BROADBAND MILLIMETRIC SEMICONDUCTOR JUNCTION CIRCULATORS AT 77K

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ABSTRACT

Broadband circulation at millimetric frequencies is currently unavailable. However on utilising the gyrotropic behaviour of the magnetised semiconductor this appears possible. Low-loss theoretical results are presented which suggest GaAs and InSb circulators are feasible with bandwidths greater than an octave and operating up to 125 GHz at a temperature of 77K.

Introduction

Broadband operation of the ferrite junction circulator is limited to upper frequencies of around 40 GHz due to the maximum saturation magnetisation of ferrites available, currently around 5500 Gauss. Presented here for the first time are theoretical results for broadband semiconductor junction circulators. A gallium arsenide device operating up to a frequency of 125 GHz and an indium antimonide design operating at a centre frequency of 50 GHz are shown. The 'tracking' behaviour of the GaAs device against the perfect circulation conditions with frequency is also demonstrated. Previous theoretical designs examined narrowband examples of this novel device [1]

The gyroelectric effect arises from cyclotron motion of nearly-free electrons under the influence of an applied steady magnetic field. The semiconductor characteristics according to the Drude model where electrons are assumed to be 'nearly free', give rise to a tensor relative permittivity, as in equation 1. Here the static magnetic field applied in the z-direction [1].

$$[\varepsilon] = \begin{bmatrix} \epsilon & -j\kappa & 0 \\ +j\kappa & \epsilon & 0 \\ 0 & 0 & \zeta \end{bmatrix} \qquad (1)$$

where,

$$\epsilon = \varepsilon_r - \frac{\omega_p^2(\omega - j\nu_c)}{\omega\left[(\omega - j\nu_c)^2 - \omega_c^2\right]} \qquad (2)$$

$$\kappa = \frac{\omega_p^2\omega_c}{\omega\left[(\omega - j\nu_c)^2 - \omega_c^2\right]} \qquad (3)$$

$$\zeta = \varepsilon_r - \frac{\omega_p^2}{\omega(\omega - j\nu_c)} \qquad (4)$$

Here ε_r is the static dielectric constant of the semiconductor, ω_p is the plasma frequency and ω_c is the cyclotron frequency. The plasma frequency is determined by the carrier density, N, and the cyclotron frequency by the applied static magnetic field, B_o. Losses in the semiconductor plasma are governed by electron collisions at an average frequency, ν_c. For relatively low doping levels the electron collision frequency is essentially temperature dependent, decreasing strongly on cooling.

Semiconductor Junction Circulator

Applying the permittivity tensor to Maxwell's equations and solving gives the Helmholtz equation of 5. Here it is assumed that for a thin disk of semiconductor plasma there is no variation in the z-direction and only the TE_{nm} modes that give rise to non-reciprocity are of interest.

$$\frac{\partial^2 H_z}{\partial r^2} + \frac{1}{r}\frac{\partial H_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 H_z}{\partial \phi^2} + k^2 H_z = 0 \qquad (5)$$

Here, $k^2 = \omega^2\mu_o\varepsilon_o\frac{\epsilon^2 - \kappa^2}{\epsilon}$ and the general solution to this equation for a realizable finite magnetic field at the centre of the disk is given by the Bessel function expression of equation 6.

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$$H_{z,n}(r,\phi) = a_n J_n(kr) e^{jn\phi} \qquad (6)$$

where, a_n are constants and J_n is the *n*th order Bessel function of the first kind Expressions for the electric fields E_ϕ and E_r can also be derived. The ideal boundary conditions on the semiconductor disk are that an electric wall exists on the curved surface except at the ports which connect to slotline, and a magnetic wall is found on the top and bottom of the thin disk. Slotline is used to give the necessary electromagnetic field orientations at the ports such that the electric field across the slot equates to the angular electric field E_ϕ. The boundary conditions are illustrated in figure 1.

