An FE Adjustment of a Waveguide Turnstile Junction Circulator Using a Three Quarter Wavelength Gyromagnetic Resonator

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Abstract - One difficulty with the design of millimetre waveguide junction circulators using quarter-wave long gyromagnetic resonators, beside that of fabrication, is the inability to realize the required gyrotropy using existing ferrite materials. This shortcoming fundamentally restricts not only the gain bandwidth product of a degree-2 circulator but also produces complex gyrator circuits which are incompatible with those using single quarter wave long resonators. There is no way to alleviate the former difficulty but one way to partly deal with the latter is to have recourse to a three-quarter wave long gyromagnetic resonator in a re-entrant cavity. The purpose of this paper is to adjust the first circulation condition of one device in WR15 waveguide using a 3 dimensional commercial F.E. solver and adjust the second one experimentally.

# Introduction

T

he inability to increase the magnetization (0M0) of ferrite materials beyond about 0.5000T restricts the gain bandwidth product of standard circulators above 40 GHz. It also produces unduly large element values in the descriptions of the G-STUB loads entering in the synthesis of a degree-2 specification. The actual element values depend in part upon whether 90 deg. UE’s, or 180 deg. UEs are used for the matching networks. There is little that can be done about the former product but the shortcoming of the latter can to some extent be alleviated by having recourse to a higher order planar or turnstile gyromagnetic resonator. The purpose of this paper is to adjust a re-entrant turnstile junction in WR15 waveguide using one or two three quarter-wave long resonator open circuited at one end and short circuited at the other [11]. The possibility of using such resonators has been mentioned in [1] but has not been embodied in a degree-2 arrangement so far. It is necessary, in order to accommodate this sort of resonator in a degree-2 structure, to recess it into the body of the waveguide. The geometry of the arrangement investigated here is shown in figure 1a.

The susceptance slope parameter of the geometry using a single three quarter wave long resonator is typically three times that of a single quarter wave arrangement.

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Such resonators are appropriate in the design of circulators for which the lower bound on the loaded

quality factor of the complex gyrator circuit of the junction is about 3½. The arrangement based on a 90 deg UE has been characterized separately from that based on a 180 deg UE. The first structure has to be done in half height waveguide and the second in full

**Fig. 1a Recessed three quarter wavelength turnstile geometry**

height waveguide. The two differ in that each has a different midband frequency as well as a complex gyrator circuit with a different quality factor.It may also be shown that the

gyrator conductance of a junction based on a three quarter-wave long gyromagnetic resonator is three times that of a single quarter-wave long resonator.

Figure 1b shows an arrangement utilizing a pair of 3λ/4 resonators.



**Fig. 1b geometry using a pair of 3λ/4 resonators**

The paper includes the design of a degree-2 junction in WR15 waveguide using a single resonator with a return loss of 23dB over a bandwidth of 13%. Its development relies on an F.E. solution of the first circulation condition of the degree-1 arrangement, an experimental adjustment of its second circulation condition, an F.E. adjustment of the first circulation condition of the degree-2 geometry and an experimental adjustment of the second degree-2 condition.

The phenomenological description of the circulator under consideration has been interpreted in terms of a Faraday rotation effect [1,2]. The interpretation of the so-called partial height circulator in terms of a turnstile junction has been introduced with in [3,4]. The nature of the split phase constant along a gyromagnetic waveguide is separately reviewed for the sake of completeness. The analysis of the turnstile waveguide circulator using various numerical techniques has been separately dealt with in the open literature [11] but these by and large fail to reconcile the network and e.m. relationships. Engineering papers are available in [11]

# The Degree-2 Circulator Using a single 90 deg. U.E.

The complex gyrator circuit of the 3-port circulator is a G-STUB load whose susceptance slope parameter (b’) and gyrator conductance (g) are ideally fixed by both its gain-bandwidth product and the matching network. The former quantity may be expressed in terms of the normalized bandwidth (20), return loss, RL, (dB), quality factor (QL) of the circuit in question and the degree of the frequency response. The gain-bandwidth product of a degree-n network is approximately defined by



The constant on the right hand side of this equation is, in practice, somewhat dependent upon both the minimum and maximum values of the return loss inside the passband and the degree of the circuit. The corresponding gain-bandwidth product of a degree-2 network is

 (4)

The G-STUB elements associated with the above gain-bandwidth product are, in practice, readily realizable provided the quality factor is equal or less than 2½. This condition cannot, however, be satisfied beyond about 20 GHz without a consequent degradation in the performance of the circulator.

