THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 59, No. 5, May–June 1980
Printed in U.S.A.

Series- and Shunt-Tuned Lumped-Element Microwave Circulators

By R. H. KNERR

(Manuscript received November 14, 1979)

Practical lumped-element microwave circulators are generally shunt tuned. S-parameter eigenvalue measurements on the Hewlett-Packard automatic network analyzer are used to demonstrate, however, that series tuning adds considerably to design flexibility. This is especially true in the high-field mode of operation and in conjunction with a capacitor common to all three arms. The measured eigenvalue curves also provide a more basic understanding of the two tuning mechanisms. The power of the approach becomes obvious in cases where the device dimensions are restricted. The flexibility of this design approach has been demonstrated with the development of three lumped-element circulators having identical size housings and similar circuit patterns. Circulators at 1.4 GHz and 1.0 GHz utilized shunt tuning and operated in the low-field mode. The other unit operated at 500 MHz with series tuning and the high-field mode.

I. INTRODUCTION

Commercially available lumped-element circulators (LECs) are almost exclusively shunt tuned. This is probably a result of the inherently smaller junction diameter for shunt tuning. The introduction of a capacitor common to all three arms[1] sheds a different light on the approaches.

In the process of designing three LECs (500 MHz, 1,000 MHz, 1,400 MHz) using identical housings, these schemes were re-evaluated, together with the high- and low-field mode of operation. *S*-parameter measurements on the Hewlett-Packard automatic network analyzer showed some very interesting aspects of series tuning, which add a large degree of flexibility to the design.

II. SERIES AND SHUNT TUNING

Applying Q and bandwidth considerations to the two structures in Fig. 1, it was recognized very early[2] that the shunt-tuned circuit

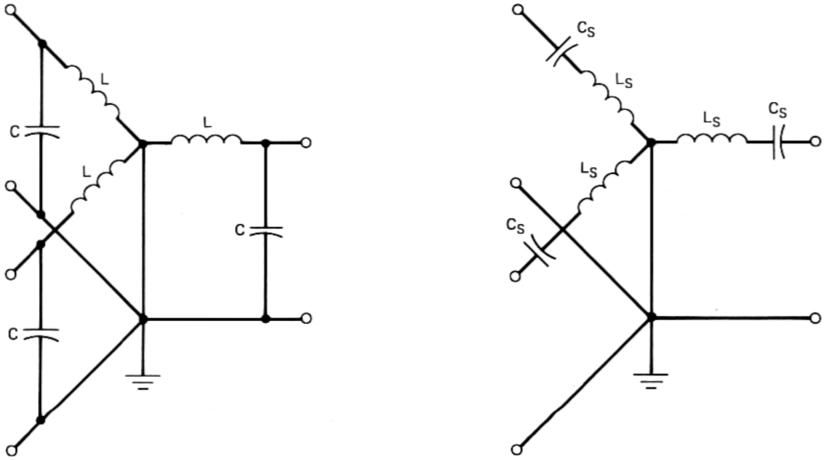

Fig. 1—Equivalent circuits for shunt- and series-tuned lumped-element circulator.

required significantly less inductance but more capacitance than the series-tuned circuit. The resulting smaller junction diameter associated with shunt tuning was probably the main reason for its almost exclusive use in commercial lumped-element circulators. If one considers the simple broadband lumped-element circulators[1] in Fig. 2, the conclusions from the analysis of Fig. 1 are still valid as they concern the different junction inductance required for shunt and series tuning. The

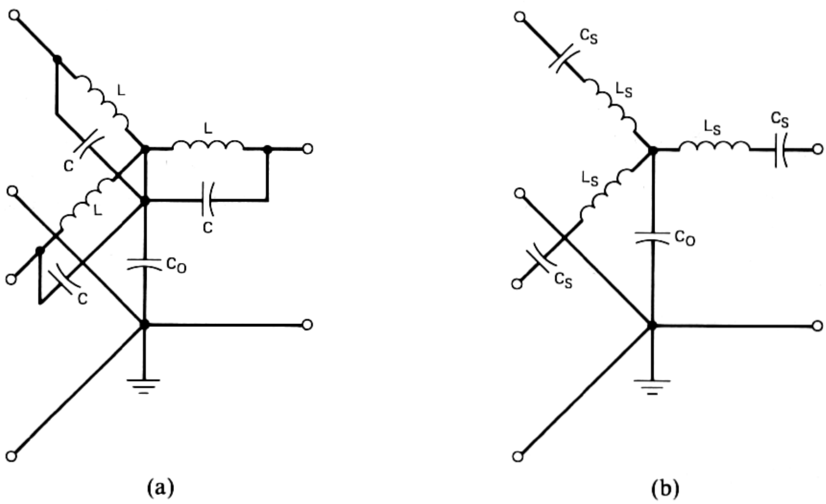

Fig. 2—Equivalent circuits for broadband shunt- and series-tuned lumped-element circulator.

