A LUMPED-ELEMENT CIRCULATOR ON CERAMIC SUBSTRATES

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Abstract

By mounting a lumped-element ferrite-junction on the ceramic substrate, a small-sized circulator compatible with microwave integrated circuits is obtained. An L-band model with compensating microstrip circuits for broadbanding is also constructed on the one inch square alumina substrate.

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The present hybrid microwave integrated circuits which use semiconductor devices need ferrite circulators, compatible in size and construction. All the microwave components can be assembled in the same manner by mounting the circulators on top of ceramic substrates. Lumped-element circulators have been quite successful in VHF and UHF[1] because of their small dimensions. The development of lumped-element circulators is very important at lower microwave frequencies (below 4 GHz) because in a distributed element, the size of the ferrite is proportional to the wavelength. The results of such earlier efforts have already been reported.[2] This paper presents the experimental results of L-band lumped-element circulators mounted on ceramic substrates. An expression for the optimum bandwidth is numerically derived.

There are two possible circuit configurations for the lumped-element circulators: The parallel and series types as shown in Fig. 1 (a) and (b). The parallel circuit can be modified as shown in Fig. 2, and was first treated by Knerr, et al.[3] In our case the interwoven center conductor pattern was formed by photolithographic techniques and thru-hole plating on a thin plastic sheet. Two 10 mm diameter and 1 mm thick ferrite discs were used. The material is Al-substituted YIG with a saturation magnetization of 350 gauss and is biased just at saturation. In order to increase the filling factor of the magnetic energy within the ferrite, the two ferrite discs were packed into a shielding case with a sandwiched center conductor. The resulting nonreciprocal inductor was then bonded on the ceramic substrate, where a center electrode and three microstrip conductors had been prepared in advance. Since the parasitic capacitances, between interwoven center conductors, act as capacitor C_1 (Fig. 2), no additional capacitor is needed. The area of center electrode controls the capacitor C_2. Thus a lumped-element circulator can be mounted on top of a ceramic substrate.

Figure 3 is a photograph showing the experimental L-band lumped-element circulator. The biasing magnetic field is provided by a single permanent magnet placed just below the 0.635 mm thick alumina substrate. The performance is shown in Fig. 4. The fractional bandwidth for isolation greater than 20 dB is about 7 percent.

A larger bandwidth can be obtained by additional external matching circuits. The input admittance showed the same frequency dependence as that of a parallel resonant circuit. A compensating parallel resonant circuit composed of both a short-circuited stub and an open-circuited stub was added at each transmission line, a quarter wavelength away from the nonreciprocal junction. The broadband circulator fabricated on an alumina substrate 25.4 mm square is also shown in Fig. 3. The 20 dB bandwidth is 18 percent as shown in Fig. 4.

We will now derive the expressions for the bandwidths of the lumped element circulators shown in Fig. 1 and 2. Starting from the normalized admittance eigenvalues, and taking into account the circulation conditions, the expressions for the fractional bandwidths were obtained and are shown in Table 1. The operation with the biasing magnetic field at saturation is still assumed. The appreciable frequency dependence of the permeabilities is included in the calculation of the input reflection coefficients as a function of frequency. The fractional bandwidth of the series-type circulator is larger than that of a parallel one but is still only 24.2 percent for the normalized magnetization $p_0 = 0.7$.

In the case of the modified parallel circuit, there are two degrees of freedom in the choice of the parameter values. That is the main difference from the simple cases shown in Fig. 1 where there is only one degree of freedom in the choice of parameter. In spite of a simple mathematical concept, the numerical calculations are lengthy and best treated with a computer. The results of many computations are shown in Fig. 5, where the fractional bandwidth is plotted versus the normalized magnetization with the value of inductance as a parameter. The maximum bandwidth reaches 45 percent in the case of $p_0 = 0.6$, L = 4nH. The corresponding values of capacitances are $C_1 = 1.15$ pF, $C_2 = 7.57$ pF. Therefore it is most desirable to develop an optimized lumped-element circulator of this type. However, in this case a nonreciprocal inductor, where the capacitances between interwoven center conductors are small, would be needed. The rather high insertion loss measured is a problem which has not been considered yet.

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References

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

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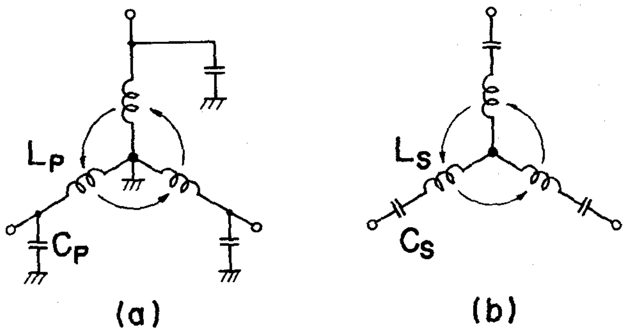

FIG. 1 SCHEMATIC OF LUMPED-ELEMENT CIRCULATORS. (a) PARALLEL TYPE, (b) SERIES TYPE.

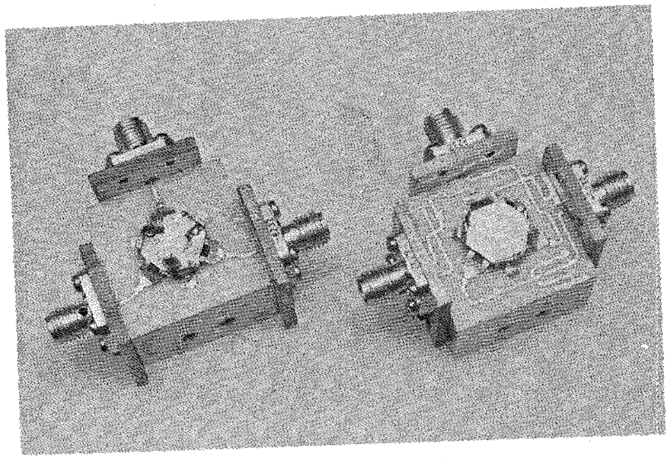

FIG. 3 SINGLE-TUNED AND BROADBANDED LUMPED-ELEMENT CIRCULATORS ON CERAMIC SUBSTRATES.