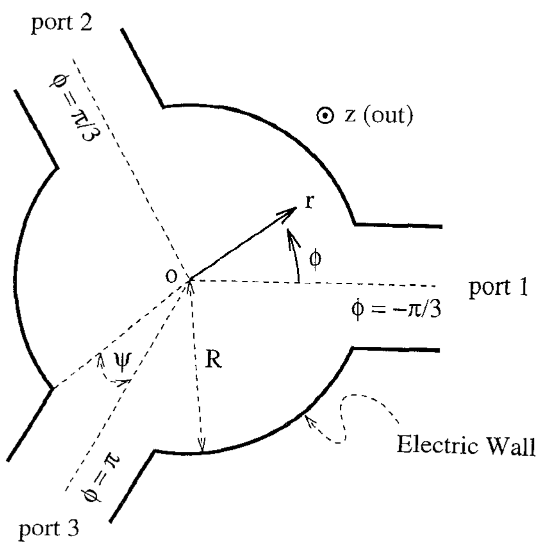

Figure 1 Boundary conditions for the semiconductor junction circulator.

The general solution to the electromagnetic field distributions in the semiconductor disk involve the Green's function This form of analysis was first derived by Bosma [2] for a gyromagnetic medium rather than the gyroelectric case studied here For a lossless cyclic symmetrical three port device the scattering matrix can be found [1,3]. And for perfect lossless circulation, that is with the electron collision frequency set to zero, the circulation conditions can be derived. These are shown in figures 2 and 3. Using these curves the radius R and coupling half-angle, ψ can be determined for any given magnitude of κ/ϵ in the range 0 to 1 The value of the gyrotropic ratio κ/ϵ is dependent upon the frequency of operation and upon the material characteristics of the semiconductor [1]. Typically the gyrotropic ratio has value between zero and unity at frequencies above and below the extraordinary wave resonance frequency f_{res}, which is given by:

$$f_{res} = \frac{1}{2\pi}\left[\omega_c^2 + \frac{\omega_p^2}{\varepsilon_r}\right]^{1/2} \qquad (7)$$

Once the circulator dimensions have been selected for a given frequency and value of κ/ϵ, the lossy scattering parameter response can be calculated by including the collision frequency. This requires the Bessel function to take a complex argument in the Green's function [1,2].

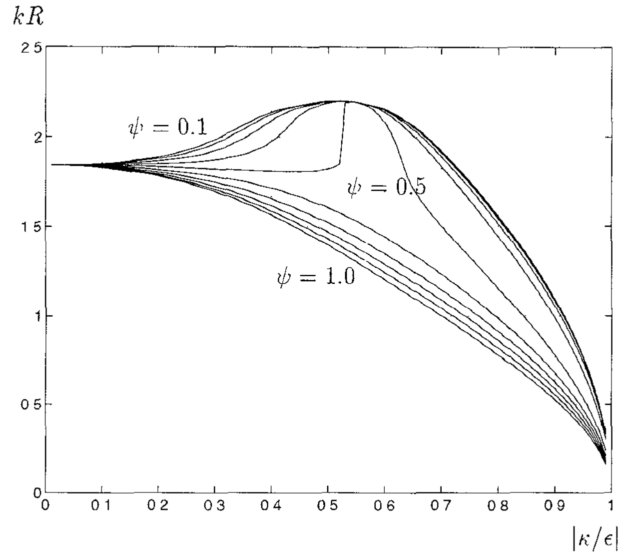

Figure 2 The first perfect circulation condition for the semiconductor junction circulator.

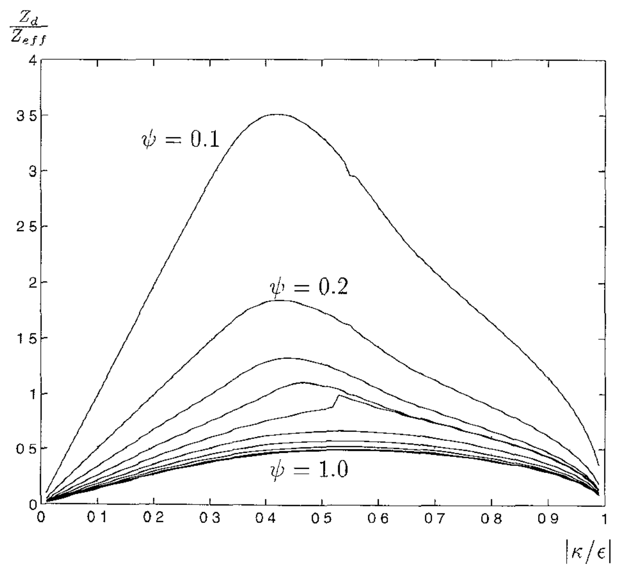

Figure 3 The second perfect circulation condition for the semiconductor junction circulator.

