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The Reference Plane of the Inverted Re-entrant Turnstile Junction Circulator

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Abstract*— The characterization of the turnstile circulator is usually arbitrary undertaken at the physical terminals of the resonator. This plane does not, in general, ensure that the electrical and mechanical planes of the junction coincide. The purpose of this paper is to characterize the first of the two circulation conditions of the junction outside its mechanical plane by introducing a short radial waveguide (U.E.) at each port of the resonator. The U.E.'s separately serve to decouple the junction from any quarter-wave transformer in the design of practical degree-2 circulators. The phase error of the no uniform radial annulus connecting the circular resonator to the triplet of uniform rectangular waveguides compared to that of a uniform waveguide is given special attention. The paper includes the optimization of a degree-2 junction.

Index Terms— **Circulators, eigenvalues, first term, second term, third term, fourth term, fifth term, sixth term.**

I. INTRODUCTION

The adjustment of many commercial waveguide circulators may be reduced to that of two so called circulation conditions [1]–[6]. The first essentially fixes all the physical variables of the junction except for the gyrotropy of the resonator and the second fixes the gyrotropy. One practical approach, is to meet the first by having recourse to a numerical calculation and to satisfy the second experimentally. The purpose of this paper is to deal with the first condition in the case of a waveguide re-entrant or inverted re-entrant turnstile junction. It is met provided that its in-phase and degenerate counter-rotating reflection eignevalues of the junction are commensurate and are 180 deg. out of phase at the mechanical boundary of the resonator. The innovation introduced here is to place the resonator on an oversized platform in order to located the reference plane of any matching network outside the fringing field of the junction. The introduction of this off-set goes a long way in reconciling the foreshortening of the electrical length of the U. E. met in practice from its ideal value of 90 deg. One numerical method that has been introduced in connection with a 2-port switch using a turnstile junction is obtained by satisfying the return loss at one port with the other terminated in a matched load using a mode matching (M.M.) engine [7]. It is extended here in the case of a 3-port junction. Another method is obtained by meeting the relationship between the in-phase and degenerate counter-rotating eigenvalues at the terminals of the junction using a finite element (F.E.) algorithm [4]. The required boundary condition is solved using both methods and verified by measurements. The reference plane in the M.M method is obtained by assuming that the optimization plane is connected to the resonator by a uniform waveguide, whereas in the F.E. method this is established exactly by constructing a separate drawing with the ferrite or dielectric resonator replaced by a metal post. It is shown that of the assumption that the resonator is connected to the triplet of rectangular waveguides by similar waveguides only produces a second order offset in the reference phase and may perhaps be neglected for the purpose of engineering.

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Both a small and large gap so called solution have been identified and verified recently in connection with a 2-port switch using such a resonator in a similar standard WR75 waveguide. The geometry investigated in this paper is restricted to the large gap solution. A small gap solution in WR90 waveguide is described in [7] and a large gap solution in WR229 waveguide in [4]. The work in this paper is undertaken in standard WR75 waveguide at a frequency of 13.25 GHz. Some early literature on the operation of the turnstile circulator is available in [8]-[18]

II. THE INVERTED RE-ENTRANT TURNSTILE JUNCTION USING AN OVERSIZED PLATAFORM

The junction under consideration is the H-Plane inverted re-entrant turnstile circulator illustrated in Fig. 1. Its operation is a classic topic in the literature and shall not be revisited here [3], [4]. It is described in terms of an in-phase and a pair of degenerate counter-rotating 1- port reflection eigenvalues. The in-phase geometry consists of a region with the dielectric constant of the ferrite and a region with the dielectric constant of the gap between the circular plates. The counter-rotating eigenvalues are determined by a pair of degenerate modes in a quarter wave long cylindrical resonator open-circuited at one flat face and short circuited at the other. The geometry is defined by the free space wave number k_0, the aspect ratio of the resonator R/L (radius and length), the gap factor q_{eff} of the junction and the radial wave number k_0R. q_{eff} is separately fixed by the gap S between the open face of the resonator and the top wide wall of the waveguide. The additional independent variable is the radius of the resonator mount, R_0/R. It is introduced here R_0 in order to place the reference plane of the junction outside the fringing field of the geometry. The arrangement under consideration is depicted in Fig. 2.

