Bandwidth and Losses of 4-port Ferrite Coupled Line Circulators

Cham Kiong Queck, and Lionel E. Davis

Microwave Engineering Group, Dept. of Electrical Eng. & Electronics, University of Manchester Institute of Science and Technology (UMIST), PO Box 88, Manchester M60 1QD, United Kingdom

***Abstract* — For the first time, the bandwidth and the losses of a 4-port Ferrite Coupled Line (FCL) circulator are analysed and reported. A broadband hybrid coupler with an improved air-bridge has been designed for the circulator and the performance of a 4-port microstrip FCL circulator is predicted by cascading the S-matrices of the FCL and hybrid coupler using signal flow graphs. The possibility of realising a broadband circulator is investigated and it is found that there is a trade-off in performance between bandwidth and loss.**

I. INTRODUCTION

Since the experimental discovery [1] of the nonreciprocal behaviour of the longitudinally-magnetised FCLs, several papers [2]-[7] have proposed methods of analysis, condition for optimum operation and their possible applications. There is an interest in the FCL circulator due to its potential advantages over the classical junction circulator at millimeter wavelengths. The advantages are: 1) the former does not suffer from size constraint, hence the cost of production is low, 2) only a weak biasing field is needed for a longitudinally-magnetised structure instead of strong biasing field for the disk-shape junction circulator.

A 4-port FCL circulator can be realised by cascading a longitudinally-magnetised FCL structure with a 180° hybrid coupler. Teoh and Davis [7] performed a proof-of-principle experiment and demonstrated the nonreciprocal behaviour of the microstrip FCL circulator with ferrite on top. However, the performance of this early device was not satisfactory. A second stripline-type circulator [8] was designed and measured, but without much improvement, and the unavoidable use of the air-bridge has been identified as a significant factor in those poor performances. In this paper, a 4-port microstrip FCL circulator with ferrite as a substrate is designed with improvement in the hybrid coupler and the air-bridge. The performance of this design is predicted by cascading the FCL structure with the hybrid coupler using signal flow graph. For the first time, the bandwidth of such device is predicted and the effect of losses is analysed.

II. 4-PORT MICROSTRIP FCL CIRCULATOR

A 4-port microstrip FCL circulator was designed at 11.4 GHz and it is made up of two main components, i.e. a microstrip FCL section and a 180° hybrid coupler with an air-bridge. Each of these components was analysed separately and the overall performance was predicted.

A. Microstrip FCL Section

A FCL section has a pair of closely spaced parallel lines with ferrite loading that is magnetised in the direction of propagation (longitudinal magnetisation). Several different different FCL structures have been designed and analysed [6] using finite element method (FEM) based on normal-mode theory [4]. A microstrip FCL with ferrite as a substrate has been selected with the following parameters; permittivity of ferrite, ε_f =12; substrate thickness, h = 0.2 mm; width of microstrip, w = 0.16 mm; separation between the strips, s = 0.2 mm; magnetisation $4\pi M_s$ = 3000 G. This structure was simulated in Ansoft HFSS and it can observed from the electrical field distributions at 11.4 GHz in Fig. 1, that for a signal input at port 1, coupling takes place in the magnetised FCL resulting in ouput at port 3 and port 4. For an equal output condition, the length of the FCL section, L was set to 36 mm using $L = 0.5\pi(\beta_1-\beta_2)^{-1}$, where β_1 and β_2 are propagation constants for the mode 1 (RHCP) and mode 2 (LHCP) of the magnetised FCL [4]. It can be seen from the simulated frequency response in Fig. 2, that an equal power output (even) occurs at approximately 10.7 GHz. It should be noted that this structure was selected for convenient fabrication and is not optimised. Defining the bandwidth as the frequency range where the insertion loss is between –3.75 dB to –2.5 dB, the FCL bandwidth is from 9.75 to 11.25 GHz. Over the bandwidth, the isolation S_{21} and reflection loss are below –14 dB. Note that the bandwidth in this paper is defined at a fixed length whereas in [6], the bandwidth is defined at a variable optimum length. It was also observed in simulation that the even output signal becomes odd when either the direction of magnetisation was reversed or the signal was fed into port 2 instead of port 1. This behaviour has been discussed earlier [2]-[7].

0-7803-7239-5/02/$10.00 © 2002 IEEE 2002 IEEE MTT-S Digest

Fig. 1. Electric field distributions in the microstrip FCL section when input is at port 1

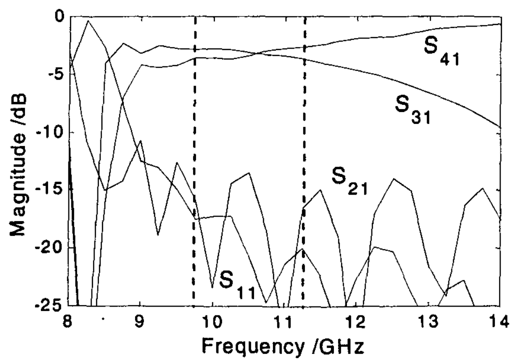

Fig. 2. Simulated frequency response of the FCL section.

