Suppression of Higher Order Modes in Waveguide-Junction Circulators Using Coupled Open Dielectric Resonators

F. C. F. TAN AND J. HELSZAJN

***Abstract*—It is well known that some waveguide circulators exhibit an unwanted spurious mode within their passband, which limits their insertion loss and bandwidth. This mode is identified as the $TE_{0,1,\delta}$ one in the case of the waveguide junction which relies on the $TM_{1,1\delta}$ mode for its operation. The influence of the saturation magnetization on the separation between the two modes is studied in detail. A mode suppressor is also described which decouples the coupled $TE_{0,1,\delta}$ mode without altering the frequency of the circulation ones. This suppressor consists of a thin metal ring placed on the open face of one of the ferrite disks.**

INTRODUCTION

It is now well established that many waveguide-junction circulators using partial-height ferrite geometries rely on the $TM_{1,1,\delta}$ lowest order open dielectric resonance for their operation [1]–[6]. Although an infinite dielectric waveguide only supports hybrid modes except for the symmetric ones, the ideal open-circuited boundary conditions on the circumferential and end faces of the resonators satisfy $TM_{1,1,\delta}$ resonances. The performance of this junction is often limited by the presence of an undesirable mode within its passband which does not contribute to its operation but which limits its bandwidth and insertion loss. This mode has been identified in the case of the waveguide circulator using a full-height ferrite post as the $TE_{0,1,\delta}$ open dielectric resonator one [7]. It may be suppressed by ensuring that there are no airgaps between the ferrite post and the waveguide walls. The higher order mode encountered in the waveguide junction, which relies on the $TM_{1,1,\delta}$ mode for its operation, is also found to be the $TE_{0,1,\delta}$ one. However, in this construction some other form of suppression is obviously required. The purpose of this letter is to study various methods in which this can be done. These include the effect of saturation magnetization, the influence of the aspect ratio of the open dielectric resonator, and the effect of a thin metal ring placed on the open face of the ferrite disk.

The experimental work was carried out on the standard *H*-plane waveguide circulator in Fig. 1, consisting of two ferrite disks supporting $TM_{1,1,\delta}$ modes mounted in a reduced-height radial cavity.

$TE_{01\delta}$ OPEN DIELECTRIC RESONATOR

It has recently been demonstrated that the waveguide-junction configuration used here supports axially resonating modes associated with the hybrid HE_{11} unbounded dielectric-waveguide mode. This section shows that the spurious higher order mode encountered in such circulators is associated with the $TE_{01\delta}$ one on the unbounded dielectric waveguide for which the boundary condition is $H_z = 0$ at $r = R$.

A complete expansion of the fields inside the unbounded dielectric waveguide is given by

$$H_z = a_0{}^i J_0(kr)$$

$$E_\theta = j\frac{\omega\mu_0\mu_r}{k} a_0{}^i J_0'(kr)$$

$$H_r = -\frac{j\beta}{k} a_0{}^i J_0'(kr)$$

$$E_z = E_r = H_\theta = 0$$

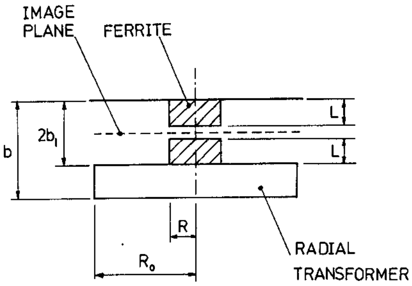

Fig. 1. Schematic diagram of coupled-resonators radial-waveguide circulator.

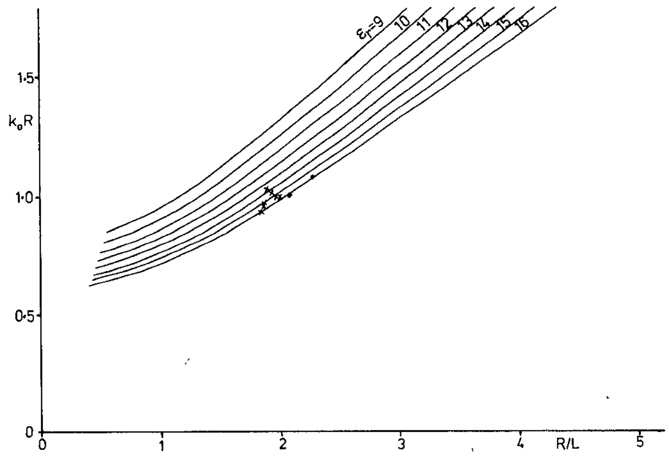

Fig. 2. Mode chart for $TE_{01\delta}$ mode.

where

$$k^2 = \omega^2\mu_0\mu_r\varepsilon_0\varepsilon_r - \beta^2, \qquad \beta = \frac{2\pi}{\lambda_g}.$$

A factor of $e^{j(\omega t - \beta z)}$ is omitted in the field equations.