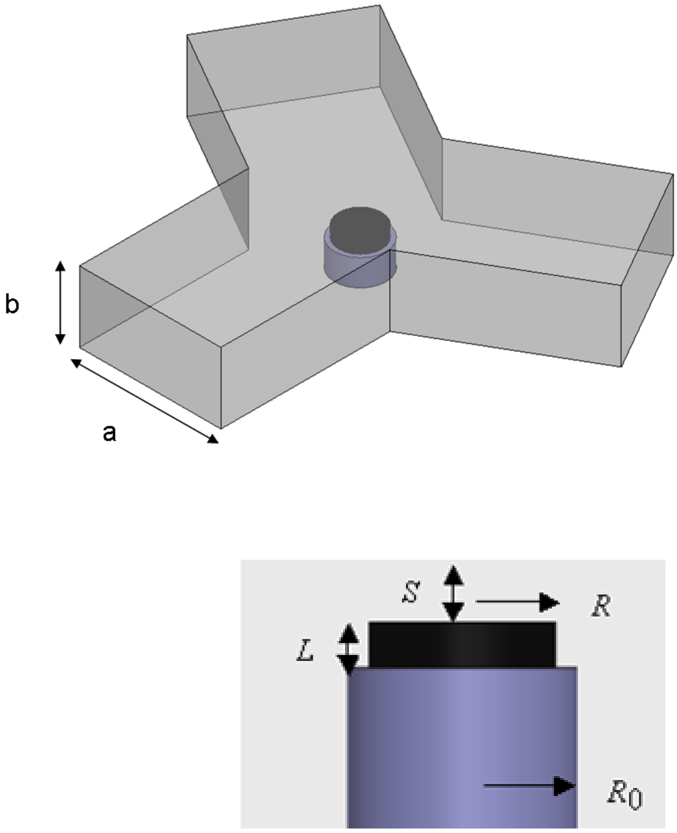

Fig. 1. Schematic diagram of inverted re-entrant junction.

The problem under consideration is undertaken at a frequency of 13.25 GHz in standard WR75 waveguide with side dimensions a and b. The independent quantities are

$$a = 2b$$

$$\frac{f_0}{f_c} = 1.683$$

$$k_0 = 0.278\,rad$$

$$\varepsilon_f = 15.0$$

$$R_0 = 1.10R$$

The ratio of the radius R and length L of the resonator is restricted in this work to

$$\frac{R}{L} = 2.0$$

The gap factor q_{eff} is defined in terms of the gap S between the open face of the resonator and the top wall of the waveguide and the length of the resonator, L, by

$$q_{eff} = \frac{L}{L+S} \tag{1}$$

The dependent variables are $k_0 R$ and, q_{eff} .

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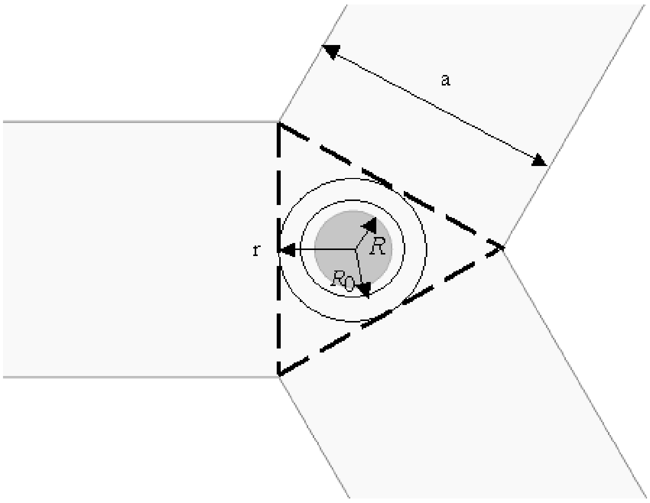

Fig. 2. **Planar view of inverted re-entrant junction**

III. THE FIRST CIRCULATION CONDITION OF THE 3-PORT-JUNCTION CIRCULATOR

The first circulation condition of the junction circulator may be deduced by either minimizing the return loss at one port with the other two terminated in matched loads or by satisfying its eigenvalue problem. Each approach has its origin in the relationships between the scattering parameters of the junction and its reflection eigenvalues.

