Computer - Aided Design and Optimisation of Broadband Stripline Circulators For 18 - 30 GHz and 18 - 40 GHz

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Abstract

Computer programs have been written for the design and optimisation of tracking stripline circulators, and used to predict the performance of broadband designs, 18 - 30 GHz and 18 - 40 GHz, using ferrites with $4\pi M_s \approx 5000G$. Initial results show promising agreement between predicted and experimental performance and an undesirable insertion-loss spike has been identified as due to an inherent mismatch associated with circulator modes. The design and location of matching transformers are discussed, and the programs can be used with a commercial design software.

Introduction

The work described here uses the tracking circulator approach[1] to develop computer programs for the design of three-port circulators. Further software has been written which optimises the ferrite disc diameter and coupling angle for a specified permittivity of the surrounding dielectric medium, and then computes the s-parameters for the optimised intrinsic design. Impedance transformers are then designed to match the circulator at the design frequency to 50Ω feed lines. The overall performance of the circulator with its transformers can be obtained using one of the commercially available microwave design packages.

It is well known that the design of a junction circulators at higher microwave frequencies is made more difficult by the lack of a ferrite with large enough value of saturation magnetisation ($4\pi M_s$). For example, in principle, a tracking circulator with $2f_m$=40 GHz requires a material with $4\pi M_s$ = 7143 G, but the largest value of $4\pi M_s$ for presently available commercial ferrite is 5370 G. The effect of the low value is to decrease the bandwidth of empirical designs which, when coupled with the small dimensions and close tolerances, significantly increases design and production costs. Therefore, there is a need for a computer-aided design and optimisation technique which

(a) establishes a theoretical optimum behaviour for a speecified ferrite material in a specified frequency range,
(b) allows the effect of transformer design and position to be assessed,
(c) enables the effects of tolerances in material parameters and mechanical dimensions to be computed and
(d) provides data on circulator performance which can be used in microwave design software for the design of sub-systems.

Computer programs have been developed to generate graphs illustrating the first and second circulation conditions[1]. For a specified ferrite and surrounding dielectric medium, ε_d, these graphs can be used to estimate the coupling angle, Ψ, and the ferrite disc radius, R. required for the circulator. These data are then used in our main program. The four principal aims of the main program are :

1. To predict the behaviour when the design parameters are specified.
2. To optimise the performance over a specified frequency range by variation of the parameters.
3. To produce data file of s-parameters for use with commercially available software for microwave design.
4. The program should run on an IBM PC or compatible machine.

Details are given below of two designs, 18-30 GHz and 18-40 GHz, which were deliberately chosen to "push" the tracking circulator concept with commercially available ferrites.

18 - 30 GHz Design

For the 18-30 GHz design, the ferrite selected was Trans-Tech TT2-111 ($4\pi M_s$ = 5000 G, E_f= 12.5). Since $f_m = \gamma\ (4\pi M_s)$ = 14 GHz it is clear that the upper frequency limit of the tracking concept, i.e. $2f_m$ does not quite reach the design requirements. The optimum parameters were found to be ε_d = 9.5, R_0 = 1.058 mm and Ψ_0 = 0.57 rad, and the predicted behaviour of the intrinsic design is shown in Fig.1. To suppress higher-order stripline modes a disc thickness of 0.55 mm was selected. The stripwidth required to obtain Ψ_0 is 1.412 mm, and the strip thickness was 0.127 mm. These values yield a characteristic impedance of 18.57Ω for the strip at the edge of the disc. Several different single-section and double-section 50Ω transformers were designed, and the behaviour of the circulator with each transformer design was computed. The best predicted behaviour is shown in Fig.2, and the measured

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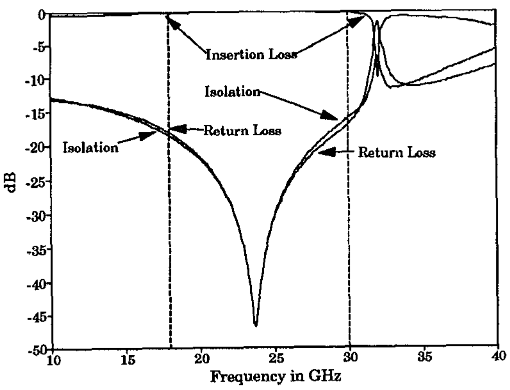

Fig.1 Predicted Performance of Optimised Intrinsic Circulator 18 - 30 GHz. Ferrite TT2-111 R_0 =1.058 mm : Ψ_0 = 0.57 rad : ε_d = 9.5

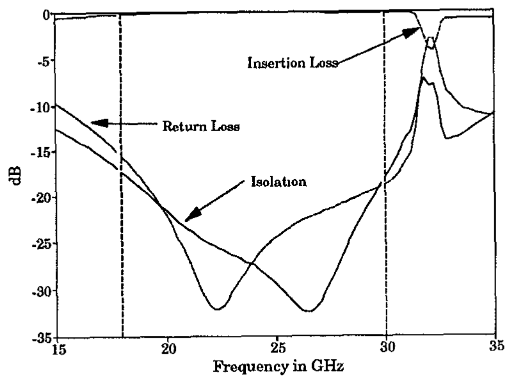

Fig.2 Predicted Performance of Circulator in Fig,1 with 50Ω Transformers.

