# LOW LOSS, 3MM JUNCTION CIRCULATOR

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## Abstract

This paper describes the design and performance of a 3mm H-plane waveguide junction circulator which exhibited, with appropriate partial height ferrite and transformer dimensions, 0.5 to 1 dB insertion loss, 23 to 30 dB maximum isolation and 3 to 5 GHz 20 dB isolation bandwidth over the 80 — 100 GHz frequency range. Application of the resonant mode theory of H-plane waveguide circulator operation indicated that said circulator resonated in the axial "compact turnstile" mode, with strong correlation between theoretical and measured center frequencies.

## Introduction

The low loss three-port junction circulator has become an increasingly important component in the receiving and/or transmitting portions of the expanding number of high resolution radar and radiometry and high data rate communication systems applications in the 3mm low atmospheric attenuation "window". Particular uses for a low loss circulator in these applications include utilization as:

- A nonreciprocal coupling mechanism for a low noise parametric amplifier in a 3mm receiver.
- A transmitter output isolator or receiver input isolator.
- A coupling mechanism for a transmitter path-length modulator.

The low insertion loss capability of the circulator ($L_c$) is particularly critical in the parametric amplifier application, in which the contribution of $L_c$ to overall paramp noise temperature is $\gtrsim (L_c-1)T_o$ at ambient temperature $T_o$, corresponding to about 7 degrees K per 0.1 dB insertion loss at room temperature ($T_o = 300^oK$).

In accordance with the above, this paper* will describe in detail the design and performance of 3mm three-port H-plane waveguide junction circulators developed for low-noise parametric amplifier application in the 85-100 GHz region and will examine the relationship of said measured performance to existing millimeter wave H-plane circulator design theory.

## Description of 3mm Circulator Embodiment

Reasonably high performance millimeter wave three-port circulators utilizing symmetric H-plane waveguide wye junctions have been successfully realized [1-3] at frequencies as high as 258 GHz. These circulators generally incorporated axially magnetized full or partial height ferrite rods across the junction midpoints. Of the circulators reported in the literature, the partial-height configurations operated in the "compact turnstile" mode[2,3] exhibited the lowest insertion loss capability and hence formed the basis for the 3mm H-plane wye-junction circulator design reported herein.

The resulting configuration, depicted conceptually in Figure 1, utilized an axially magnetized partial-height ferrite cylinder axially mounted with the proper ferrite coupling gap on a larger-diameter cylindrical platform that provides symmetrical matching transformer sections in each of the waveguide arms of the junction. The circulator was fabricated as a machined, tellurium copper split-block structure with the symmetrical H-plane wye junction formed in WR-10 waveguide. A photograph of the circulator structure is presented in Figure 2.

A detailed set of measurements was conducted of circulator isolation, insertion loss and input impedance locus as functions of frequency and magnetic bias field for a multiplicity of ferrite and transformer dimensions. Circulator operation was observed in each case over 3 to 5 GHz bandwidths centered from 85 to 100 GHz with low (0.5 to 1.0 dB) insertion loss, 20 dB-or-greater isolation and 23 to 30 dB maximum (band-center) isolation per pass within each operating band.

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Representative measured isolation and insertion-loss responses for 96 GHz and 85 GHz circulators are depicted in Figure 3 whereas the corresponding measured input impedance loci (referenced to transformer interface and obtained by tuning isolated port for maximum isolation and thereby eliminating multiple reflections) are presented in Figure 4.

The measured 3mm circulator performance described above, certainly satisfactory for low noise parametric amplifier application raises additional questions, however, as to the extent of agreement with current theory, as will be discussed in the following paragraphs.

## Comparison of Measured Performance with Theory

The theoretical model[3,4] of an H-plane waveguide junction circulator most amenable to analysis in terms of the ferrite properties and dimensions is that of a three-port ferrite junction represented by three symmetrical non-reciprocally inductively coupled (gyrator-coupled) resonators, each quarter-wave-transformer-coupled (via the cylindrical platform) to its corresponding external waveguide port. Each resonator, shown in equivalent circuit form in Figure 5, in turn represents the composite standing wave pattern in the axially magnetized ferrite rod (resonant frequency $f_o$, effective permeability and dielectric constant $\mu_{eff}$ and $\epsilon_{eff}$), formed by the superposition of two counter-rotating circularly polarized resonant modes within the rod, with differing permeabilities $\mu^{\pm}$ and resonant frequencies $f_o^{\pm}$.

It has been shown[3] that a partial height ferrite rod of length L and diameter D can accommodate two distinct types of dominant resonant modes:

- $TM_{1,1,0}$ cylindrical cavity resonance-counter-rotating mode, with standing wave pattern in azimuthal direction and electric field parallel to rod axis. The resonant frequency associated with this mode is given by: $f_o \approx 1.84/\pi D\sqrt{\mu_{eff}\,\epsilon_{eff}}$
- $HE_{1,1,m}$ hybrid-mode, excited by field in coupling gap and formed by capacitive-coupled, m-quarter-wave, short-circuited ferrite-rod surface-waveguide resonator counter-rotating modes and standing wave pattern in longitudinal (axial) direction on the rod, as typical of the "compact-turnstile" mode of operation. The resonant frequency $f_{o,m}$ associated with this mode is that at which the dispersive propagation constant $\beta$ (f) satisfies the relationship

$$\beta(f)\,L = \frac{m\pi}{2} \quad (m = 1, 3, \ldots)$$

The theoretical[4,5] resonant frequencies associated with each of these dominant ferrite resonator modes are used to predict the center frequencies of the 3mm circulator model over the range of ferrite rod diameter and length used therein. These in turn are compared with measured values as tabulated below for typical ferrite samples:

| Sample | Measured $f_o$ (GHz) | Theoretical $f_o$ (GHz) $TM_{1,1,0}$ | Theoretical $f_o$ (GHz) $HE_{1,1,3}$ |
|---|---|---|---|
| a | 98.0 | 95.5 | 98.5 |
| b | 96.0 | 92.0 | 95.2 |
| c | 86.0 | 80.0 | 85.7 |
| d | 96.0 | 91.0 | 96.0 |

