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# LUMPED-ELEMENT CIRCULATOR OPTIMIZATION

Ernst Schloemann

Raytheon Company Research Division
Lexington, Massachusetts

ABSTRACT

A detailed theoretical model for lumped-element circulators is used as the basis for a synthesis procedure, in which the various circuit parameters are determined such that the lossless 3-port junction is a perfect circulator at the desired design frequency and that it has maximum bandwidth for given size of the ferrite disc.

The objective of the present paper is to describe a systematic procedure for the synthesis and optimization of lumped-element circulators based on an extension of the theoretical model developed by Knerr et al.[1] An equivalent circuit for the lumped-element circulator is shown in Figure 1. Here the effect of the ferrite disc is only symbolically indicated by the large circle, and will be taken into account by appropriate mathematical equations. The synthesis and optimization procedure is used to derive theoretical expressions for the maximum bandwidth that can be achieved for given circulator size if all other parameters are adjusted for optimal performance.

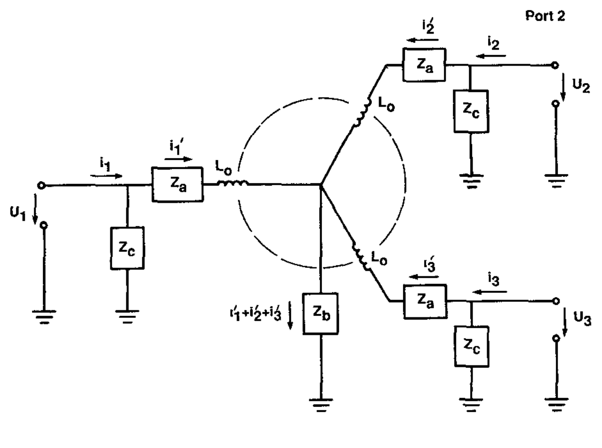


Figure 1. Equivalent Circuit of Lumped-element Circulator.

The procedure used in this work is as follows: Theoretical expressions for the "internal" and "external" permeabilities are derived from the Laudau-Lifshitz equations. The y-connected lumped-element circulator is then analyzed on the basis of a very general equivalent circuit (see Figure 1), which applies to ferrite samples of arbitrary spheroidal shape. Theoretical expressions for the impedance matrix of the ferrite loaded junction including the effect of other lumped circuit elements, are derived, and the scattering matrix is calculated. An algorithm has been constructed for finding consistent sets of parameter values (capacitances, inductances, etc.) that will result in perfect circulation (in the lossless case) at any desired design frequency. Optimization for maximal bandwidth at given design frequency is obtained by imposing the additional constraint that the frequency derivatives of the phases of the eigenvalues of the scattering matrix are equal at the design frequency.

An import parameter that largely determines the bandwidth is the external quality factor $Q_e$ of the ferrite disc, which may be defined in the same way as for YIG-filters[2] by

$$1/Q_e = \mu_0 \; 2\pi \; f_M \, V_f \, K^2/Z_0 \quad . \tag{1}$$

Here $\mu_0$ is the permeability of vacuum, $f_M$ the magnetization frequency, $V_f$ the volume of the ferrite disc, $Z_0$ the characteristic impedance of the transmission lines connected to the junction and K is a coupling factor defined as the ratio of the magnetic field (averaged over the sample volume) to current. The coupling factor K and the external quality $Q_e$ have been calculated for the device geometries of interest, in particular for hexagonal discs with a pair of conductive strips located symmetrically with respect to the disc center and at a given distance from the disc surface (see Figure 2). It is convenient to define $1/Q_{e0}$ by

$$1/Q_{e0} = \mu_0 \; f_M \; a/Z_0 \tag{2}$$

The ratio $Q_{e0}/Q_e$ then depends only on normalized disc thickness d/a, normalized conductor spacing b/a and normalized conductor to ferrite spacing s/a.





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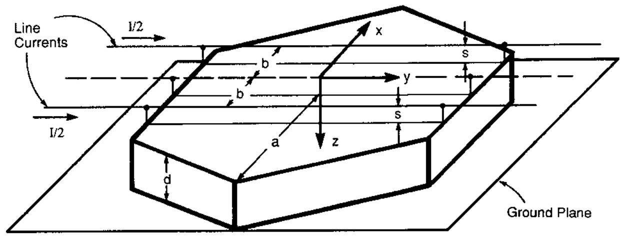


Figure 2. Geometrical Configuration of Hexagonal Disc and Coupling Line Used in Calculation of Coupling Factor K and External Quality Factor $Q_e$.