The quality factor is given in the usual way by the ratio of the susceptance slope parameter (b’) and gyrator conductance (g) of the complex gyrator circuit of the junction

(2)

Figure 2 depicts two possible degree-2 arrangements of re-entrant circulators using three quarter wave long The connections between bandwidth and quality factor in the case of a degree-2 circuit, using a single 90 deg. U.E. are shown graphically for different ripple specifications in figure 3. The relationships between



**Fig. 2 Schematic diagrams of quarter-wave coupled turnstile circulator**

the bandwidth and the susceptance slope parameter b’ for one value of QL are indicated in figure 4. The gyrator conductance is separately specified by equation (2).

One often adopted solution for the ripple specification is

 (3)

A commercial circulator of some interest is one at 60 GHz in WR15 waveguide. A realizable value of quality factor at this frequency is



A possible specification is now obtained by introducing this value of quality factor into the gain bandwidth condition. One solution is described by a minimum return loss of 20 dB, a maximum one of 23 dB, and a bandwidth of 17.6 %. The complex gyrator circuit defined by this specification is separately fixed by





The admittance of the 90 deg. U.E. is

 (5)

The complex gyrator circuit obtained in this instance is

unfortunately outside that displayed by a junction employing a single quarter-wave long resonator. It can, however, be realized by having recourse to a higher order mode. Another possibility is to introduce a coupling iris on the open flat face of the resonator.

resonators.







**Fig. 3 Relationship between bandwidth, and quality factor of a degree-2 circuit for parametric values of return loss.**

**Fig. 4 Relationship between bandwidth, and susceptance slope parameter of degree-2 circuit using 90 deg. UE’s for parametric values of return loss.**

# The Short Line Transformer

Another impedance transformer met in the design of degree-2 junction circulators is the alternate line transformer. It consists, in its simplest form, of two electrically short U.E.’s with impedances of the load and generator impedance. The U.E. adjacent to the load is that of the generator one. It is perhaps the most appropriate arrangement in the design of millimeter devices in that the small gap section is offset from the terminals of the junction. Another attraction of this structure is that the characterization of its degree-1 complex gyrator circuit remains valid when embedded in a degree-2 geometry. Fig. 5 illustrates the schematic diagram of the arrangement under discussion.



**Fig. 5 Schematic diagram of degree-2 turnstile circulator using short line transformers**

# The Degree-2 Circulator Using a single 180 deg. U.E.

A difficulty with the design of the classic degree 2 circulator, using either a short line, or a 90 deg U.E., at millimetre wavelengths, is that the element values of its complex gyrator circuit become unrealizable when its quality factor, as is the case here, exceeds some critical value. One way to partly avoid this difficulty is to have

recourse to a matching network in the form of a filter circuit (11).

Fig. 6 illustrates the topology under discussion. The gyrator conductance (g) is in this kind of arrangement in the vicinity of unity and the susceptance slope parameter (b’) is equal to the quality factor (QL) of the gyromagnetic resonator. This sort of circuit is actually realizable with a quarter wave long gyromagnetic resonator.



**Fig. 6 Schematic diagram of a short-line coupled turnstile circulator.**

# Gyrotropy

The gain-bandwidth of a typical 3-port circulator is determined by the quality factor of its resonator. This quantity is uniquely fixed by the magnetization of the gyromagnetic material and the radio frequency of the resonator. In practice ferrite materials are available with values of magnetization (0M0) between 0.0250 T and 0.5000 T. This range of materials allows commercial specifications to be essentially reproduced anywhere between 100 MHz and 40 GHz. Above the latter frequency some significant degradation in performance is unavoidable.

The diagonal and off diagonal elements of the tensor permeability in a partially magnetised ferrite material are given by

 (5)

 (6)

d is the demagnetized permeability of the magnetic insulator.

 (7)

For a saturated material

 (8)

and

 (9)

 (10)

0M0 is the saturation magnetization of the ferrite material (T), 0M is that of the partially magnetized one,  is the gyromagnetic ratio (2.21 x 105 rad/sec per A/m), is the radian frequency (rad/sec), 0 is the free space permeability (4 x 10-7  H/m).