The boundary condition for the open dielectric waveguide is $H_z = 0$ at $r = R$. The result is

$$kR = 2.405$$

where k is given previously.

For a quarter-wave dielectric resonator open circuited at one end and short circuited at the other

$$L = \frac{\lambda_g}{4}.$$

Combining the last two equations yields

$$k_0 R = \frac{1}{\sqrt{\mu_r\varepsilon_r}}\left[\left(\frac{\pi}{2}\frac{R}{L}\right)^2 + (2.405)^2\right]^{1/2}.$$

The results are given here in the form of a mode chart from which the ferrite shape may be obtained. This is shown in Fig. 2 in the form k_0R versus R/L for $\mu_r = 1.0$. It applies to the single cylinder of length $2L$ and diameter $2R$ which is open circuited at both ends and for which $H_z = 0$ at $r = R$. It also applies to a disk L long, short circuited at one end and open circuited at the other. Some experimental results obtained at Ferranti Ltd., Dundee, Scotland, and in this work are superimposed on the mode chart for *H*-plane waveguide-junction circulators using the coupled-disk geometry, and they suggest that the higher order mode is indeed the $TE_{01\delta}$ open dielectric resonator one.

Fig. 3 depicts the mode charts for the counterrotating and higher order modes. This illustration shows that the separation

Manuscript received May 15, 1975; revised November 24, 1975.
The authors are with the Department of Electrical and Electronic Engineering, Heriot-Watt University, Edinburgh, EH1 2HT, Scotland.

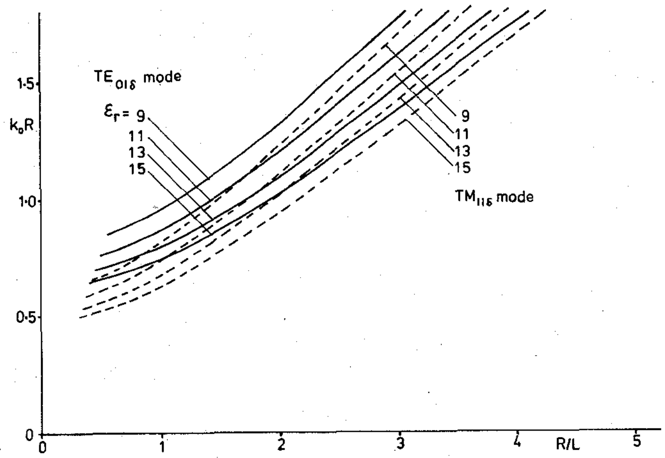

Fig. 3. Mode charts for $TE_{01\delta}$ and $TM_{11\delta}$ modes.

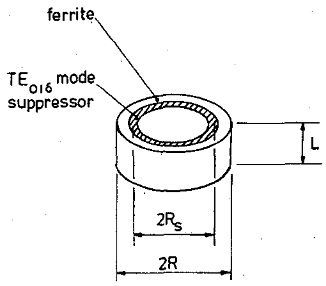

Fig. 4. Dielectric resonator with mode suppressor.

between these modes does not exhibit a strong dependence on the aspect ratio R/L. This is precisely the problem encountered in the design of waveguide circulators using coupled open dielectric resonators.

Effect of Saturation Magnetization on Separation Between the $TM_{1,1,\delta}$ and $TE_{0,1,\delta}$ Modes

It is experimentally observed in many waveguide junctions that the higher order mode of the junction is a function of the direct magnetic field used to bias it. This suggests that the saturation magnetization of the ferrite material may be used as a suitable independent variable to influence its frequency. However, some results obtained on a 6-GHz device WR 137 waveguide for three different magnesium ferrite materials do not support this assumption.

In the experimental work the saturation magnetizations were 0.1500, 0.1750, and 0.2150 Wb/m^2. The junctions were slightly perturbed in each instance to ensure similar frequency characteristics. However, since the partial magnetization remains essentially unchanged in the experiment, the higher order mode is not significantly shifted in frequency by the saturation magnetization of the material.

This result also suggests that many junctions are constructed using materials with values of saturation magnetizations which are too large for the ripple level and bandwidth of the device.