Figures 3 and 4 show the dependence of $Q_{e0}/Q_e$ on d/a with b/a as parameter and for s = 0 (Figure 3) and s/a = 0.1 (Figure 4). The largest values of

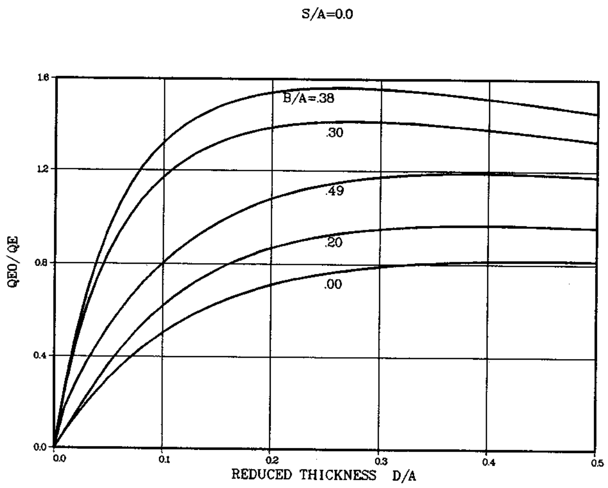


Figure 3. $Q_{e0}/Q_e$ as Function of Reduced Disc Thickness d/a for Split Coupling Lines in Contact with Ferrite Surface with the Reduced Splitting b/a as a Parameter.

$Q_{e0}/Q_e$ are realized when b/a ≈ 0.3. For given $f_M$ and $Z_0$, optimal aspect ratio of the disc and optimal spacing of the conductive strips $1/Q_e$ is substantially proportional to the disc diameter.

The optimization procedure described above has been used to find the various device parameters of the lumped-element circulator model, such as shunt capacitance $C_c$, node-to-ground capacitance $C_b$, loop inductance $L_0$, (see Figure 1) and ferrite resonant frequency $f_H'$ as functions of $1/Q_e$ for given design frequency $f_0$. A separate numerical calculation is then carried out to determine the bandwidth at 20 dB isolation.

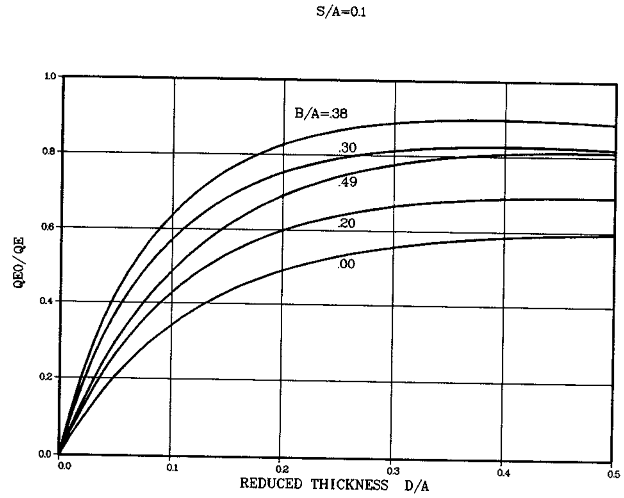


Figure 4. $Q_{e0}/Q_e$ as a Function of Reduced Disc Thickness d/a for Split Coupling Lines at a Finite Distance s from Ferrite Surface with the Reduce Splitting b/a as Parameter. The reduced line-to-ferrite distance s/a is assumed to be 0.1.

Figure 5 shows the calculated frequency dependence of the eigenvalue phases in the vicinity of the design frequency for an optimized design corresponding to $1/Q_e$ = .176.