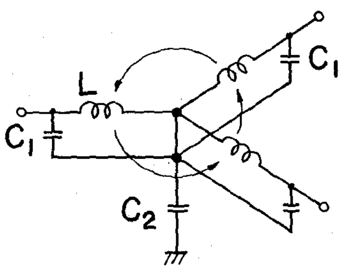

FIG. 2 SCHEMATIC OF MODIFIED PARALLEL-TYPE LUMPED-ELEMENT CIRCULATOR.

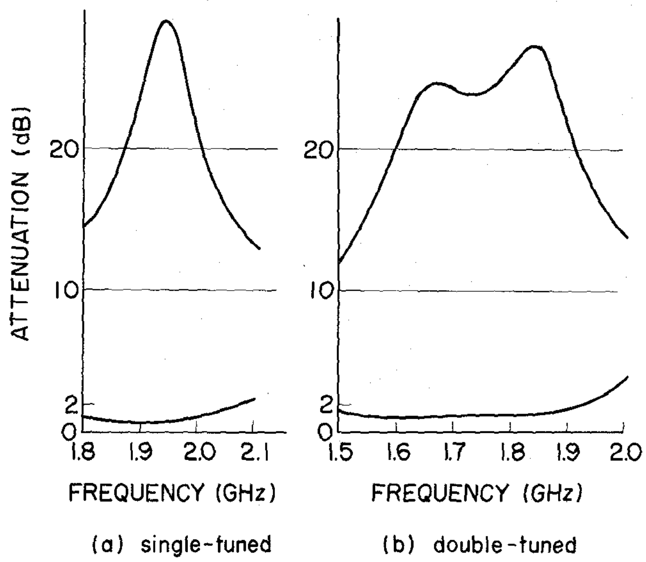

FIG. 4 PERFORMANCE OF LUMPED-ELEMENT CIRCULATORS ON CERAMIC SUBSTRATES

TABLE 1

COMPARISON OF THE FRACTIONAL BANDWIDTHS

Circuit Configuration		Parallel	Series	Modified Parallel
Figure No.		1 (a)	1 (b)	2
Admittance/ Impedance Eigenvalues	Same phase excitation	$y_0 = \infty$	$z_0 = \infty$	$y_0 = j\omega \frac{C_2}{3} R_0$
	Rotational excitation	$y_\pm = j(\omega C_p - \frac{1}{\omega\mu_\pm L_p}) R_0$	$z_\pm = j(\omega\mu_\pm L_s - \frac{1}{\omega C_s}) \frac{1}{R_0}$	$y_\pm = j(\omega C_1 - \frac{1}{\omega\mu_\pm L}) R_0$
Circulation Condition		$y_\pm = \mp j \frac{1}{\sqrt{3}}$	$z_\pm = \mp j \frac{1}{\sqrt{3}}$	$S_0 + S_+ + S_- = 0$
Differential of Input Refl. Coeff. δS_{11}		$\frac{1}{1 - p_0^2} (1 - j \frac{1}{\sqrt{3} p_0}) \delta$	$j \frac{1}{\sqrt{3}\, p_0} \delta$	———
Fractional Bandwidth (percent)		$20 (1 - p_0^2)/(1 + \frac{1}{3p_0^2})^{1/2}$	$20 \sqrt{3}\, p_0$	See Fig. 5

where ω: angular frequency
δ: normalized frequency variation
$\mu_\pm$: permeabilities for circular polarizations ($= 1 \mp p$)
p: normalized magnetization ($= |\gamma| 4\pi M_s/\omega$)
γ: gyromagnetic ratio (= -2.8 MHz/Oe)
$4\pi M_s$: saturation magnetization

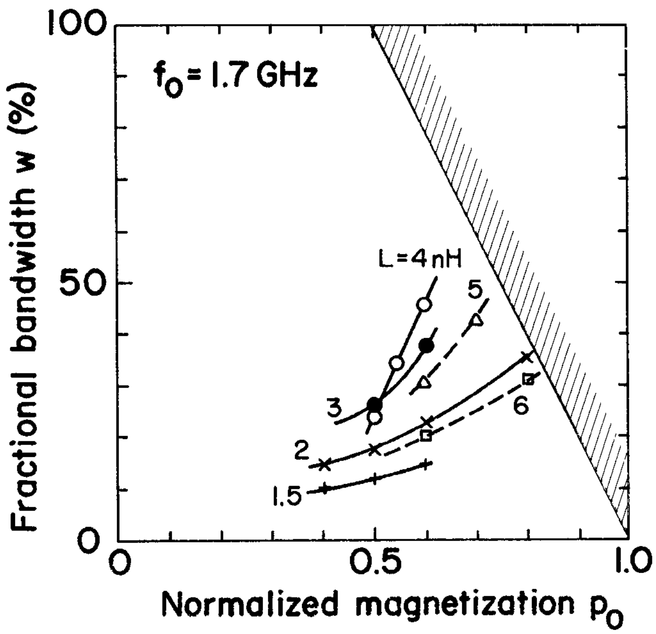

FIG. 5 FRACTIONAL BANDWIDTH VERSUS NORMALIZED MAGNETIZATION