In figure 3, Z_d is the intrinsic impedance of the TEM wave incident at each port of the circulator and Z_{eff} is defined as the extraordinary wave impedance of the unbounded plasma. Note the value of Z_d (and hence the impedance ratio Z_d / Z_{eff} of figure 3), can be scaled by the judicious choice of the dielectric surrounding the semiconductor disk and that this impedance ratio is the reverse of the equivalent ratio for ferrite circulators.

Circulation solutions occur at frequencies both above and below the extraordinary wave resonance frequency f_{res}. One example of a broadband circulator in GaAs operating below this frequency is shown in figure 4.

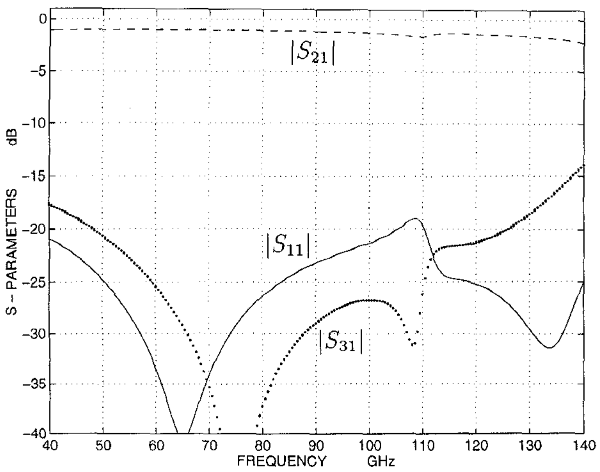

Figure 4 Predicted performance of a GaAs junction circulator including electron collision losses. R = 0.28 mm, $\psi = 0.54$ rad, $\varepsilon_d = 20$, $B_o = 0.6$ Tesla, and $f_{res} = 286$ GHz.

Here the 20dB isolation bandwidth extends from 50 GHz to 125 GHz, i.e. approximately 90% which is a large theoretical improvement over the equivalent ferrite device which at frequencies above 50 GHz is only capable of narrowband performance. The typical theoretical insertion loss of this semiconductor junction circulator is around 1dB. It is assumed that the GaAs device is operating at a temperature of 77K and the applied magnetic field is 0.6 Tesla.

It is a pre-requisite that $\omega_c > \nu_c$ for proper interaction between electrons and the electromagnetic fields before random scattering occurs. In this design the disk is surrounded by a dielectric of constant $\varepsilon_d = 20$, which reduces the impedance ratio Z_d/Z_{eff} by a factor of around 4.5 over the comparable ratio for an air dielectric surround. Careful choice of this dielectric gives the tracking behaviour of this device as shown in figures 5 and 6. It can be seen from these figures that as κ/ϵ varies with frequency between unity and approximately 0.65, both kR and Z_d/Z_{eff} (shown as the dashed lines) closely follow the perfect circulation curves. The half angle ψ subtended by each port in this design is chosen to be 0.54 radians.

One further circulator design is shown in figure 7, in this case InSb is the selected semiconductor. This has an advantage over GaAs in that due to the very low electron effective mass a weaker steady magnetic field as compared to the GaAs design, gives a satisfactory value for the cyclotron frequency. This circulator has a 20dB isolation bandwidth of 86% and an insertion loss of 0.4dB at 77K.