The connection between the scattering parameters of a reciprocal and symmetric 3 port junction and its in-phase degenerate counter-rotating reflection eigenvalues are specified in the usual way by

$$S_{11} = \frac{\rho_0 + 2\rho_{\pm}}{3} \tag{2a}$$

$$S_{21} = S_{31} = \frac{\rho_0 - \rho_{\pm}}{3} \tag{2b}$$

The reflection eigenvalues have unit amplitude and are specified by the angles ϕ_0 and $\phi_\pm$

$$\rho_0 = 1.\exp - j\phi_0 \tag{3a}$$

$$\rho_\pm = 1.\exp - j\phi_\pm \tag{3b}$$

One possible first circulation condition of a junction circulator is satisfied provided

$$\rho_0 = -1 \tag{4a}$$

$$\rho_+ = \rho_- = +1 \tag{4b}$$

This gives

$$\phi_0 = \pi\, rad. \tag{5a}$$

$$\phi_\pm = 2\pi\, rad. \tag{5b}$$

The other definition of the first circulation condition is defined by

$$S_{11} = \frac{1}{3} \tag{6a}$$

$$S_{21} = S_{31} = -\frac{2}{3} \tag{6b}$$

This solution coincides with a return loss a (R.L.) of 9.5dB at port 1 of the junction with the other two ports terminated in matched loads.

IV. THE OPTIMUM REFERENCE PLANE

The junction under consideration is a quarter wave long circular resonator with a radius R with an electric wall on one flat face and a magnetic one on the other mounted on a circular platform with a radius R_0 in a radial waveguide region connected to a triplet of rectangular waveguides. The arrangement under consideration is indicated in Fig. 3a. The internal radius of the equilateral triangle formed by the intersection of the three waveguides is

$$r = \frac{a}{2\sqrt{3}} \tag{7}$$

The radius of the resonator may be calculated using a typical trial value for its radial wave number

$$k_0 R = 0.80 \quad (say) \quad rad. \tag{8}$$

The linear length of the radial annulus is

$$l = r - R_0 \tag{9}$$

The exact calibration of the problem region is established by constructing an auxiliary drawing which embodies the exact geometry of the region. The resonator is either replaced by a metal post or by locating a short circuit plate across the waveguide. The approximate calibration procedure translates the scattering parameters at the port terminals to those of the resonator by assuming that the two are connected by a uniform length of waveguide instead of a radial one.

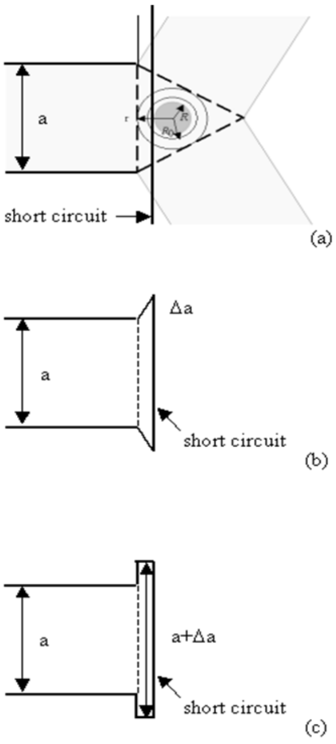

Fig. 3. (a) Schematic diagram showing reference plane of turnstile junction. (b) Topology of 1-port nonuniform calibration network. (c) Equivalent waveguide representation.

The 1-port network obtained by placing a short-circuit plate across the waveguide at the terminals R_0 of the resonator is separately indicated in Fig. 3b. It embodies a short nonuniform tapered waveguide that has to be accounted when the resonator is assumed to be connected by a uniform line. The error of neglecting this region will now be deduced by replacing the tapered waveguide by a uniform one with a waveguide opening equal to the arithmetic means of the input and output waveguides.

The maximum displacement $2\Delta a$ of the tapered waveguide from that of the regular one is

$$2\Delta a = 2\sqrt{3}\left(r - R_0\right) \quad mm \tag{10}$$

An appreciation of the phase error produced by this nonuniform section may be deduced by replacing it by a uniform waveguide with a width

$$a \quad = a + \Delta a \quad \mathrm{mm} \tag{11}$$

The absolute phase of the equivalent waveguide in Fig.3c is

$$\phi_1 = \beta_1\left(r - R_0\right) \quad rad / mm \tag{12}$$

The absolute phase shift across a uniform waveguide with the same mechanical length is

$$\phi_2 = \beta_2\left(r - R_0\right) \quad rad / mm \tag{13}$$

The phase error is

$$\phi_1 - \phi_2 = (\beta_2 - \beta_1)(r - R_0) \quad rad/mm \tag{14}$$

A typical calculation in WR75 waveguide at a frequency of 13.25 GHz is summarized below

$$a = 19.05\,mm$$

$$r = 5.50\,mm$$

$$R = 2.88\,mm$$

$$l = 2.62\,mm$$

$$\Delta a = 4.53\,mm$$

$$\Delta\beta = 0.031 \ \ rad/mm$$

$$(\Delta\beta)l = 0.081 \ \ rad$$

This calculation indicates that the phase error produced in assuming that the resonator terminals are connected to the feed waveguides by uniform waveguides is of the order of 4.62 deg. This calculation indicates that the phase error produced in assuming that the resonator terminals are connected to the feed waveguides by uniform waveguides is of the order of 4.62 deg.