B. Broadband Hybrid Coupler With Improved Air-Bridge

A broadband rectangular hybrid coupler with an air-bridge has been designed and optimised at 11.4 GHz on a substrate of $\varepsilon_r = 10.2$ and of thickness, $h_a = 0.254$ mm, as shown in Fig. 3. The stepped-impedance broadbanding technique [9]-[10] has been employed, where the section impedances Z_1, Z_2, Z_3, Z_4 are 56.8Ω, 46.6Ω, 27.5Ω and 16.7Ω and the impedances Z_{1C} and Z_{2C} of the quarterwave transformer section are 46.7Ω and 37.2Ω respectively. One major factor that degraded the performance of the early 4-port devices in [7]-[8] was the unavoidable air-bridge, which caused reflection loss at the adjacent port. It has been found that the reflection loss of an air-bridge can be minimised by introducing square pads of width S at both ends of the air-bridge [11] using a design proce-dure described in [12]. For a microstrip air-bridge of height 0.25 mm, width 0.4 mm, length 1.6 mm on a substrate of ε_r =10.2, Momentum analysis (air-bridge alone without the coupler) shows that when S = 0.45 mm, the minimum of the reflection loss (-54 dB) is near to 11.4 GHz, as shown in Fig. 4. This is a significant improvement over the conventional design where the reflection loss is about −12 dB at 11.4 GHz. With reference to the port numberings in Fig. 3, a Momentum simulation was carried out on the broadband coupler with the improved air-bridge and the results are shown in Fig. 5. Defining the bandwidth as the frequency range where insertion loss is −3 ± 0.5 dB, it can be seen that the bandwidth is from 8.3 to 14.3 GHz (6 GHz), i.e. over 50% of the design frequency, as compared to approxi-mately 27% of that of the conventional coupler. Over this bandwidth, the reflection loss and isolation are mostly below −17 dB and the maximum phase difference between S_{43} and S_{13} are 25°. Note that the reflection loss in Fig. 5 was taken at the port near to the air-bridge. The rectangular hybrid coupler design is preferred to the ring design as the former is neater especially with the air-bridge and simulation shows that it has a slightly broader bandwidth than that of the latter.

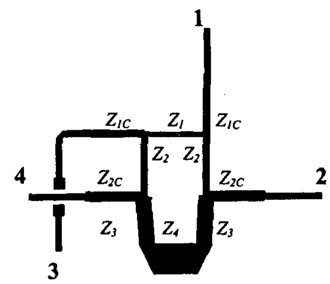

Fig. 3. Broadband hybrid coupler with air-bridge design

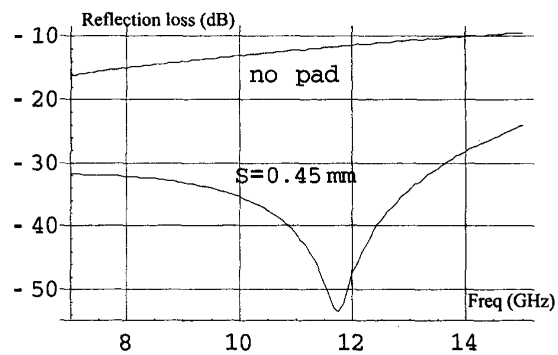

Fig. 4. Simulated reflection loss of the air-bridge with and without pads.

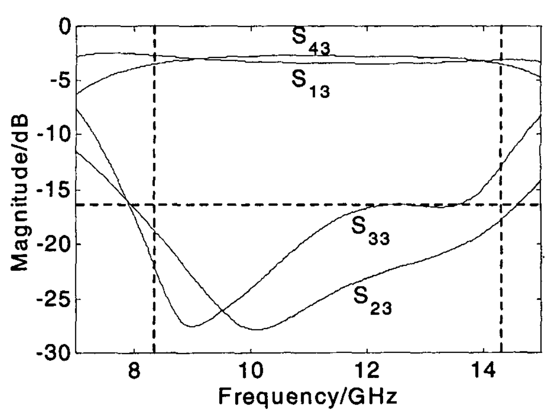

Fig. 5. Simulated frequency response of the broadband hybrid coupler with an improved air-bridge design in Fig. 3.

