{k\left[\left(\frac{\kappa}{\mu}\right) - \left(\frac{\kappa}{\mu}\right)_{\text{eff}}\right]} \tag{14}$$

$$\kappa = \frac{\left(\frac{\kappa}{\mu}\right)_{\text{eff}}(1-k)}{k\left[\left(\frac{\kappa}{\mu}\right) - \left(\frac{\kappa}{\mu}\right)_{\text{eff}}\right]} \cdot \left(\frac{\kappa}{\mu}\right). \tag{15}$$

Since the effective gyrotropy is fixed by the quality factor of the resonator and the actual gyrotropy and the filling factor the values of μ and κ cannot be calculated until these quantities are specified.

The design is not of course complete until the magnetization of the ferrite material and the direct magnetic field are determined. If there is no restriction upon the choice of the magnetization of the garnet material then the solution is unique otherwise it is not. The detailed calculations are outside the remit of this paper. One solution is

$$\begin{aligned} \kappa &= 1.20 \\ \mu &= 4.00 \\ \frac{\kappa}{\mu} &= 0.30 \\ \mu_e &= 3.64 \\ k &= 0.333 \\ \left(\frac{\kappa}{\mu}\right)_{\text{eff}} &= 0.205 \\ (\mu_e)_{\text{eff}} &= 1.924 \\ \sigma &= 2.58 \\ p &= 7.0. \end{aligned}$$

σ and p are the normalized internal direct magnetic field and normalized magnetization, respectively.

VI. Loaded Q-Factor

The three quantities that enter into the description of a junction circulator are its frequency and its loaded and unloaded quality factors. The latter quantity must be fixed on the basis of experience; the two former quantities may be derived from an understanding of its gyromagnetic resonator. The required relationships are

$$k_f R = \text{const} \tag{16}$$

and

$$\frac{1}{Q_L} = \sqrt{3}\left(\frac{\omega_+ - \omega_-}{\omega_0}\right). \quad (17)$$

If a degree-2 quarter-wave coupled filter circuit is used then [16]

$$2\delta_0 = \frac{\sqrt{2}(\mathrm{VSWR}-1)^{1/2}}{Q_L}. \quad (18)$$

VSWR is the voltage standing wave ratio and $2\delta_0$ is the normalized bandwidth

$$2\delta_0 = \left(\frac{\omega_2 - \omega_1}{\omega_0}\right). \quad (19)$$

Taking the VSWR as 1.15 (say) with Q_L equal to 5.14 gives

$$2\delta_0 = 10.4\%.$$

The degree-1 gain bandwidth product relationship is defined for comparison and measurements purposes by

$$2\delta_0 = \frac{(\mathrm{VSWR}-1)}{Q_L\sqrt{\mathrm{VSWR}}}. \quad (20)$$

Taking Q_L again as 5.14 and the VSWR again as 1.15 gives in this instance

$$2\delta_0 = 2.7\%.$$

If the effective dielectric constants of the garnet and dielectric materials $\epsilon_f(\text{eff})$ and $\epsilon_d(\text{eff})$ are the same and if the radial filling factor is not too different from unity then the radial wavenumber may be assumed to coincide with that of the homogeneous resonator. These assumptions permits some initial design parameters to be established as a preamble to some exact calculations.

In the description of a composite disk resonator it is convenient to define an effective radial filling factor [13]. If this notation is adopted then the loaded Q-factor is related to the split frequencies of the resonator in the usual way by

$$\frac{\omega_+ - \omega_-}{\omega_0} = \frac{2k_r}{(k_f R)^2 - 1}\left(\frac{\kappa}{\mu}\right)_{\text{eff}}. \quad (21)$$

The radial wavenumber (k_f) and the radial filling factor (k_r) are separately established once (k/μ)eff is specified by solving the composite resonator problem in the next section. The fine adjustment in this paper is the radial filling factor.

One solution for the quality factor assumed here based on the model employed in this section is obtained by taking k_r as 0.67, k as 0.35, and $(\kappa/\mu)_{\text{eff}}$ as 0.20 (say).

