# THEORETICAL AND PRACTICAL CHARACTERISTICS OF A BROAD TUNING RANGE Y.I.G. SPHERE CIRCULATOR

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## Summary

This paper presents a theoretical and practical evaluation of the tunable y.i.g. sphere junction circulator. The analysis has been extended to cover the circuit dual. Circuit applications are discussed and the basic design is extended to include lumped element circulators of planar form.

## Introduction

The simplest 3-port circulator can be represented by a 3-port network containing a single cyrator network in a series of parallel configuration[1] (Figs. 1a, 1b). This paper shows that the series form has been realised by modifying the structure of a single sphere y.i.g. filter[2]. With orthogonal loop coupling and magnetic bias perpendicular to the loops this type of filter has inherent gyrator properties. The gyrator action occurs around gyromagnetic resonance for the sphere. The semi-loop coupling of the conventional y.i.g. filter has been altered so that the connections which are normally short circuited are joined together to form the inner conductor of the third port (Fig. 2). The measured performance of the circulator is compared with the theoretical predictions of a computer optimised equivalent circuit based on a 2-port analysis.

## Theoretical Considerations

The theoretical analysis of the circulator is based on Carter's[3] equivalent circuit for the y.i.g. gyrator shown in Fig. 3a.

Where

$$L = \frac{R}{\omega_r}\left(1 - \frac{\omega_r^2}{\omega_c^2}\right) \text{ for perfect isolation } L_{21}$$

and

$$L_a = \frac{R}{\omega_r}\left(\frac{\omega_r^2}{\omega_c^2}\right) \text{ for perfect match.}$$

R is the terminating resistance, $\omega_c$ the circulating frequency and $L_a$ comprises the inherent inductance of the semi-loop, the stray lead inductance and some additional lead inductance. This structure has only one plane of symmetry and therefore calculations of four loss characteristics are required to completely characterise the circulator:- $L_{12}$, $L_{13}$, $L_{23}$ and $L_{21}$. Since $L_{32} = L_{13}$ $L_{23} = L_{31}$ where $L_{nm}$ is the loss in going from port 'n' to port 'm'

## Tuning Range Limitations

Evaluation of equation 1 and 2, for a particular y.i.g. sphere, show that the frequency for peak isolation of $L_{21}$ will always occur at a constant ratio to the gyromagnetic frequency. Since $\omega_r/\omega_c = (1 - (\text{constant})/R)^{\frac{1}{2}}$. However the condition for perfect match is only satisfied at the initial design frequency. The computer has been used to optimise the circuit parameters using a 2-port analysis technique. The analysis shows that the isolation characteristic $L_{13}$ and insertion loss characteristics $L_{12}$ and $L_{23}$ are frequency dependent. Fig. 3b shows the frequency dependence of a circulator theoretically optimised at $\omega_r$ = 6.0 GHz and $\omega_c$ = 6.03 GHz.

The general circuit analysis has been simplified by a limited frequency band approximation to give simple formulae that predict the circulator performance at the optimised frequency. The approximate expressions for insertion losses and isolations for $\omega = \omega_c + \Delta\omega$ are

$L_{12} = F/(m+2)^2$, $L_{21} = F/m^2$, $L_{32} = L_{13} = F/2m^2$
$L_{23} = L_{31} = F/(2m^2 + 4m + 4)$ where $m = 2\Delta\omega/\omega_c \cdot R/(\omega_r L)$ and $F = 5m^2 + 4m + 4$. Circulation occurs at $m = 0$.

The shape of the characteristics about the optimised circulation frequency are shown in Fig. 4a.

## Parallel (or Bridged) Sphere Circulator Configuration

The simple parallel configuration using a single gyrator (Fig. 1b) is the dual of the series circulator. At first sight it appeared that the duality only applied to the circuit configuration not to the y.i.g. filter section. However, we have shown that for the matched condition, complete duality does exist between the two circuits. The characteristics are related in all respects by the transformation. jW becoming 1/jW where W is the frequency variable normalised to the circulation frequency.

Existing cross loop, y.i.g. filter structures could be made into isolators using the parallel form as a suitable resistor is all that is required between the input and output coupling wires.

## Practical Construction

The semi-loop structure (Fig. 2) was constructed using 0.15 mm diameter copper wire with semi-loop diameter of approximately 1 mm. The semi-loops were soldered into 50Ω o.s.s.m. semi-rigid cable which form the three output ports. The y.i.g. structure was rigidly held by soldering the 50Ω cables into a brass ring. The ring thickness was 3 mm and was positioned between the metallic poles of an electromagnet. The inner of the ring, contained the centrally positioned 0.48 mm diameter y.i.g. sphere and 3 mm diameter semi-loops.