use of a capacitor common to all three arms sheds a different light on the bandwidth consideration, as is explained in the following sections. The results presented are actually the product of an attempt to build lumped-element circulators at 1 and 1.4 GHz operating below resonance and another one at 500 MHz, above resonance, all using the same junction diameter and housing.

III. BELOW RESONANCE LEC

Circulators can be designed for two different modes of operation. They are commonly referred to as above and below resonance or low-field and high-field circulators.

Since garnets are only available with a saturation magnetization as low as approximately 200 Gauss, low-field operation is usually applied at frequencies from about 0.8 GHz up. For lower frequencies, the so-called low-field losses[3] become significant. Since the permeability for the low-field operation is smaller than that for high-field operation, the junction diameter is usually larger for equal inductance, but the low-biasing field required outweighs this small disadvantage in most applications.

Eigenvalue measurements of a typical L-band LEC using the parallel tuning of Fig. 2 are shown in Figs. 3 and 4[4] (λ'_+ and λ'_- are the rotating eigenvalues and λ'_o is the in-phase eigenvalue as defined in Ref. 1). The different resonances of the curves have been extensively explained in Ref. 1. Here attention is focused on two special features.

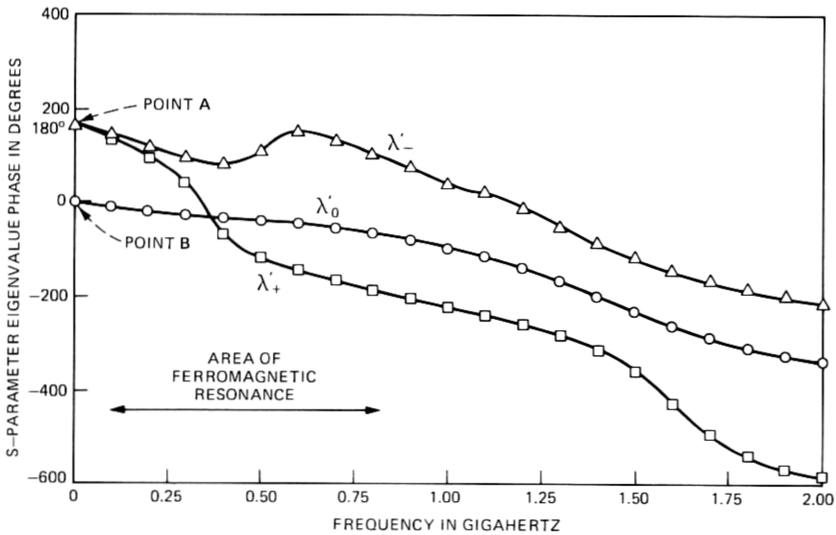

Fig. 3—Measured eigenvalue phase for low-field operation (parallel tuning).

(*i*) Since for the rotating eigenvectors, the inductors L and L_s of Fig. 2 appear as short circuits for low frequencies, their eigenvalue phase approaches 180 degrees (point A in Fig. 3), while the in-phase eigenvector "sees" an open circuit due to the capacitor common to all three arms,[2,5] i.e., a 0-degree phase (point B). It is now quite obvious that the application of the series tuning of Fig. 2b would make the rotating modes "see" an open circuit for low frequencies and therefore move their origin to point B.

(*ii*) This will increase the possible frequency range over which the eigenvalue phases can have 120-degree separation but Fig. 4, which shows the corresponding eigenvalue magnitudes, then indicates that this movement will not have any advantages, since any improvement in the desired 120-degree phase separation which will be required for circulation is masked by the ferromagnetic resonance losses which occur at the low frequency end of the circulator band.

IV. ABOVE-RESONANCE LEC

This limitation does not exist for above-resonance operation; there, ferromagnetic resonance losses occur at the high frequency end of the circulator. This is confirmed in Figs. 5 and 6, which show eigenvalue measurements made for a parallel-tuned circulator operating in the high-field mode.