C. Cascaded Performance

The cascaded design and its port numbering are shown in Fig. 6, where regions A and C are isotropic and region C contains ferrite. The overall cascaded performance has been obtained by cascading the S-matrices of the FCL section and the hybrid coupler, using signal flow graphs [13]. Note that the interconnects between the coupler and the FCL and to ports 2 & 4 have been taken into consideration, while region A has been neglected for simplicity. Defining the bandwidth as the frequency range where insertion loss is above –0.5 dB, it can be seen from Fig. 7 that the bandwidth is from 9.6 to 11.4 GHz (1.8 GHz), i.e. 16% of design frequency. Over this bandwidth, the isolation and reflection loss are below –15 dB. This result clearly demonstrates the nonreciprocal behaviour of the cascaded design.

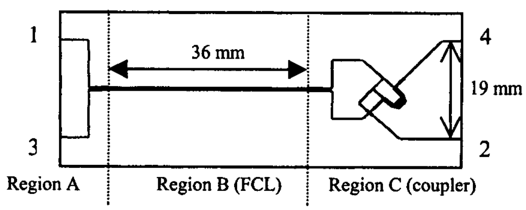

Fig. 6. Actual circuit of 4-port microstrip FCL circulator.

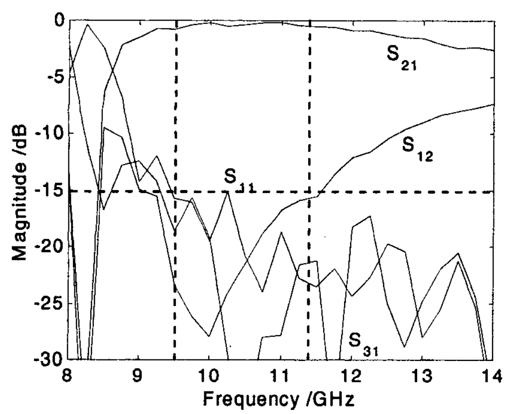

Fig. 7. Predicted frequency response of the 4-port microstrip FCL circulator. Note that the air-bridge is adjacent to port 2.

III. Broadband Circulator

Despite the use of the broadband coupler, the bandwidth of the circulator in Section II is limited by the microstrip FCL section. However, the bandwidth of FCL section can be broadened by 1) replacing the microstrip FCL with a stripline FCL, or 2) increasing the separation between the two parallel lines. Initial investigation has revealed that the bandwidth of a stripline FCL could be as broad as over 100% of the design frequency. Therefore, if we assume a perfect FCL section, i.e. –3 dB outputs and zero phase difference throughout a specific frequency range, the limitations due to the coupler behaviour (amplitude and phase) can be explored. Fig. 8 shows the result of such a calculation and compares the results obtained assuming a conventional and a broadband coupler (neglecting the effects of the T-junctions in the couplers). The performance of each coupler was derived using even-odd mode analysis, and the simulation shows the limitation to the overall FCL behaviour due only to the amplitude and phase behaviour of the coupler. As can be seen from Fig. 8, the bandwidth (for insertion loss above –0.1 dB) for the broadband circulator is 4.7 GHz (43%) as compared to 3 GHz (27%) for the conventional one. Over the bandwidth, the reflection loss and the isolation are below –20 dB. The broader bandwidth is however at the expense of a deteriorated performance at the design frequency of 11 GHz.

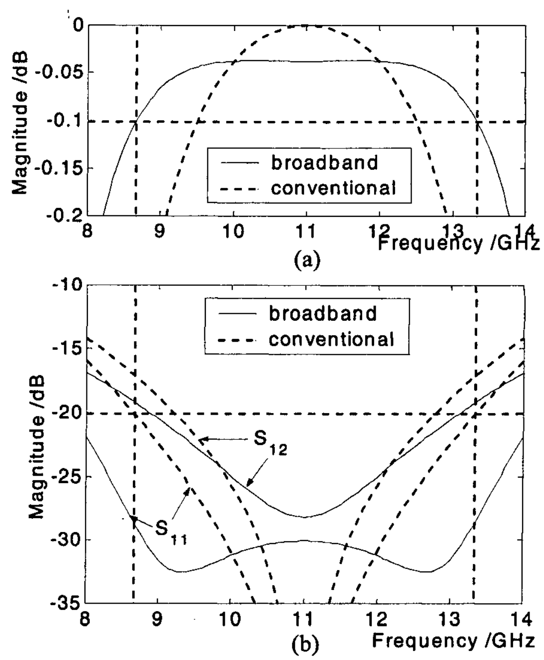

Fig. 8. Ideal performance of the broadband and conventional 4-port circulator in term of (a) insertion loss S_{21} (b) isolation S_{12} and reflection loss S_{11}

IV. Losses In Circulator

The conductor (copper where $\sigma = 5.8 \times 10^7$ S/m) loss has been identified as the main contributor to the losses in the 4-port circulator in Section II. Simulation shows that the insertion loss of the 36 mm FCL section is increased by approximately 1.5 dB at 11.4 GHz, solely due to the copper loss. Simulation also shows that the insertion loss S_{43} for the coupler (including interconnects) in subsection II(B) is increased by about 0.7 dB and calculation of conductor loss [14] shows close agreement (at about 0.72 dB), assuming average surface roughness of 5 μm. The overall performance of the lossy circulator is shown in Fig. 9 where the increase is approximately 2-3 dB.