This comparison indicates excellent correlation between theory and experiment and that the circulator model is indeed operating in the axial "compact turnstile" mode, with strong correlation between measurements and theory for the $HE_{1,1,3}$ ($0.75\,\lambda_g$) resonance. It was also seen that due to the highly dispersive nature of the surface wave on the ferrite rod, that the resonant frequency thereof is highly diameter as well as length dependent.

## Conclusions

A 3mm H-plane waveguide junction circulator was developed which exhibited, with appropriate partial-height ferrite and transformer dimensions, 0.5 to 1 dB insertion loss, 23 to 30 dB maximum isolation and 3 to 5 GHz bandwidth over the 85-100 GHz frequency range. Application of the resonant mode theory of H-plane waveguide circulator operation indicated that said circulator resonated in the axial "compact-turnstile" mode, with strong correlation between theoretical and measured center frequency.

## References


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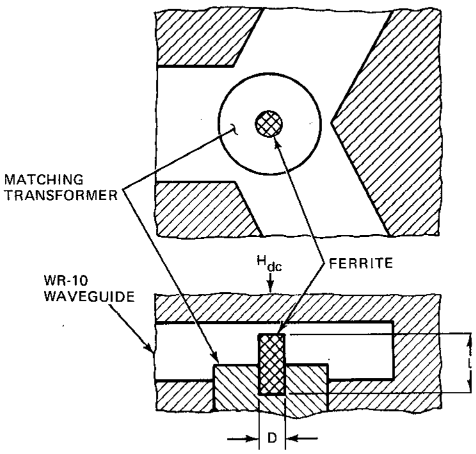



FIG. 1 CONCEPTUAL LAYOUT OF 3MM H-PLANE JUNCTION CIRCULATOR

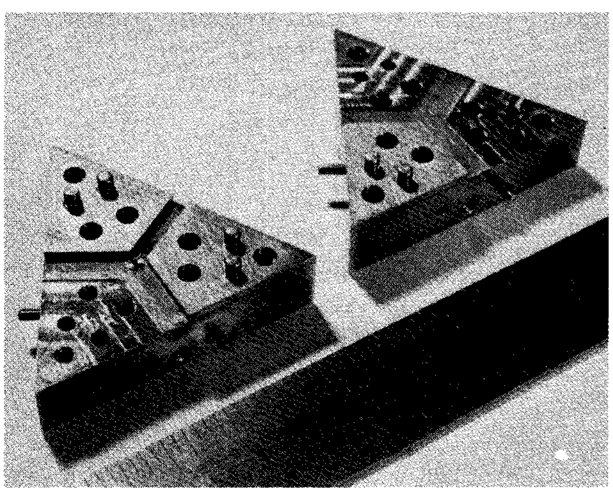


FIG. 2 PHOTOGRAPH OF 3MM H-PLANE JUNCTION CIRCULATOR

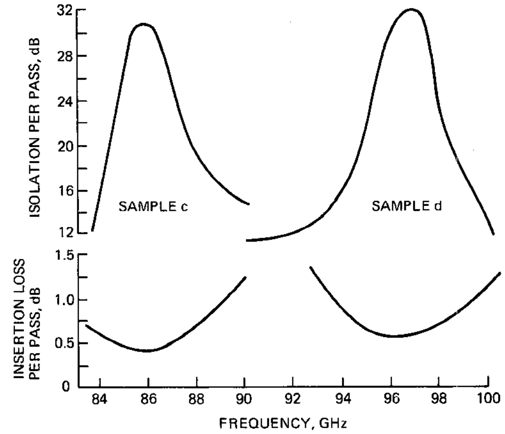
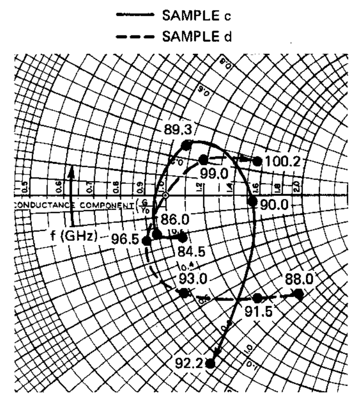



FIG. 3 MEASURED CIRCULATOR ISOLATION AND INSERTION LOSS




IMPEDANCE NORMALIZED TO WR-10 WG

FIG. 4 REPRESENTATIVE MEASURED CIRCULATOR IMPEDANCE LOCI

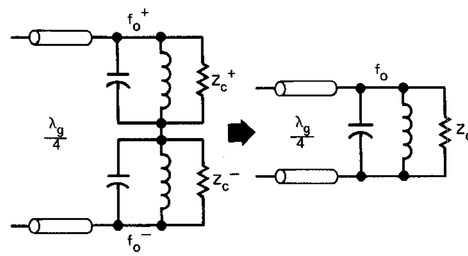



FIG. 5 INPUT IMPEDANCE MODEL FOR H-PLANE JUNCTION CIRCULATOR

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