Table 1 gives a summary of the performances of a practical circulator together with theoretical results for a similar structure. The insertion loss and tuning range deviate from the theoretical performance. The observed insertion loss is higher than theory predicts since the theoretical model neglects the loss terms in the susceptibility tensor. Furthermore the insertion loss of the practical circulator includes reflection losses, losses in coupling due to finite unloaded Q-factor and image effect in the surrounding metal walls. Magnetostatic modes, which are evident in the practical circulator especially when using small spheres, further increase the insertion loss.

At frequencies below 3.4 GHz circulator operation is restricted to low power levels (-20 dBm max.) since pronounced coupling to the first order non-linear spin wave mode occurs at higher power levels.

The smaller tuning range of the theoretical model has not been fully explained. However, the computation neglects propagation effects in the ferrite sphere which will introduce a second-order perturbation of the resonant frequency. It was also assumed that the isolation ($L_{21}$) was always infinite and occured at $\omega_c/\omega_r = 1.005$. It appears in the practical case that $\omega_c/\omega_r$ varies across the tuning range for $L_{21}$. These two factors could account in part for this anomally.

The shapes of the theoretical characteristics of the circulator for all three ports are drawn in Fig. 4a to a linear scale of power. This scale was chosen to provide a convenient comparison with the practical characteristics shown in Fig. 4b.

## Extension to Flat Substrates

It is possible to produce a gyrator by having the semi-loops around the same hemisphere rather than opposite hemispheres. Such a cross-over pattern can be flattened to produce a lumped circulator in planar form using conventional microwave integrated circuit techniques. The assymetrical structure of a single cross-over can be modified to a symmetrical structure. The symmetrical structure shown in Fig. 5 has been used in practical circulators. The microwave performance is summarised below. A similar performance is found in the assymetrical case. Using a substituted y.i.g. polycrystalline substrate material a circulator with a centre frequency of 6 GHz was tunable over 2 GHz. The isolation was greater than 18 dB and insertion loss less than 1.2 dB for a bandwidth of 3%. The ground plane is normally removed beneath the lumped element structure. The previous analysis for the y.i.g. sphere circulator operating within the gyromagnetic resonance region can be extended to cover these circulators.

## Device Applications

The y.i.g. sphere circulator can be used as a circulator or isolator tunable over two octaves. The inclusion of the circulator in existing y.i.g. filter systems is an obvious application.

Table 1

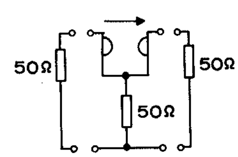
| Circuit Dimension | Practical | Theoretical Optimised at 6.030 GHz |
|---|---|---|
| Semi-loop radius | 0.5-0.6mm | 0.53 mm |
| Lead inductance | ~0.8 nH | 1.31 nH |
| **Circuit Performance** | | |
| Tuning range | 3.4-11 GHz to 2.05 at low input drive (coincidence limiting) | 4-8 GHz |
| Isolation | >18 dB | >18 dB |
| Insertion loss | <1 dB to 6.4GHz <1.8 to 11GHz | <0.2 dB |

## References

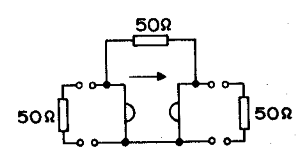

1. CARLIN, H.J., "Principles of gyrator networks", Symposium on modern advances in microwave techniques. Polytechnic Institute of Brookly, 8-10th Nov. 1954, 1st Edition, 1955, p.192.

2. LONGLEY, S.R., Multi-octave tunable 3-port circulator using a y.i.g. sphere. Electronics Letters, 25th June, 1970.

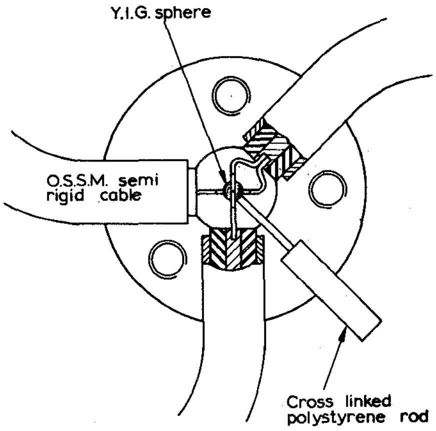
3. CARTER, P.S., Equivalent circuit of orthogonal-loop-coupled magnetic resonance filters and bandwidth narrowing due to coupling inductance. IEEE Trans. Microwave Theory and Techniques, Vol. MTT-18, No. 2, Feb. 1970.