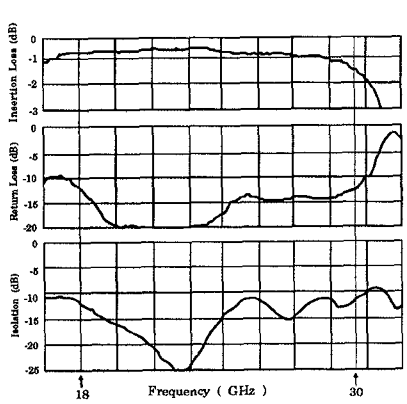

Fig.3 Measured Performance of Circulator in Fig.2

performance of this circulator transformer combination is shown in fig.3 The insertion loss is less than -1dB over most of the band except where, as expected, it begins to increase sharply as the frequency approaches an insertion loss spike at 32 GHz. The isolation is below -12 dB, and the return loss is less than -11 dB over the required frequency range.

18 - 40 GHz Design

The ferrite selected for this design was Countis C-48 ($4\pi M_s$ =5370 G , ε_f = 13.0). The optimised radius and coupling angles were obtained with three different dielectric surroundings, ε_d = 4.08, 6.30 and 9.8. Of these the best predicted performance was obtained with ε_d = 4.08 , R_{01}= 0.728 mm and Ψ_{01} = 1.0 rad. As shown in Fig.4, the isolation is less than -10 dB at the frequency band edges, the insertion loss is better than -1dB across the band and the spike in the insertion loss occurs outside the band at 46.5 GHz. For comparison, the performance of another optimised design is shown in Fig.7. Here with ε_d= 4.08, R_{02} = 0.864 mm and Ψ_{02} = 0.57 rad, the minimum isolation is -35 dB. However, an insertion loss spike occurs within the design frequency band at 38 GHz. Several two-section Chebyshev transformers were designed for each circulator using Touchstone and the predicted performance of each circulator with its "best" transformer (see later) is shown in Figs. 5 and 8.The lower dielectric constant offers the possibility of a modest performance over a broader bandwidth, whereas the higher dielectric constant offers a slightly improved performance but over a bandwidth which is narrower due to the insertion loss spike. The measured performance is shown in Figs. 6 and 9. In Fig.6 (ε_d = 4.08) the isolation is less than -10 dB across the 10-40 GHz band. In Fig.9 it can be seen that with ε_d = 9.8 the isolation and return loss both have a minimum (<-20 dB) near 25 GHz and remain less than -10 dB over the range 23-39 GHz. The insertion loss is better than -2 dB over the same frequency range. The insertion loss spike that was predicted to occur at 38 GHz did not appear, but the behaviour suggests that it may exist just above 40 GHz beyond the measurement range.

A sharp spike in the insertion loss was found in all our circulator designs and we have demonstrated that it is due to circulator modes in the ferrite disc. The frequency at which this will appear depends upon the disc radius and therefore to "push" this spike to as high as possible above the design range it is desirable to use as small a radius as possible. This in turn requires as low a value of ε_d as possible, but this is limited by the optimum coupling angle, Ψ_0, which can not exceed 60^0 = 0.524 rad.

The distance between the transformer and the edge of the ferrite disc affects the performance of the "matched" circulator[2,3]. The strip immediately adjacent to the disc is designed to provide the required coupling angle, Ψ, at the edge of the disc. To reduce the overall size it would be helpful to locate the transformer as close to the disc as possible, but if it is too close there will be interaction between the adjacent discontinuities and then neither the circulator nor the transformer will be optimum. An intrinsic circulator and the location of its transformer can be optimised as an integrated package using the s-parameters generated by the design software. This is not done at present but such variations are easily checked with existing software.

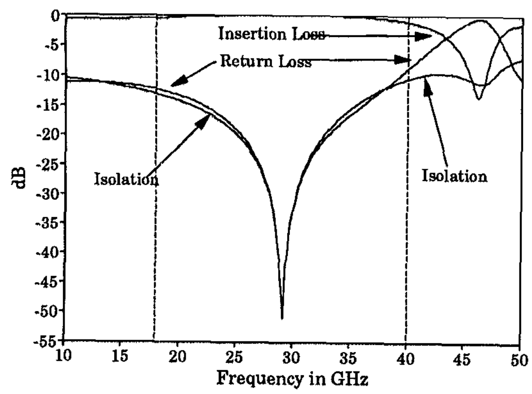

Fig.4 Predicted Performance of First Optimized Intrinsic Circulator, 18 - 40 GHz.
Ferrite C-48
$R_{01} = 0.728$: $\Psi_0 = 1.00$ rad : $\varepsilon_d = 4.08$