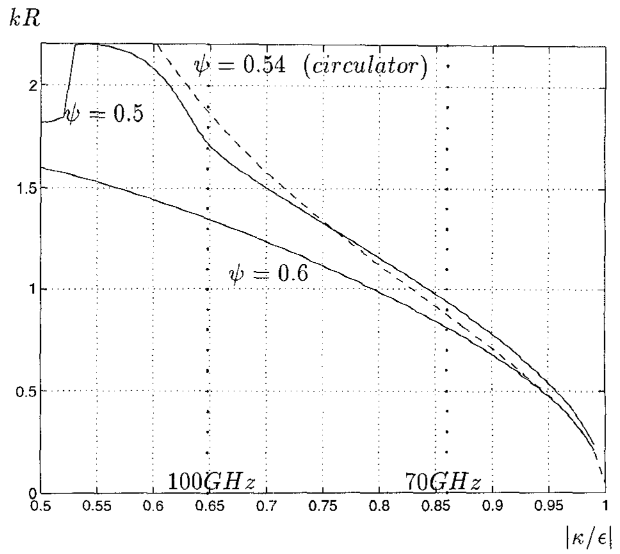

Figure 5 Tracking behaviour of the GaAs circulator of R = 0.28 mm, $\psi = 0.54$ rad, $\varepsilon_d = 20$, $B_o = 0.6$ Tesla, and $f_{res} = 286$ GHz with the first circulation condition.

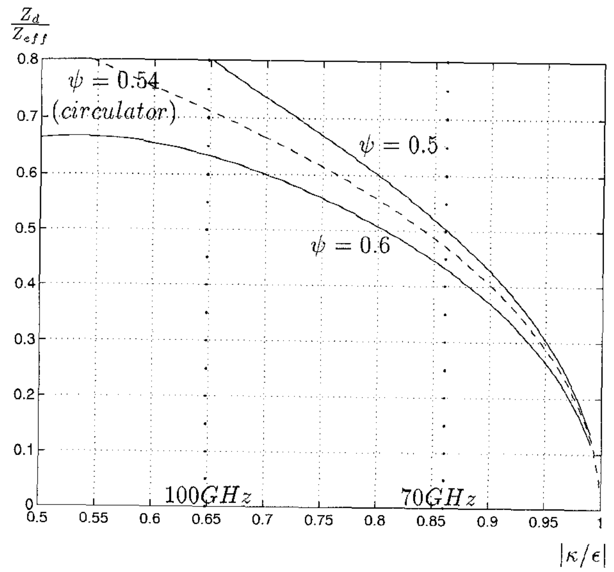

Figure 6 Tracking behaviour of the GaAs circulator of R = 0.28 mm, $\psi = 0.54$ rad, $\varepsilon_d = 20$, $B_o = 0.6$ Tesla, and $f_{res} = 286$ GHz with the second circulation condition.

Summary

The gyrotropic properties of the magnetised semiconductor have been analysed for broadband junction circulator operation at millimetric frequencies. The tracking behaviour of the broadband device has been theoretically demonstrated with the chosen design closely following the ideal characteristics for a wide range of frequencies. Low-loss examples have been given for GaAs and InSb broadband semiconductor junction designs operating at a temperature of 77K. Since these devices require a high quality semiconductor in the form of a thin disk, integration onto MMICs may be possible.

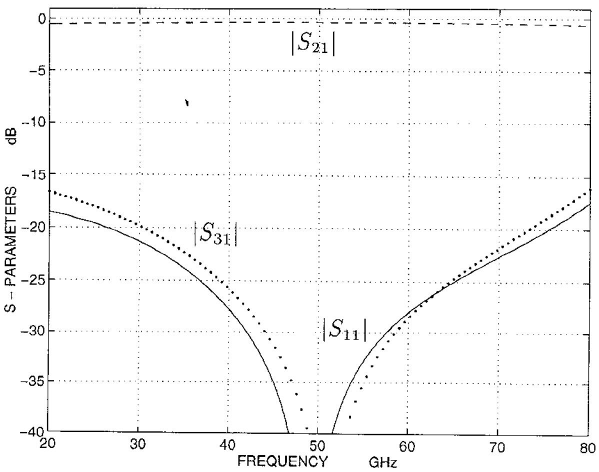

Figure 7 Predicted performance of InSb junction circulator including electron losses. R = 0.41mm, $\psi = 0.52$ rad, $\varepsilon_d = 20$, $B_o = 0.4$ Tesla, and $f_{res} = 790$ GHz.

Acknowledgments

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References

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