$TE_{0,1,\delta}$ Mode Suppressor

One method of constructing mode suppressors consists of using thin wires parallel to the electric field [8]. The electric field of the $TE_{01\delta}$ mode forms loops perpendicular to the axis of the dielectric cylinder. This suggests that a thin metal ring placed on the open face of the disk should detune this mode since it will be parallel to the electric field. This is in fact found

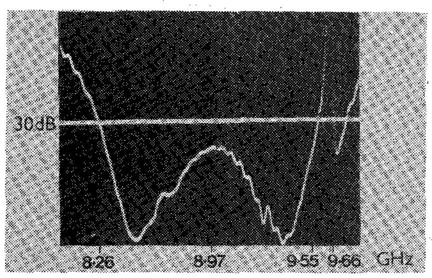

Fig. 5. Frequency responses of 9-GHz waveguide circulator without mode suppressor.

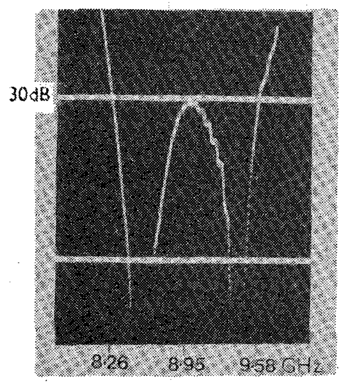

Fig. 6. Frequency responses of 9-GHz waveguide circulator with mode suppressor.

to be the case. Fig. 4 shows the dielectric resonator with such a thin metal ring suppressor. Since the electric field of the $TM_{11\delta}$ circulation mode is perpendicular to the metal ring, it is not perturbed by it provided the thickness of the wire is kept small.

The radius R_s at which the electric field of the $TE_{01\delta}$ mode is a maximum is given by

$$kR_s = 1.841$$

which gives

$$\frac{R_s}{R} = \frac{1.841}{2.405} = 0.765.$$

Figs. 5 and 6 show some results obtained on a 9-GHz circulator in WR 90 waveguide with and without the mode suppressor. The experimental results obtained here apply to an arrangement which uses only one loop. The insertion loss of the final device was 0.15 dB. One ring was found to be sufficient to decouple the coupled higher order modes of the two disks. Although two rings also suppressed the $TE_{01\delta}$ mode, the insertion loss of the junction was increased to about 1 dB.

Conclusion

This letter indicates that the unwanted higher order mode often encountered in the design of the radial waveguide circulator using coupled-ferrite open resonators is the $TE_{01\delta}$ one. The mode chart for this mode is derived and found to be in good agreement with the experiment. A mode suppressor which consists of a thin metal ring on the open face of the two resonators is also described.

References

[1] B. Owen and C. E. Barnes, "The compact turnstile circulator," *IEEE Trans. Microwave Theory Tech.* (*1970 Symposium Issue*), vol. MTT-18, pp. 1096–1100, Dec. 1970.
[2] B. Owen, "The identification of modal resonances in ferrite loaded waveguide Y-junction and their adjustment for circulation," *Bell Syst. Tech. J.*, vol. 51, pp. 595–627, Mar. 1972.

[3] J. Helszajn, "Waveguide and stripline 4-port single-junction circulators," *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-21, pp. 630–633, Oct. 1973.
[4] Y. Akaiwa, "Operation modes of a waveguide *Y* circulator," *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-22, pp. 954–960, Nov. 1974.
[5] J. Helszajn and F. C. Tan, "Design data for radial-waveguide circulators using partial-height ferrite resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 288–298, Mar. 1975.
[6] ——, "Mode chart for partial-height ferrite waveguide circulators," *Proc. IEE*, vol. 122, pp. 34–36, Jan. 1975.
[7] J. B. Castillo and L. E. Davis, "Identification of spurious modes in circulators," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-19, pp. 112–113, Jan. 1971.
[8] A. Karp, H. J. Shaw, and D. K. Winslow, "Circuit properties of microwave dielectric resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 818–828, Oct. 1968.

Complex Permittivity and Penetration Depth of Muscle and Fat Tissues Between 40 and 90 GHz

JOCHEN EDRICH AND PATRICK C. HARDEE

Abstract—**First measurements of the complex permittivity and penetration depth of millimeter waves in fat and muscle tissue are reported. A new phaseless reduction technique is used. Significant variations of tissue properties after death were found.**

I. Introduction

The complex permittivity $\varepsilon^* = \varepsilon' - \varepsilon''$ as well as the penetration depth δ of electromagnetic radiation for human and animal skin, muscle, bone, and fat tissues has previously been studied in the microwave region up to approximately 24 GHz [1]–[4]. No published data exist above this frequency. However, the recent expansion of communications and radar into the millimeter wavelength region as well as the exploration of millimeter wave thermography of the human body [5] makes it desirable to determine the electrical properties of certain biological tissues in the frequency range above 24 GHz.