Good engineering demands that the material be saturated and this is the assumption here. In a junction magnetized below the so-called Kittel line the normalized magnetization resides between

 (11)

The lower bound represents the situation at high frequencies where the magnetisation of the magnetic insulator cannot be scaled. This quantity, at a frequency of 60 GHz is given by

 (12)

The condition M/M0 equal to unity is seldom achieved in practice so that the maximum value of the gyrotropy indicated above is seldom met. Taking M/M0=0.90 give

(13a)

 (13b)

# quality factor

The turnstile junction circulator is fundamentally different to the planar junction in that its operation relies on a Faraday rotation effect along a circular gyromagnetic waveguide instead of a rotation of a standing wave in a plane. A property of the Faraday rotation is that it is a distributed phenomenon, so that the angle through which the polarization rotates in a three quarter-wave length waveguide is three times that displayed by a single quarter-wave one. The corresponding split reflection angles and gyrator conductance are likewise scaled by the same factor. The complex gyrator circuit of the 3-port junction circulator is a 1-port STUB-G load. A separate condition on the quality factor of the complex gyrator circuit, besides that specified by the network problem in equation (2), is that defined in the usual way by the frequencies of the split counter-rotating eigen-networks [11].

 (14)

The split frequencies are a property of the gyromagnetic resonator and are given in [11].



C11 is a constant which embodies the variation of the alternating magnetic field across the open gyromagnetic resonator.



# Complex gyrator circuit

The two conditions for QL are compatible provided

 (15)

This equation indicates that the susceptance slope parameter and the split frequencies of the junction are independent variables and that the gyrator conductance is a dependent one.

A lower bound on the susceptance slope parameter which neglects the loading of the so called image wall of the junction is that of a short-circuited transmission line having an odd number of quarter-waves is

 (16)

where 

and m is the turns ratio of an ideal transformer which must either be computed or deduced experimentally. An approximate definition for the ideal transformer is

 (17)

F(qeff) is a function of the gap factor of the junction, a and b are the wide and narrow dimensions of the rectangular waveguide.

The quality factors of a quarter and a three quarter-wave long gyromagnetic resonator are therefore equal but the corresponding gyrator conductances and susceptance slope parameters differ by a factor of three.

The objective of this paper is to scale the design of a 60GHz circulator in WR15 waveguide using a ferrite material with a magnetization µ0M0 equal to 0.5000 T to 13.25 GHz in WR 75 waveguide. This may be done by preserving the quality factor and scaling the magnetization of the ferrite material. The gyrotropy of the junction at 60 GHz is 0.23 and the corresponding quality factor is 3.14. The magnetization at 13.25 GHz with the same value of gyrotropy µ0M0 = 0.1325 T.

# The First Circulation Adjustment of the Re-entrant Circulator Using a Three-Quarter Wave Resonator

The arrangement under consideration is a re-entrant turnstile junction using a three quarter-wave long open gyromagnetic circular waveguide with one open flat face and a short-circuit at the other at the junction of three rectangular waveguides. The specific geometry investigated here takes the length of the resonator as 3L and the thickness of the gap between the open-flat wall of the resonator and the piston on the broad waveguide wall as 3S. This nomenclature preserves the definition of the gap factor met in the description of the conventional circulator using a single quarter wave resonator with an open circuit at one flat face and a short circuit at the other.



This parameter is primarily set by the in-phase reflection eigenvalue.

The extent by which the resonator penetrates the body of the housing (L1) and the aspect ratio (R1/L1) of the re-entrant cavity are two other variables of the geometry. The penetration L1 is here taken, in order to accommodate a degree-2 realization as

Other parameters of the junction are the ratio (R/L), the radial wave number (k0R) and the dielectric constant (f). The demagnetized permeability d is another parameter that has to be taken into account. It is related to the magnetization of the magnetic insulator and the frequency of the device.

The adjustment of the 3-port junction circulator is a standard eigenvalue problem. It involves a single in-phase eigen-network and a pair of counter-rotating ones. The first of the two usual circulation adjustments of this class of junction is satisfied when the in-phase and degenerate counter-rotating eigen-networks are commensurate. This condition is met provided

**Fig. 7 Frequency response of three quarter wave long resonator**



where







andare pure polynomials in k0R which satisfy s0= -1 and s±= 1 for parametric value of R/L. The connection between qeff and k0R for parametric values of R/L is



qeff is calculated from eitheroronce k0R is deduced.