VII. Characteristic Equation of Composite Gyromagnetic Resonator

In order to proceed with the design of the resonator and calculate the radial filling factor in terms of its quality factor it is necessary to have its midband and split frequencies. The characteristic equation of a demagnetized planar resonator consisting of a ferrite disk surrounded by a dielectric ring is a standard result in the literature [13]. It is approximately obtained by establishing a magnetic wall on the sidewall of the resonator. The required result is

$$B_1 J_1'(k_d R_d) + C_1 Y_1'(k_d R_d) = 0. \quad (22)$$

A knowledge of the ratio of the arbitrary constants B_1/C_1 is sufficient to solve this equation. It is given by satisfying the boundary condition between the two regions

$$\frac{C_1}{B_1} = \left\{\frac{-J_1(k_d R)}{Y_1(k_d R)}\right\} \cdot \left\{\frac{\left[\frac{J_1'(k_f R)}{(k_f R) J_1(k_f R)}\right]\frac{\epsilon_f(\text{eff})}{\epsilon_d(\text{eff})} - \frac{J_1'(k_d R)}{(k_d R) J_1(k_d R)}}{\left[\frac{J_1'(k_f R)}{(k_f R) J_1(k_f R)}\right]\frac{\epsilon_f(\text{eff})}{\epsilon_d(\text{eff})} - \frac{Y_1'(k_d R)}{(k_d R) Y_1(k_d R)}}\right\} \quad (23)$$

and

$$k_f = k_0\sqrt{\mu_e(\text{eff})\epsilon_f(\text{eff})} \quad (24)$$

$$k_d = k_0\sqrt{\epsilon_d(\text{eff})} \quad (25)$$

and

$$k_0 = \frac{2\pi}{\lambda_0} \quad (26)$$

$\epsilon_f(\text{eff})$, $\epsilon_d(\text{eff})$ and $\mu_e(\text{eff})$ are the effective constitutive parameters. $J_1(k_f R)$ is the Bessel function of the first kind of order 1 and argument $k_f R$. $k_f R$ is the Bessel function of the second kind of order 1 and argument $k_f R$. $J_1'(k_f R)$ and $Y_1'(k_f R)$ are the respective derivatives. R is the radius of the ferrite region, R_d that of the dielectric region.

The relationships between the radial wave number $k_d R_d$ and $k_f R$ for parametric values of the effective permeability $\mu_e(\text{eff})$ is indicated in Fig. 9.

Fig. 10 separately indicates the relationship between $\mu_e(\text{eff})$ and $k_d R_d$ for $k_f R = 1.84/\sqrt{2}$.

If $\epsilon_f(\text{eff}) = \epsilon_d(\text{eff})$ then the characteristic equation of the demagnetized resonator reduces to

$$J_1'(k_f R) = 0 \quad (27)$$

or

$$k_f R = 1.84. \quad (28)$$

The characteristic equation of the magnetized resonator is again fixed by (22) but with the ratio of the arbitrary constants

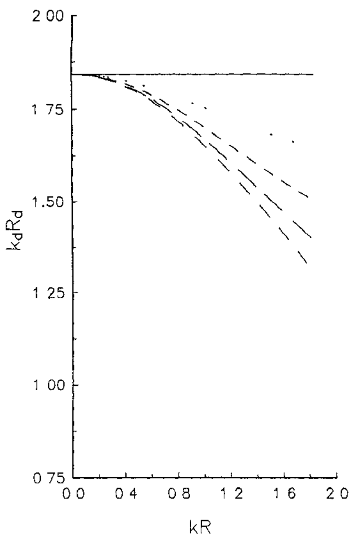


Fig 9. Relationship between k_dR_d and k_fR for parametric values of μ_e(eff) for $\mu_e(\text{eff}) = 1$, $\mu_e(\text{eff}) = 1.25$, $\mu_e(\text{eff}) = 1.5$, $\mu_e(\text{eff}) = 1.75$, $\mu_e(\text{eff}) = 2$.

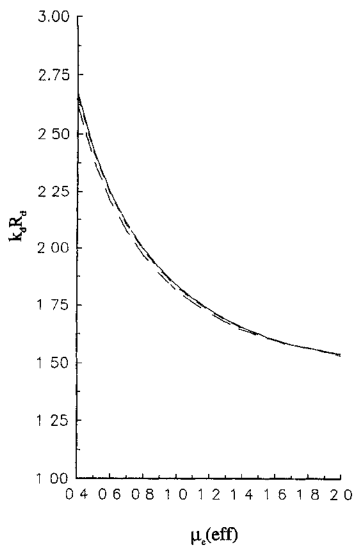


Fig. 10. Relationship between μ_e(eff) and k_dR_d for $k_fR = 1.84/\sqrt{2}$ and $\epsilon_f(\text{eff})/\epsilon_d(\text{eff}) = 1$, $\epsilon_f(\text{eff})/\epsilon_d(\text{eff}) = 1.02$, $\epsilon_f(\text{eff})/\epsilon_d(\text{eff}) = 1.08$.