The phase of the rotating eigenvalues approaches 180 degrees at low frequencies. Series tuning will move the low-frequency rotating eigenvalues to 0 degrees and in some cases increase the frequency range over which the 120-degree phase separation occurs (Fig. 7). Since no

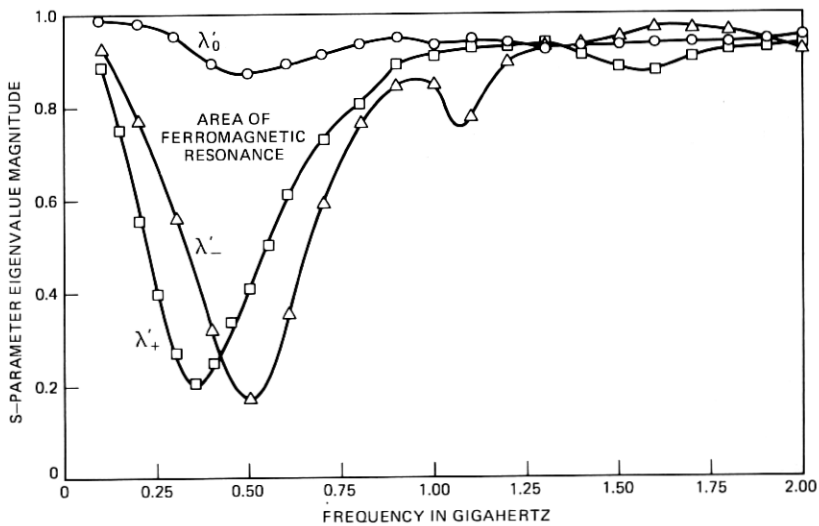

Fig. 4—Measured eigenvalue magnitude for low-field operation (parallel tuning).

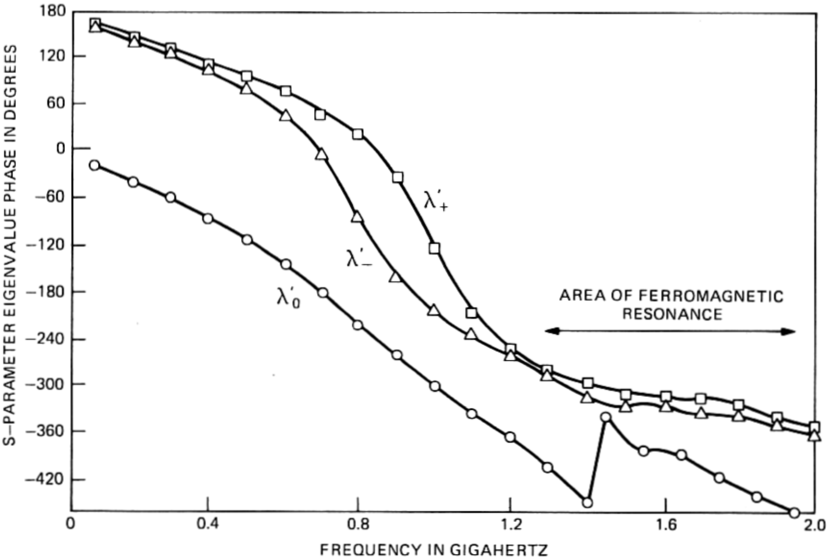

Fig. 5—Measured eigenvalue phase for high-field operation (parallel tuning).

resonance losses are present, this principle can be used to achieve broader bandwidth or lower frequency operation of circulators.

The discussion was intentionally restricted to the simple cases of Fig. 2, because of the practical advantages of this design and also to