V. THE EIGENVALUE METHOD

Some calculations on the first circulation condition of the inverted re-entrant turnstile circulator with the mount off-set from that of the resonator using the eigenvalue method are summarized in this section. This is done in standard WR75 waveguide at a frequency of 13.25 GHz. The required condition coincides with that for which the in-phase and counter-rotating eigen-networks are commensurate and its reflection coefficients are out of phase.

A typical solution obtained in this way at the plane of the mount with R_0/R equal to 1.10 is illustrated in Fig. 4. The result is

$$k_0 R = 0.825\ rad$$

$$q_{eff} = 0.429$$

The Smith Chart of its frequency response at port 1 is indicated in Fig. 5. The in-phase and degenerate eigen-solutions obtained with R_0/R equal to 1.0, 1.05, and 1.15 and 1.2 are separately summarized in Fig. 6 and Fig. 7. The first circulation condition is illustrated in Fig. 8 for parametric values of R_0/R. Each solution has been individually verified by constructing the appropriate Smith chart.

Polynomial representations of this graphical solution are

$$k_0 R = a + b\left(\frac{R_0}{R}\right) + c\left(\frac{R_0}{R}\right)^2, \quad \frac{R}{L} = 2.0 \tag{15a}$$

Where

a = 1.3078

b = -0.6291

$$c = 0.1714$$

and

$$q_{eff} = d + e\left(\frac{R_0}{R}\right) + f\left(\frac{R_0}{R}\right)^2, \quad \frac{R}{L} = 2.0 \qquad (15b)$$

$$d = -0.3436$$

$$e = 1.027$$

$$f = -0.2874$$

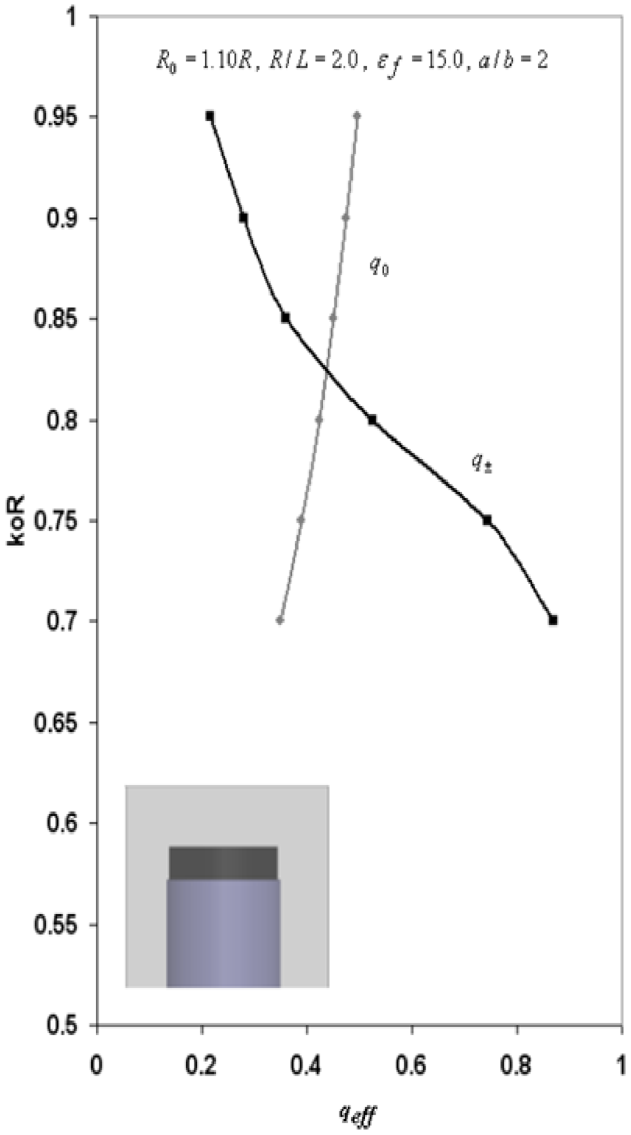

Fig. 4. .In-phase and counter-rotating eigenvalues at 13.25 GHz. in standard WR75 waveguide. (R/L=2.0).