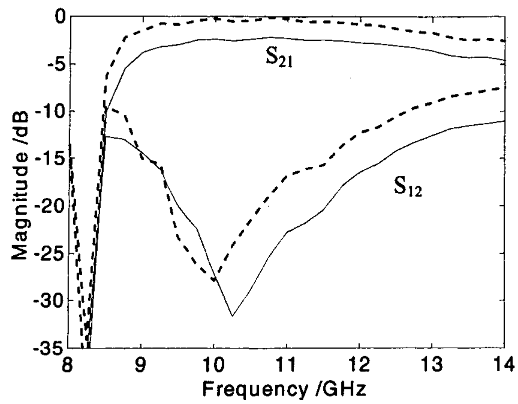

Fig. 9. Simulated performance of the 4-port microstrip FCL circulator; with (solid lines) and without copper loss (dotted lines)

It was also found that the dielectric loss of the 4-port circulator is comparatively small, e.g. the dielectric loss of S_{13} for the hybrid coupler was 0.11 dB, calculated using expression in [15]. Besides conductor and dielectric losses, other losses, which were assumed to be negligible, were magnetic loss, radiation and surface-wave propagation. Although by increasing the separation between the lines can broaden the bandwidth, it requires the FCL section to be made longer in order to compensate the weaker coupling and this will results in a higher conductor loss. Hence, there is a compromise in performance between the bandwidth and the losses. One way of reducing the conductor loss is by replacing the copper with a superconductor.

V. Conclusion

A 4-port microstrip FCL circulator using a broadband hybrid coupler with an improved air-bridge has been designed and its nonreciprocal behaviour has been demonstrated. It is shown that a broadband circulator can be realised by cascading a broadband FCL section with a broadband hybrid coupler. The bandwidth and the losses of the circulator have been analysed and reported for the first time and there is a trade-off in performance between the bandwidth and the losses. Fabrication and measurement of the circulator is planned, and techniques to reduce the length of the FCL section are being considered.

References

[1] L. E. Davis and D. Sillars, "Millimetric nonreciprocal coupled-slot finline components", *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-34, no. 7, pp. 804-808, July 1986.

[2] J. Mazur and Michal Mrozowski, "On the mode coupling in longitudinally magnetized waveguiding structures", *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-37, no. 1, pp. 159-164, Jan 1989.

[3] J. Mazur, "Millimeter-wave three-port finline circulator using distributed coupling effect", *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-41, no. 6/7, pp. 1067-1070, June/July 1993.

[4] C. S. Teoh and L. E. Davis, "Normal-mode analysis of ferrite-coupled lines using microstrips or slotlines", *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-43, no. 12, pp. 2991-2998, Jan 1995.

[5] K. Xie and L. E. Davis, "Nonreciprocity and the optimum operation of ferrite coupled lines", *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-48, no. 4, pp. 562-573, April 2000.

[6] K. Xie and L. E. Davis, "Performance of axially-magnetized ferrite coupled lines", *URSI XXVI General Assembly*, Proceedings/Abstracts, Toronto, paper B1.P.13, August 1999.

[7] C. S. Teoh and L. E. Davis, "Design and measurement of microstrip ferrite coupled lines", *Int. Journal on RF and Microwave CAE*, vol. 11, Issue-3, pp. 121-130, May 2001.

[8] C. K. Queck, *et al*, "Performance of stripline-type FCL circulators", submitted to *Int. Journal on RF and Microwave CAE.*

[9] D. I. Kim, "Broadband design of improved hybrid-ring 3-dB directional couplers", *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-30, no. 11, pp. 2040-2046, Nov 1994.

[10] C. K. Queck and L. E. Davis, "Broadband hybrid microstrip couplers – Amplitude and Phase", to appear in Microwave and Optical Technology Letters on 20 Feb 2002

[11] T. S. Horng, "A rigorous study of microstrip crossovers and their possible improvements", *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-42, no. 9, pp. 1802-1806, Sept 1994.

[12] C. K. Queck and L. E. Davis, "Improved design of microstrip air bridges", submitted to *Int. Journal on RF and Microwave CAE*

[13] P. A. Rizzi, "Microwave engineering passive circuits", *Prentice Hall Inc.*, 1998

[14] R. A. Pucel, *et al*, "Losses in microstrip", *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-16, no. 11, pp. 342-350, Nov 1968.

[15] K. C. Gupta, *et al*, "Microstrip lines and slotlines", *Artech House Inc.*, 2nd ed., Norwood, MA, 1996.