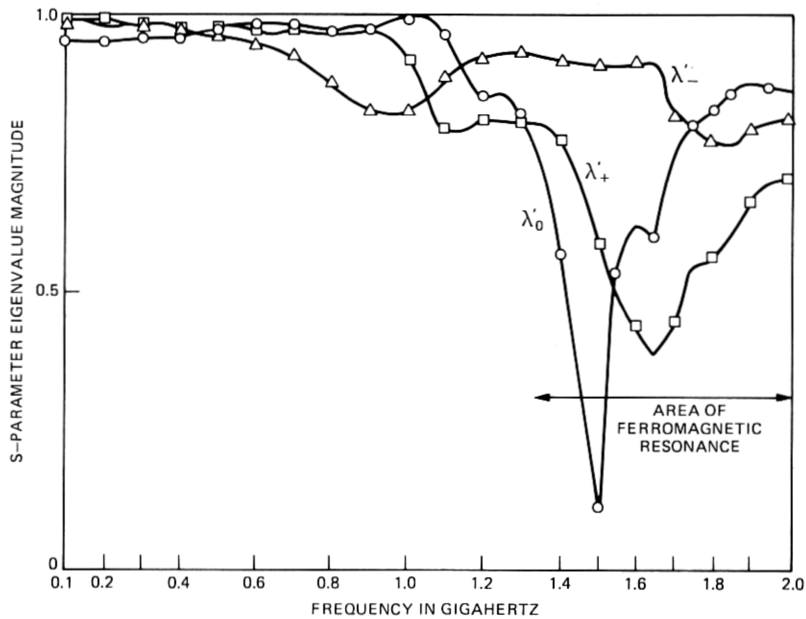

Fig. 6—Measured eigenvalue magnitude for high-field operation (parallel tuning).

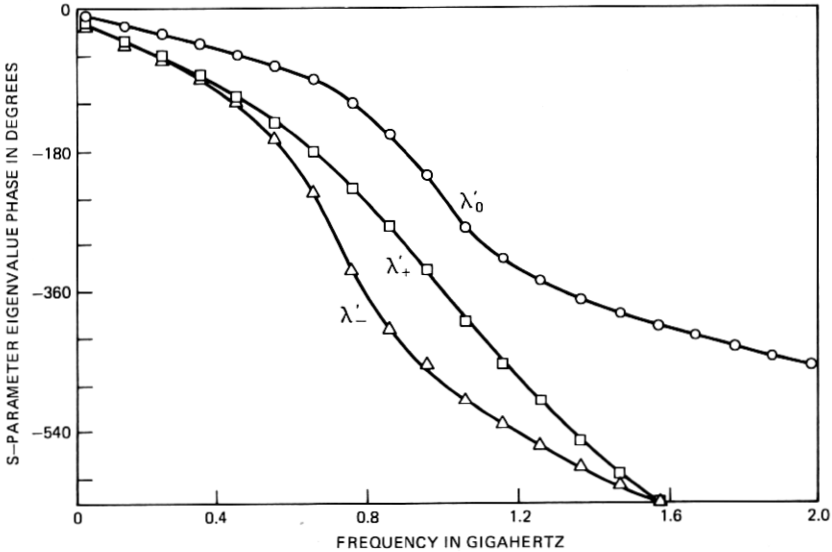

Fig. 7—Measured eigenvalue phase, high-field operation (series tuning).

simplify the arguments to better gain an understanding of the device. It is certainly possible to extend the approach to arbitrary impedances replacing the capacitors C_s, C, C_o in Fig. 2. This "shaping" of the eigenvalues has been applied to waveguide circulators.[6]

V. EXPERIMENTAL RESULTS

Three lumped-element circulators using the same junction diameter were investigated. For the circulator which operated in the low-field mode (below resonance), no top ferrite disk was necessary. A 20-dB isolation bandwidth of 500 MHz (1.1–1.6 GHz) and an insertion loss of <0.7 dB was obtained (Fig. 8). The same tuning principles were utilized in the development of an isolator with a center frequency of 1 GHz with a 20-dB isolation bandwidth of about 25 percent, insertion loss <0.4 dB (Fig. 9). The lower frequency was achieved by adding shunt capacitance between each port and the capacitor C_o common to all three ports, as shown schematically in Fig. 2.

The same junction pattern operated in the high-field mode with a higher $4\pi M$ garnet was used in the 500-MHz isolator. This resulted in the garnet disk being too thin (~0.015 inch) for economical manufacture. The circulator was then operated series tuned. Suitable adjustment of the capacitors led to a garnet disk which was twice the thickness of the original version. Both times (in the above resonance case), the conductor pattern was sandwiched between two garnet disks. Performance of this unit was similar to the 1-GHz version (insertion