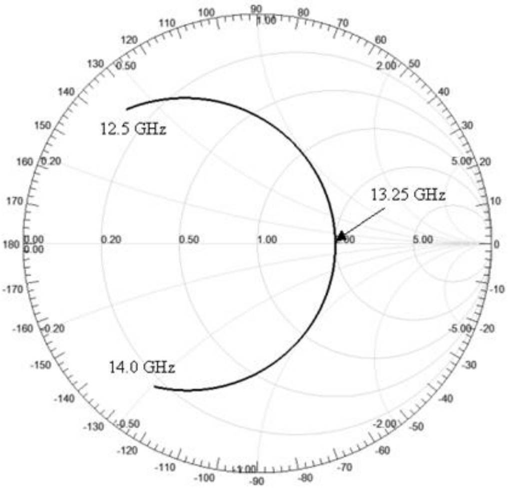

Fig.5. Smith chart of first circulation condition of inverted re-entrant junction about 13.25GHz in standard WR75 waveguide. (R/L=2.0).

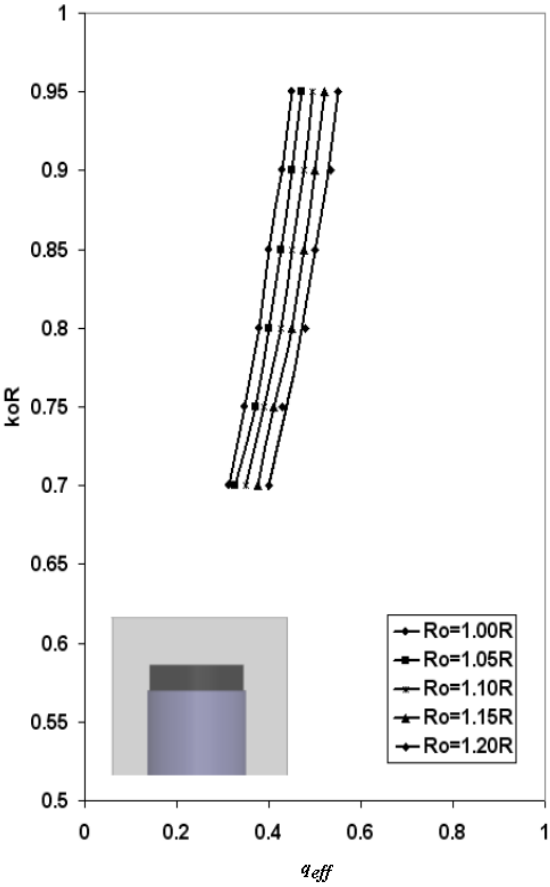

Fig. 6.. In-phase eigenvalue of inverted re-entrant turnstile junction at 13.25GHz in standard WR75 waveguide for parametric values of R_0 / R.

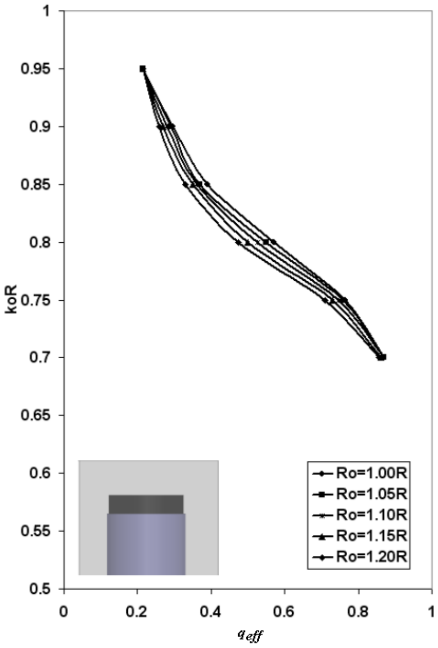

Fig. 7. Degenerate counter-rotating eigenvalues of inverted re-entrant turnstile at 13.25GHz in standard WR75 waveguide for parametric values of R_0 / R.