given by [13]

$$\frac{C_1}{B_1} = \left\{\frac{-J_1(k_dR)}{Y_1(k_dR)}\right\} \cdot \left\{\frac{\left[\frac{J_1'(k_fR)}{(k_fR)J_1(k_fR)} + \left(\frac{\kappa}{\mu}\right)_{\text{eff}}\frac{1}{(k_fR)^2}\right]\frac{\epsilon_f(\text{eff})}{\epsilon_d(\text{eff})} - \frac{J_1'(k_dR)}{(k_dR)J_1(k_dR)}}{\left[\frac{J_1'(k_fR)}{(k_fR)J_1(k_fR)} + \left(\frac{\kappa}{\mu}\right)_{\text{eff}}\frac{1}{(k_fR)^2}\right]\frac{\epsilon_f(\text{eff})}{\epsilon_d(\text{eff})} - \frac{Y_1'(k_dR)}{(k_dR)Y_1(k_dR)}}\right\}. \tag{29}$$

$(\kappa/\mu)_{\text{eff}}$ is the ratio of the effective diagonal and off-diagonal elements of the tensor permeability. The two split frequencies are deduced from the characteristic equation by replacing n by ± 1. Fig. 11 shows one result. One solution is

$$\left(\frac{\kappa}{\mu}\right)_{\text{eff}} \approx 0.20$$

$$\frac{R_d}{R} \approx 0.67$$

$$Q_L \approx 5.14.$$

VIII. Experimental Okada Resonator Mode Chart

The experimental mode chart of one Okada resonator at the junction of three WR2300 waveguides based on some of the calculations outlined in this paper is illustrated in Fig. 12. It is obtained by recording the frequencies of the split absorption lines at one port in the return loss of the device with the other two ports terminated in matched loads. The geometry considered here consisted of five inner chambers using pairs of ferrite layers and two outer ones using single ones. Of note is that each branch displays four split frequencies in keeping with the four symmetry planes of the direct magnetic field along the axis of the resonator. These symmetry planes may be understood in connection with the constant direct magnetic field contours of the electromagnet illustrated in Fig. 13. This suggests that the middle of the chamber resonates at f_0, the

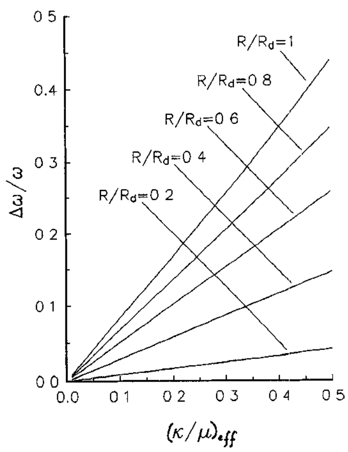


Fig. 11. Normalized split frequencies of composite resonators for $\epsilon_f(\text{eff})/\epsilon_d(\text{eff}) = 1.66$, $\mu_e(\text{eff}) = 1.5$.

inner pair of chambers at $f_0 + \Delta f_0$, the next pair of chambers at $f_0 + 2\Delta f_0$ and the outer two chambers at $f_0 + 3\Delta f_0$.

Since the mode chart has been split by the direct field profile of the resonator the average upper and lower split frequencies must be used for calculations.

Scrutiny of the mode chart in Fig. 12 gives one possible solution between any pair of split modes

$$(f_0) \text{ average} \approx 325 \text{ MHz}$$

$$(f_+) \text{ average} \approx 335 \text{ MHz}$$

$$(f_-) \text{ average} = 307 \text{ MHz}.$$

The applied direct magnetic field was established by superimposing a small direct magnetic field using a coil arrangement on a re-entrant magnetic structure.