II. Theoretical Considerations

The complex permittivity of structurally well-defined materials with high dielectric constants like ceramics is conventionally determined by measuring the reflection coefficient or by changing the sample length [6]. Both of these methods were found to be unsuitable for the measurement of fresh tissue at the very short millimeter wavelengths. Dimensional variations caused large uncertainties in the angle of the reflection coefficient and therefore unacceptable errors of ε^*. The high values of ε' and ε'' of tissue also require a very short sample length (< 0.5 mm) for the second method which involves a change of the sample length; however, repeated slicing of fresh and therefore soft tissue to this thickness within the required accuracy of about 0.01 mm is very difficult if not impossible.

Therefore only the VSWR values obtained from reflection measurements of tissue could be used. The tissue samples measured were enclosed in a section of standard-height waveguide [7] or placed against the open end of a waveguide [8]. The reflection technique involving the open-ended waveguide allowed *in situ* measurements and also made it possible to complete the measurements readily, before an alteration of the tissue properties could take place. In a third measurement the insertion loss of the same tissue sample enclosed in a waveguide section was determined. Assuming single-mode propagation,

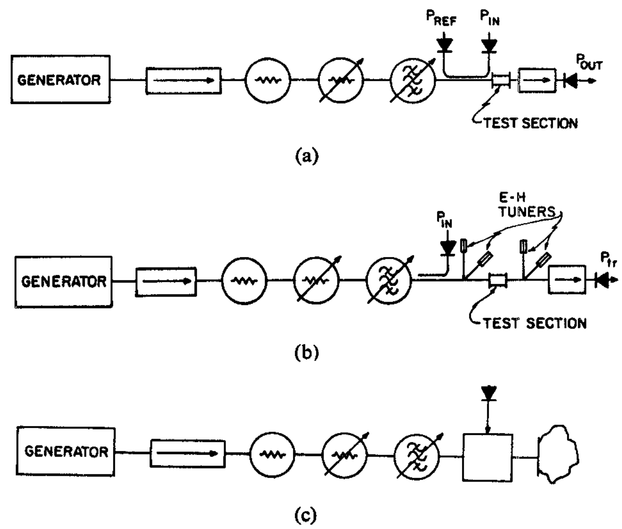

Fig. 1. Reflection and transmission measurement configuration of waveguide-enclosed samples [(a) and (b)] and VSWR measurement using the *in situ* method [(c)].

one can determine from this loss the penetration depth δ where the field strength reduces to $1/e$ of its original value. For operation far above the cutoff frequency of the waveguide, one can express the complex permittivity ε^* and the penetration depth δ of tissue by the following simplified equations [8]:

$$\varepsilon^* = \varepsilon_r \varepsilon_0 - j\sigma/\omega = \mu_0/\bar{Z}^2 + \pi^2/(\omega^2 \mu_0^2 a) \quad (1)$$

and

$$\delta = c_0(\varepsilon_r^2 \omega^4 + \sigma^2 \omega^2 \varepsilon_0^{-2})^{-1/4} \sin^{-1} \{0.5 \arctan [\sigma/(\omega \varepsilon_r \varepsilon_0)]\} \quad (2)$$

where c_0, ε_0, and μ_0 represent the velocity of light, the dielectric constant, and the permeability of free space, respectively. $\bar{Z}$ is the complex impedance of the tissue sample imbedded in a waveguide section of width a measured at the radian frequency ω. Another assumption made in the foregoing equation is that multiple reflections within the tissue samples are negligibly small; this assumption is reasonable for high values of ε_r and σ despite the short sample length l (l = 1.5 mm for muscle, and l = 6 mm for fat).

The method used for the determination of ε_r and σ consisted in calculating ε_r and σ for a given VSWR as a function of the phase angle of the reflection coefficient according to (1). Given ε_r and σ one can calculate a theoretical value of the penetration depth δ as a function of the phase angle according to (2). Assuming single-mode propagation one can now use the experimentally used value of δ to find the correct phase angle and hence the correct values for ε_r and σ.

III. Experiments

The experimental investigation of the tissue properties was carried out over the two frequency bands 40–54 GHz and 85–90 GHz. Fig. 1 shows the basic setups for the various reflection and transmission measurements. A thin mica window at the tissue sample helped to control the geometry of the tissue and minimize the generation of higher order propagation modes [9].

A jig made out of an opened section of waveguide was used to cut the samples accurately with a slot-guided razor blade (Fig. 2a). Afterwards this waveguide section was covered with a lid and the tissue block pushed against the mica window in the test flange section (Fig. 2b). Special care was taken to obtain a well-

Manuscript received September 19, 1975; revised December 17, 1975.
The authors are with the Department of Electrical Engineering and the Denver Research Institute, University of Denver, Denver, CO 80210.