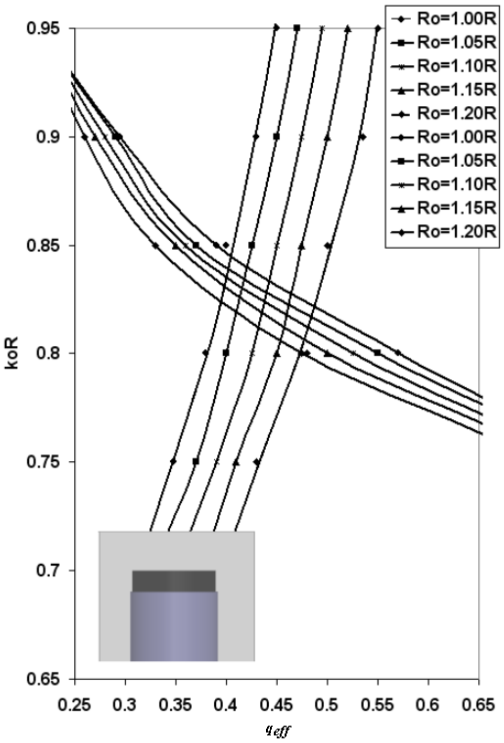

Fig. 8. First circulation condition of inverted re-entrant turnstile junction at 13.25GHz in standard WR75 waveguide for parametric values of R_0 / R. (R/L=2.0, $\varepsilon_f = 15.0$)

The frequency responses of two typical arrangements are separately compared in Fig. 9. This result suggests that the factor R_0 / R has no significant effect on the bandwidth of the junction.

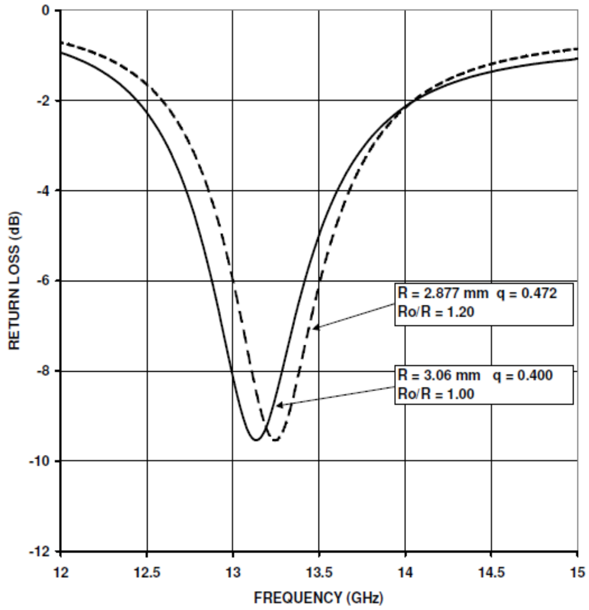

Fig. 9. Return losses of inverted re-entrant junctions, with R_0 / R equal to 1.0 and 1.20 about 13.25GHz in standard WR75 junction with R_0 / R equal to 1.0 and 1.20.

VI. THE REFLECTION COEFFICIENT METHOD

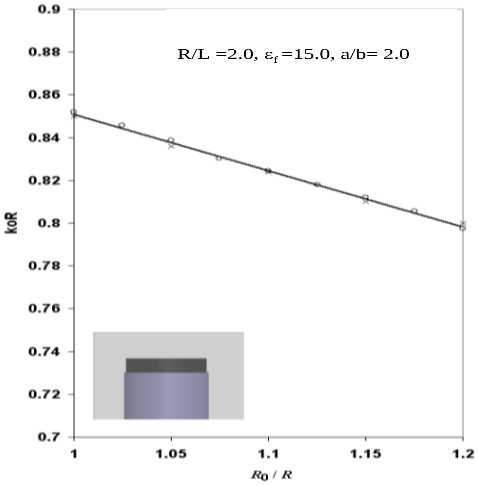

Fig. 10. Connection between $R_0 / R$and k_0R at 13.25GHz in standard WR75 waveguide. (R/L=2.0). × Eigen value method, ° K_0R (M.M).

The second possible numerical method is obtained by varying the details of the junction in order to minimize the return loss at one port at some distance from the junction with the other two terminated in matched loads. The numerical procedure employed in this instance is based on a propriety mode matching (M.M.) engine. The independent variables are again k_0 and R/L. It involves satisfying $\rho_0 = -\rho_{\pm}$ at some arbitrary plane without insisting that the two are commensurate. This is again done for parametric values of R_0 / R. The results obtained in this way are compared in Fig. 10 and Fig. 11 with those obtained by optimizing the individual eigenvalues.