The first circulation condition of a junction using a three quarter-wave long resonator is shown in figure 8 for one penetration of the resonator into the housing.

It is characterized by a filling factor qeff of 0.11, an aspect ratio (R/L) of 2.0 and a radial wave number (k0R) of 0.11. The development of the quarter-wave geometry has been extensively discussed in the open literature and will not be reiterated here [11]. Fig. 11 shows a typical result.

The first circulation condition is incomplete without a remark about the susceptance slope parameter of the assembly. This is actually the main purpose of the present investigation. Figure 9 compares the frequency response of one resonator with that using a conventional single quarter wave geometry.

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**Fig. 8 Frequency response of quarter wave long resonator**

**Fig. 9 Comparison of ¾ and ¼ wavelength return losses**

# Second Circulation Condition of Re-entrant Circulator Using Three-Quarter Wave Resonator

The second circulation condition is obtained by removing the degeneracy between the counter-rotating eigen-networks of the junction. This operation fixes the quality factor of the complex gyrator circuit and the gain-bandwidth product of the circulator. If the complex gyrator circuit revealed in this way is compatible with an equal ripple degree-2 frequency response then the design can proceed.

The split frequencies, ±, appearing in the definition of the quality factor correspond to those for which the return loss coincides with the outer of the four frequencies at which the frequency response passes through 9½ dB points. The two inner frequencies are associated with discrete frequencies of the in-phase eigen-network. This result has until recently been experimentally interpreted on the basis of two single 9½ dB frequencies. The quality factor defined in this way may be processed both numerically and experimentally. Figure 8 depicts some calculations based on a commercial F.E. solver. The quality factors of junctions using one and three quarter-wave long gyromagnetic resonators are compared in figure 9.

The midband gyrator conductance may be extracted numerically or experimentally by having recourse to an existing relationship. This is done by making use of the connection between the return loss at the centre frequency of the junction and the gyrator conductance. [11]





A knowledge of QL and g also allows the susceptance slope parameter of the complex gyrator circuit to be deduced. The quantity evaluated in this way is illustrated in figure 11.

One difficulty with these relationships is that large values of gyrator conductance produce VSWRs which are difficult to accurately measure.

The finite element procedure has been restricted to saturated gyromagnetic materials so that only a single reading of the gyrator conductance is possible for any given material.

One geometry for which this quantity has been extracted in this work is that of a single H-plane turnstile junction using a quarter wave long resonator. The result obtained in this way is indicated in figure 10.

# Degree-2 Circulator

The degree-2 geometry may be fixed once the complex gyrator circuit of the junction is known and the matching topology is settled. The three possible network topologies are the 90 deg UE, the 180 deg. UE and the alternate line transformer. The impedance of the U.E.’s is realized by having recourse to ridge waveguide.

A feature of a junction circulator using a three quarter-wave long resonator is that its impedance is about three times smaller than that using a single quarter-wave geometry. The transformer impedance is therefore √3 times smaller and the gap between the ridge is that much smaller. The alternate line transformer employed here avoids the need to place such an impedance at the terminals of the resonator. The topology of the network is indicated in fig. 11

Fig.13 depicts the frequency response of the reciprocal junction obtained in this way. Fig.14 shows that of the experimental circuit obtained by magnetizing the same junction.

# Conclusion

Commercial ferrite materials are incompatible with the design of high quality degree-2 millimetre circulators. This difficulty may to some extent be alleviated by employing a higher order axial or planar modes in its construction. One purpose of this paper is to establish the complex gyrator circuit of one degree-1 device using a three quarter wave long gyromagnetic waveguide open-circuited at one flat face and short circuited at the other. This is done in both full and half height waveguides in order to cater for the perturbation of the junction associated with the aspect ratio of the radial waveguide housing the resonator. The other is to realize a scale model of a 60 GHz circulator in WR15 waveguide at 13.25 GHz in WR75 waveguide with degree-2 equal ripple specification. The first circulation condition of the degree-1 device is established using an F.E. solver and the second is adjusted experimentally. The first circulation condition of the degree-2 junction is again adjusted using a commercial F.E. solver and the second is once more dealt with experimentally.