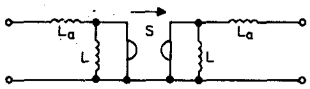

1a. 3-port circulator using a single gyrator series form.



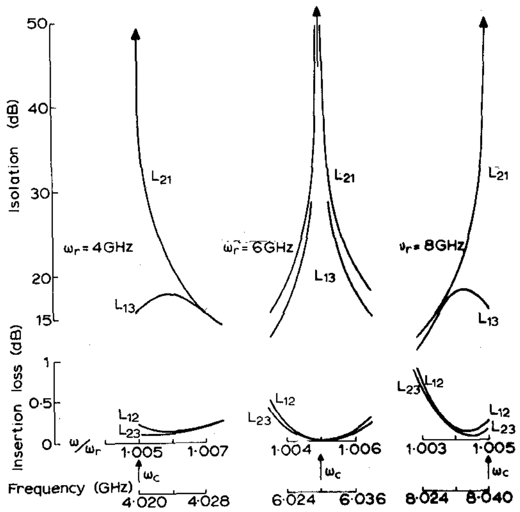

1b. 3-port circulator using a single gyrator parallel form.



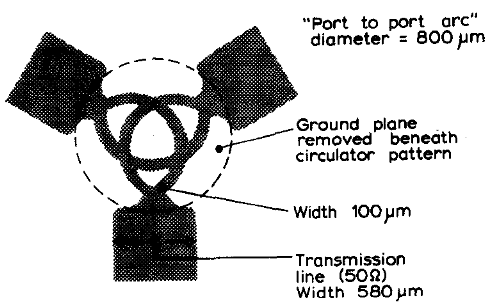

2. Y.I.G. sphere circulator series form.



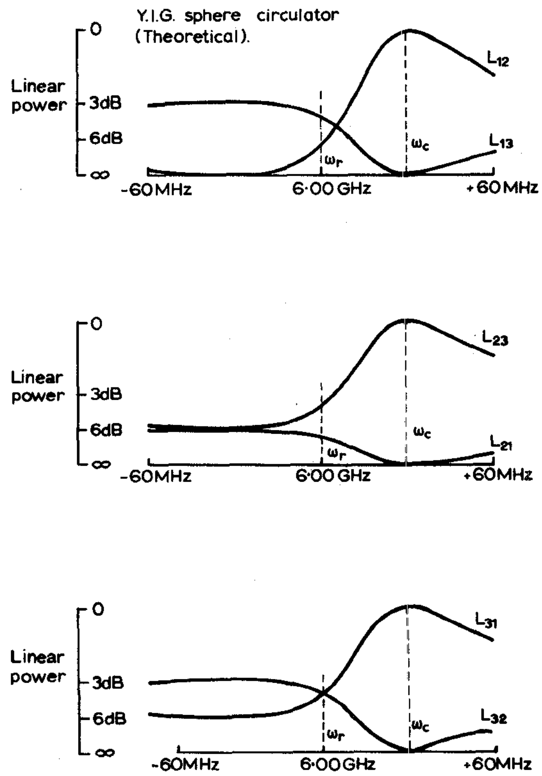

3a. Gyrator equivalent circuit.



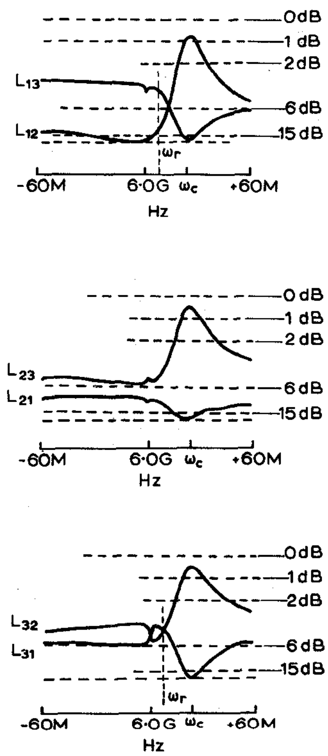

3b. Computed performance of circulator.




5. Symmetrical lumped element C-band circulator.




4a. Theoretical loss characteristics of sphere circulator.




4b. Practical loss characteristics.