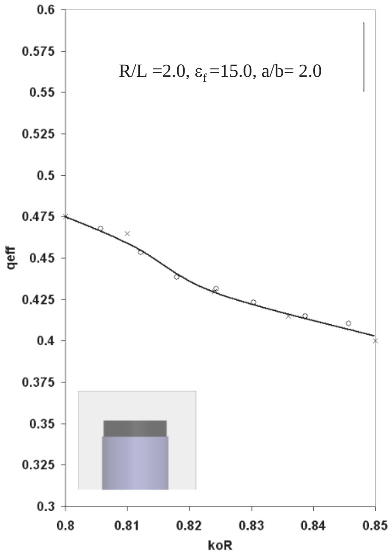

Fig. 11. Connection between $k_0 R$ and q_{eff} at 13.25GHz in standard WR75 waveguide. (R/L=2.0). × q_{eff} (Eigen value method), ° q_{eff} (M.M)

VII. LARGE GAP FABRICATION

The calculations undertaken here have been verified by fabricating one assembly in WR75 waveguide at a frequency of 13.25 GHz. The solution adopted for this purpose is described by

$$R_0 / R = 1.20$$

$$k_0 = 0.278\,rad / mm$$

$$R / L = 2.0$$

$$k_0 R = 0.80$$

$$q_{eff} = 0.475$$

$$\varepsilon_f = 15.0 \pm .10$$

The experimental and calculated frequency responses of this junction are compared in Fig. 12. The discrepancy between the two is in part due to the tolerance on the relative dielectric constant of the ferrite material and in part due to the omission of the relative demagnetized e permeability of the magnetic insulator in the calculation. The resonator employed in this work is a demagnetized yttrium iron garnet insulator with a saturation magnetization M_0 equal to

$$\mu_0 M_0 = 0.1760T$$

Its demagnetized permeability is

$$\mu_{dem} = \frac{1}{3} + \frac{2}{3}\left[1 - \left(\frac{\gamma M_0}{\omega}\right)^2\right]^{\frac{1}{2}} \qquad (16)$$

γ is the gyromagnetic ratio ($2.21x10^5$ *rad* / sec *per A* / *m*), ω is the radian frequency (rad/sec.).

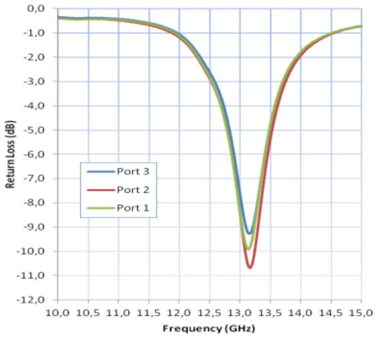

Fig .12. Comparison between calculations and experiment of return loss of inverted re-entrant junction about 13.25GHz in standard WR75 junction. $(R_0 / R = 1.20)$.

VIII. THE DEGREE-2 INVERTED RE-ENTRANT TURNSTILE JUNCTION

The type of junction under consideration is usually realized as a degree-2 circuit by introducing a suitable impedance transformer at each port. Fig. 13 depicts a schematic diagram of the arrangement. One practical geometry shown in Fig. 14 consists of a triplet of quarter wave long ridge transformers at the planes of the resonator mount. An F.E. adjustment of the frequency response of the device in the case for which R_0 / R equals 1.20 is indicated in Fig. 15. The mid-band return loss of this solution is again 9.5 dB. This result applies to a ridge waveguide transformer for which

$$s / a = 0.66$$

$$d / b = 0.5$$

a and b are the side dimensions of standard WR75 waveguide, s and d are the width and the gap of the ridge geometry respectively.

The technique employed to obtain this result consisted of inserting a 180 deg. UE in rectangular waveguide between the reference planes of the ridge waveguide and that of the measurements. This arrangement ensures that the admittance at the measurement plane in the rectangular waveguide coincides with that of the ridge section. The electrical length of the UE is then set by choosing trial values of s/a and d/b for ridge UE as a preamble to adjusting its length.

The guide wavelength of the ridge waveguide is

$$\frac{\lambda_0}{\lambda_g} = 0.841$$

The contrasts between the dispersion's of the degree 1 and 2 arrangement is in keeping with some work elsewhere [15].