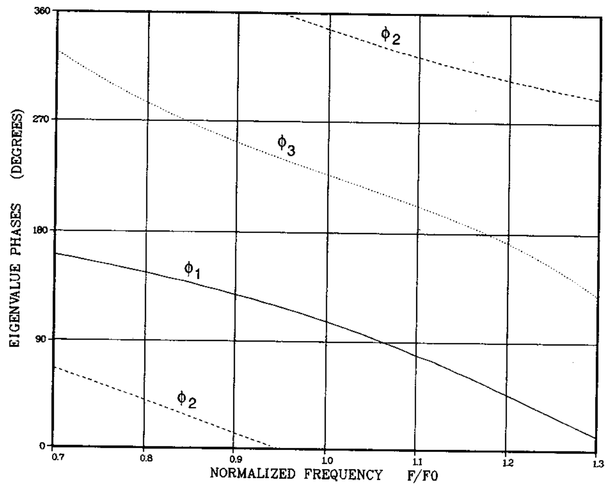


Figure 5. Frequency Dependence of the Eigenvalue Phases for an Optimized Circulator with $1/Q_e = 0.176$, $f_a = 0$, $p_1 = 0.1$.

Figure 6 shows isolation (ISOL) return loss (RL) and 10 times the insertion loss (10 × IL) as functions of frequency for the same case.

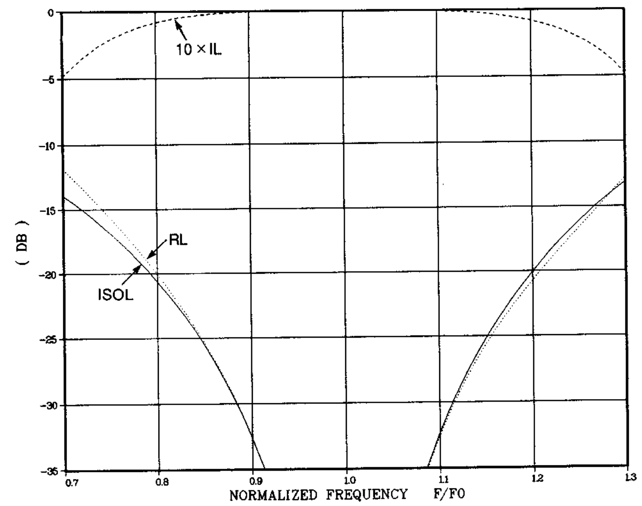


Figure 6. Isolation, Return Loss, and 10× Insertion Loss for Circulator Based on Parameter Values Given in Figure 5.

In Figure 7, the optimal device parameters and the normalized bandwidth $BW/f_1$ are shown as functions of $1/Q_e$. Here the bandwidth (BW) has been normalized with respect to the upper edge of the frequency band in which the isolation is larger than 20 dB ($f_1$). Normalization with respect to $f_1$ is preferred to normalization with respect to the design frequency $f_0$, because the latter can fall anywhere within the 20 dB isolation band, so that normalization with respect to $f_0$ can be misleading. The particular results summarized in Figure 7 are derived for the case in which no series capacitances are present in the circuit ($f_a$=0) and the

FA=0 P1=0

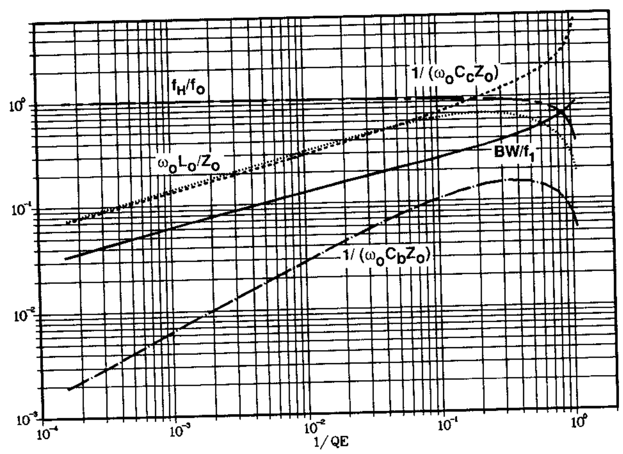


Figure 7. Normalized Bandwidth (Solid Line) and Parameter Values Required for Optimization (Broken Lines) as Function of Inverse External Quality Factor for $f_a = 0$, $p_1 = 0$.

mutual inductance in the absence of ferrite is very small compared to the loop inductance ($p_1$=0), but similar results have been obtained for other cases.

REFERENCES

[1]R. H. Knerr, C. E. Barnes and F. Bosch, "A Compact Broadband Thin-Film Lumped-Element L-Band Circulator," IEEE Trans. MTT-18, pp. 1100-1108, December 1970.

[2]J. Helszajn, "YIG Resonators and Filters," John Wiley and Sons, pp. 131-138, 1985.