The quality factor is

$$\frac{1}{Q_L} = \sqrt{3}\left(\frac{\omega_+ - \omega_-}{\omega_0}\right)$$

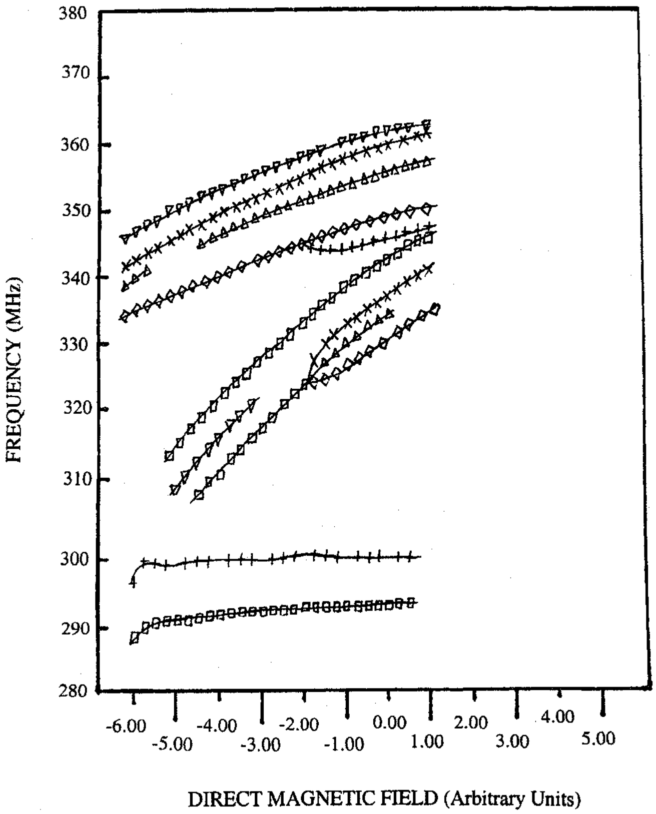


Fig. 12. Experimental split frequencies of Okada composite resonator using five inner double chambers and two outer single ones.

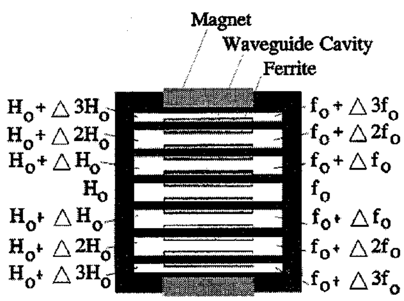


Fig. 13. Direct magnetic field of Okada resonator.

or

$$Q_L = 6.25.$$

This compares with a calculated value of $Q_L = 5.14$ at the same value of direct magnetic field.

Fig. 14 illustrates a photo of a practical 320 MHz Okada junction in WR2300 waveguide using five inner double chambers and two single outer ones. Fig. 15 indicates the resonator in some more detail.

The filling factor of each chamber and its number are determined by the peak power rating of the resonator. These considerations are outside the remit of this work.

IX. Conclusion

A resonator of some interest in the design of high power circulators is the Okada one. One important property of such a resonator is its loaded quality factor. The paper describes some design considerations entering into the description of this quantity. One experimental result at a frequency of 320 MHz in WR 2300 waveguide on one topology using five inner pairs of composite ferrite layers and two outer ones using single composite layers is separately given.

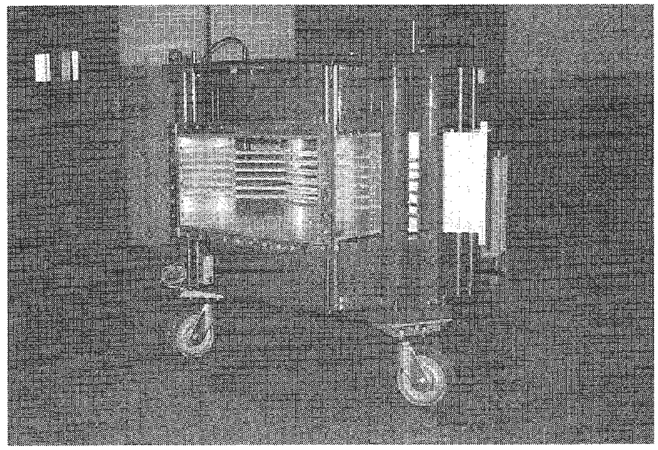


Fig. 14. Photo of Okada 3-port junction circulator.

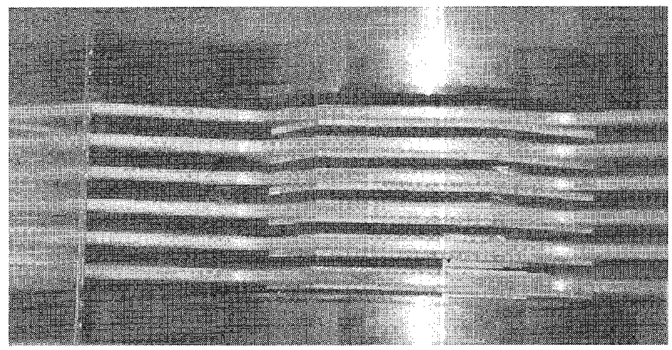


Fig. 15. Photo of Okada resonator.

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