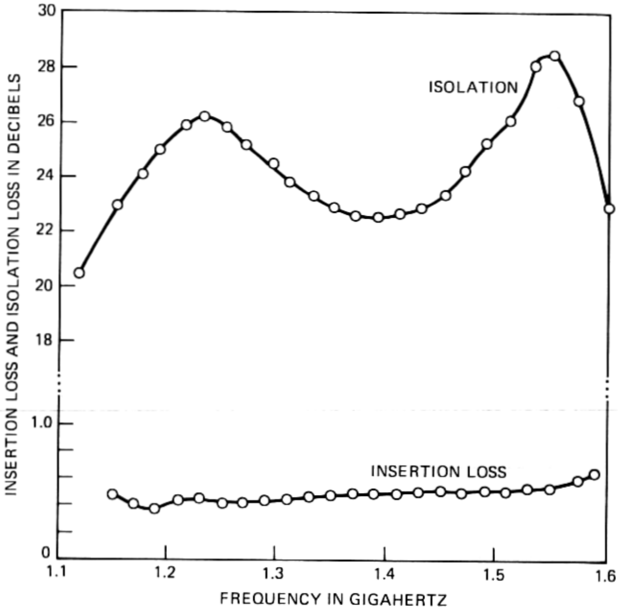

Fig. 8—Typical performance of 1.4-GHz low-field mode circulator.

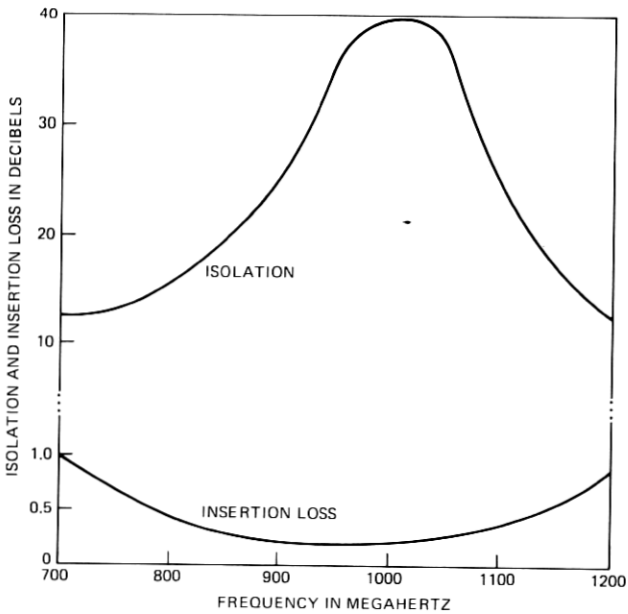

Fig. 9—Performance of 1-GHz low-field mode circulator.

loss <0.5 dB, 20-dB isolation and return loss over about 20-percent bandwidth).

VI. CONCLUSION

Series- and shunt-tuned lumped-element circulators have been discussed in terms of the S-parameter eigenvalues. It has been shown that series-capacitance tuning can be used to adjust the operation of the circulator to a lower frequency than is obtained with shunt tuning. In addition, the use of series tuning increases the required junction inductance, thus permitting the ferrite to have either a larger diameter or increased thickness. This increase partially offsets the inherent decrease in ferrite dimension associated with the higher microwave permeability at the above resonance mode of operation. In some cases, a bandwidth advantage may be obtained by going to series tuning, but this has to be decided in each individual case depending on the design restrictions.

VII. ACKNOWLEDGMENT

The author appreciates the many contributions of J. Skrapits in the experimental evaluation of these circulator design approaches and especially his continued efforts in minimizing the complexity of these potentially complicated circuits. Figures 5, 6, and 7 reflect the work of R. W. Folajtar, and information for Fig. 8 was prepared by D. J. Thibault.

REFERENCES

1. R. H. Knerr, et al, "A Compact Broad-Band Thin-Film Lumped Element L-band Circulator," IEEE Trans. Microw. Th. and Tech., *MTT-18*, No. 12 (December 1970), pp. 1100–1108.
2. V. E. Dunn, "Ultra-Compact Microwave Devices," Technical Report ECON-C0042-1, June, 1967, AD 81 8058.
3. B. Lax and K. J. Button, *Microwave Ferrites and Ferrimagnetics*, New York: McGraw-Hill, 1962, Ch. 12.
4. R. H. Knerr, "An Improved Equivalent Circuit for the Thin-Film Lumped Element Circulator," IEEE Trans. Microw. Th. and Tech., *MTT-20*, No. 7 (July 1972), pp. 446–452.
5. H. Bosma, *Advances in Microwaves*, New York: Academic Press, 1971, Vol. 6.
6. B. Owen, "The Identification of Model Resonances in Ferrite Loaded Waveguide Y-Junctions and Their Adjustment for Circulation," B.S.T.J., *51*, No. 3 (March 1972), pp. 595–627.