The closeness of the electrical length of a typical transformer section to its optimum value of 90 deg. is a measure of the robustness of the definition of the reference plane of the junction. It is historically given by about 70 deg. but here is given by

$$l = 108\,\mathrm{deg}\,.$$

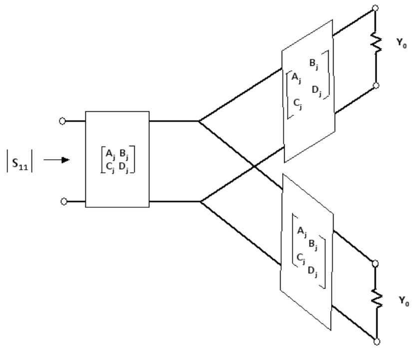

Fig. 13. Schematic diagram of degree-2 reciprocal 3-port H-plane junction.

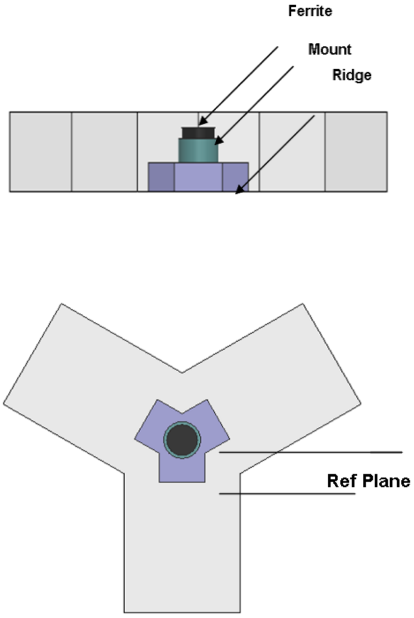

Fig. 14. Schematic diagram of inverted re-entrant turnstile junction with triplet of ridge waveguides.

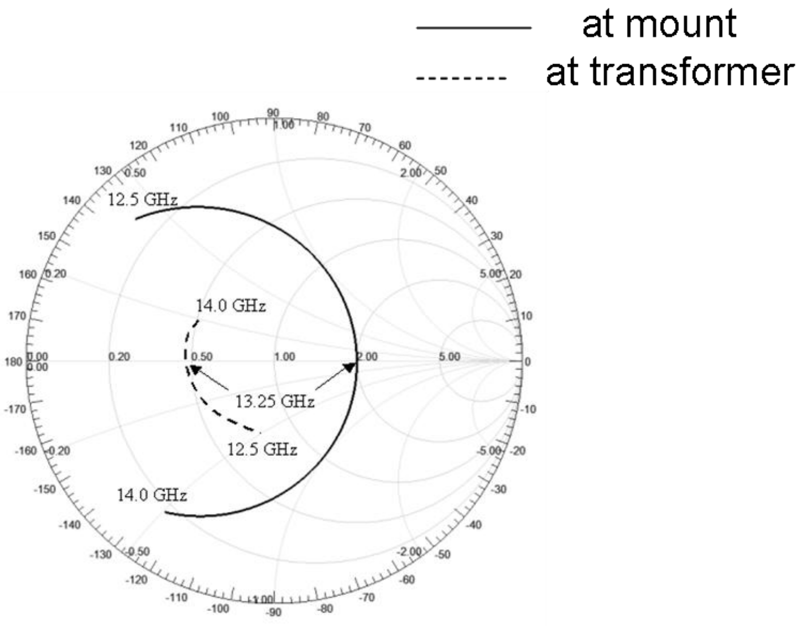

Fig. 15. Frequency response of inverted re-entrant turnstile junction with triplet of ridge waveguides.

The departure of the electrical length of the quarter wave transformer from its ideal value of 90 deg. is in part due to the perturbation of the illumination of the resonator produced by replacing the rectangular waveguide feeds in the characterization of the first circulation condition by a ridge structure.

IX. CONCLUSIONS

The geometry of the classic re-entrant or inverted re-entrant turnstile waveguide circulator consists of a quarter-wave long gyro magnetic resonator mounted on a metallic platform with its open flat face separated from the top waveguide wall by a gap. The counter-rotating reflection eigenvalues, in this arrangement are fixed by the resonator geometry and the in-phase one by the details of the gap. The perturbation in the first circulation condition of such a junction circulator produced by off-setting the radius of the platform from that of the resonator is the main endeavour of this paper. The paper includes measurements on one experimental arrangement. It is in good agreement with the calculation undertaken in this work. Whereas the results obtained are very good, the present study could be further developed with different geometries as this work has been carried out in a specific type of waveguide and with restrictions in the gap length.

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