Appendix A

# Split Phase Constants of Open Gyromagnetic Waveguides.

It is necessary, in order to place an upper bound on the gain-bandwidth product of a turnstile junction circulator, to have an accurate statement about the connection between the split phase constants and the gyrotropy of a gyromagnetic resonator with an open magnetic wall. Characteristic equations for the calculations of the split phase constants in a gyromagnetic waveguide with either electric or magnetic walls are classic results in the literature [1,2,3]. The characteristic equation of the partially filled gyromagnetic circular waveguide with an electric wall has been comprehensively dealt with in [ ]. This geometry enters into the description of the composite waveguide section embedded in the waveguide housing of the turnstile junction. A closed form solution of the magnetic wall geometry based on perturbation theory and one on a related anisotropic waveguide are also given in the literature. The agreement between the former description and the exact solution is particularly excellent. A characteristic equation of the open anisotropic gyromagnetic waveguide is described in [11]. The exact description of the gyromagnetic waveguide has historically been avoided in this sort of problem because of its complexity and the simpler approximate formulation based on perturbation theory has been used instead. The split phase constants obtained in this way are given by





The constant C11 embodies the variation of the alternating magnetic filed over the cross section of the waveguide



These quantities display both split phase constants and split cut off numbers in keeping with the exact solution. The result for the anisotropic waveguide is identical to that of the gyromagnetic one based on perturbation theory, except that the gyrotropy constant C11 is unity.

The validity of the perturbation formulation for the split phase constants may be extended by recognizing that these split phase constants can be reduced to the standard dispersion relationship below



The split cut-off numbers are defined by inspection by



defined in this way are readily recognized as the cut-off numbers of the related planar geometry with top and bottom electric walls and a magnetic side wall

This approach has actually been introduced in [11] but its presentation perhaps lacked some clarity.

The discrepancies between the split phase constants of the open and closed waveguides can, in part, be reconciled by replacing the actual waveguide by an ideal one but with and effective dielectric constant and an effective gyrotropy. The former is a much used artifice met in this kind of problem.

An estimate of the split propagation constants in an open gyromagnetic waveguide may be obtained from those of the open anisotropic waveguide by supposing that these are related in a similar way to that found in the case of the closed waveguide geometries. This may be done by replacing κ in the open anisotropic problem by .



where



and



If



then the characteristic equation reduces to that of the open isotropic waveguide.

J1(w) is the Bessel function of the first kind, K1(w) is the modified Bessel function of the second kind representing the transverse decay of the field components outside the rod, 

The discrepancy between the closed and open waveguides may be separately catered for by replacing C11 in the closed waveguide by



p is a correction term equal or less than unity. One engineering value is obtained by comparing the results of an open anisotropic waveguide with a closed geometry is



The gyrotropy constant entering into the description of the split phase constants of the resonator assumes that the direct magnetic flux density inside the geometry is uniform. This situation is of course, seldom satisfied in practice and may give rise to a further degradation of the effective gyrotropy of the resonator. The profile of the magnetic flux density is dependant upon both the details of the magnetic circuit and the geometry of the magnetic insulator. An exact solution of this problem requires both static and an E.E. F.E solver [11]. The possibility of shaping the pole pieces of the magnetic circuit in order to produce a uniform flux density within the magnetic insulator is understood.

Appendix B

# Quality factor

The split frequencies of a three quarter-wave long gyromagnetic resonator of length 3L open circuited at one flat face and short circuited at the other are given by



where



And εeff is an effective dielectric constant which takes into account the open side wall of the waveguide or resonator.

Its midband frequency is given by



where



C’11 is a constant which embodies the variation of the alternating magnetic field across the open gyromagnetic resonator.



The difference between the split frequencies is given without ado by



Strictly speaking the gyrotropy  must be separately evaluated at k+ and k-. The split frequencies described in this way apply to a cylindrical resonator with both a closed concentric wall and closed flat walls at either end. It is also necessary, however, to cater for the imperfect magnetic wall at one of its flat faces. This may be done by constructing a transverse resonance condition by assuming that the load on the open face is that of a cut-off waveguide with the same radius as that of the main section. This procedure gives an excellent result in the case of the demagnetized assembly and should prove equally good here.

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