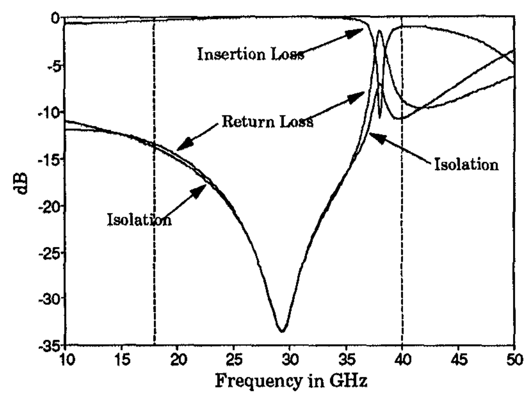

Fig.7 Predicted Performance of Second Optimized Intrinsic Circulator, 18 - 40 GHz.
Ferrite C-48
$R_{02} = 0.864$ mm : $\Psi_{02} = 0.57$ rad : $\varepsilon_d = 9.8$

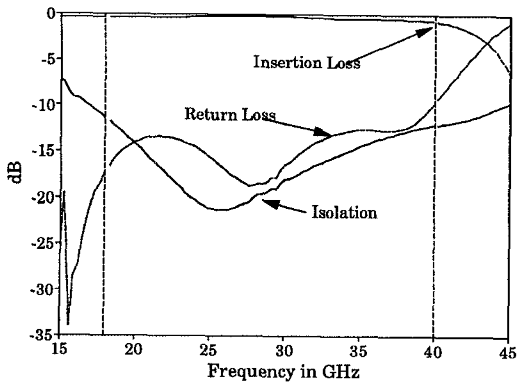

Fig.5 Predicted Performance of Circulator in Fig.4 with 50Ω Transformers.

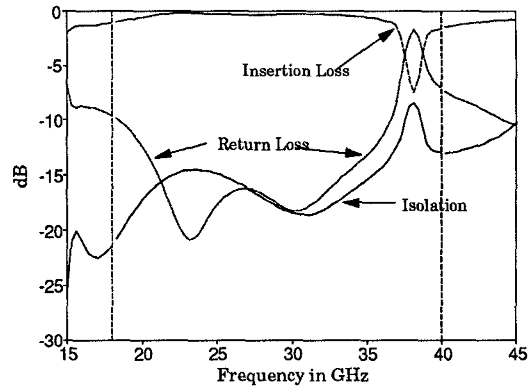

Fig.8 Predicted Performance of Circulator in Fig.7 with 50Ω Transformers.

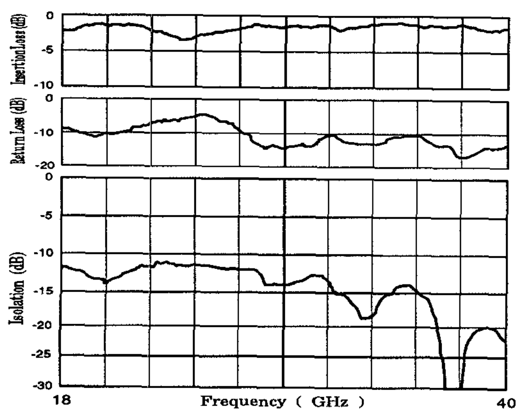

Fig.6 Measured Performance of Circulator in Fig.5

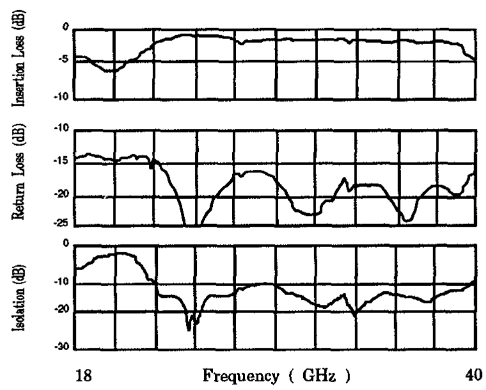

Fig.9 Measured Performance of Circulator in Fig.8

Conclusion

Computer-aided design and optimisation techniques for tracking stripline circulators in the range $f_m \leq f \leq 2f_m$ have been developed and verified experimentally. Optimised designs have been described for 18-30 GHz and 18-40 GHz in which the frequency range extends above $2f_m$. An undesirable spike above the frequency band in each case has been attributed to a mismatch associated with higher order modes of circulation. The frequency at which this mode occurs can be increased to some extent by lowering the permittivity of the surrounding dielectric. This does not reduce the bandwidth of the intrinsic circulator if the disc radius is re-optimised. The design of an intrinsic circulator with its transformer, as an integral component, has been discussed briefly. This CAD approach can be extended to microstrip circulators, and in any case can provide sensitivity analysis to determine the effects of manufacturing tolerances on performance.

Acknowledgement

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