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A Temperature-Stabilized Broad-Band Lumped-Element Circulator

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***Abstract*—An equivalent circuit including the stray reactances of a microstrip-type lumped-element circulator is derived to establish the design procedure, and it is shown theoretically that a broad-band circulator with a 30-percent bandwidth can be realized. Additionally, to obtain the broad-band characteristics over a wide range of temperatures, the necessary temperature coefficients of ferrite materials and magnets are calculated.**

A new ferrite material with a low temperature coefficient as well as a new fabrication process for thin-film crossovers have been developed. The experiments indicate that a radial magnetizing field improves the circulator characteristics in both bandwidth and loss. An experimental circulator exhibits the following characteristics over a wide temperature range from −10 to 60°C: VSWR < 1.2, loss < 1.0 dB, and isolation > 20 dB over a bandwidth of 450 MHz centered at 1.7 GHz.

I. INTRODUCTION

DURING recent years, microwave integrated circuits (MIC's) have been instrumental in reducing the size of the circuit elements used at microwave frequencies, especially at low frequencies such as L band. These MIC elements necessitate small circulators comparable in size to the elements themselves. The main function of circulators is to connect two mismatched devices in which a propagating signal suffers loss and distortion, and thus establish a good match between them.

There are two kinds of circulators: distributed-element circulators and lumped-element circulators. Distributed-element circulators become large in size at low frequencies, because the dimensions of the constructional elements must be on the order of one-half the guided wavelength [1]. On the other hand, lumped-element circulators developed by Konishi [2] and others [3]–[5] have smaller dimensions than the distributed types by a factor of 5–10 and are used practically as small circulators in the VHF and UHF bands.

At microwave frequencies, the configurations of lumped-element circulators become very small and very complicated. The stray reactances of the lumped elements, which can be ignored in the VHF and UHF bands, play a role in the circulator performance, and consequently a refined design procedure must be established. The fabricating technique which utilizes those methods such as the cutting out and interweaving of conductors cannot be used for fabricating these fine patterns.

In the last years, Knerr has developed a thin-film lumped-element circulator with a 20-dB-isolation bandwidth in excess of 30 percent, using a unique broad-banding circuit at L band [6]. Following this development, several papers dealing with the design and experimental results have been published [7]–[9]. However, changes in the characteristics of the circulators due to temperature variations and also the large dimensions (still smaller than the distributed type at the same frequency), which are important points for practical use, have merited little consideration so far.

In this paper, we will show a small circulator which operates over a temperature range from −10 to 60°C with a 30-percent bandwidth centered at 1.7 GHz. First, we will discuss an equivalent circuit including stray reactances of lumped-element circulators and show the feasibility of a broad-band circulator from an analysis of simulation results. Additionally, we will derive the necessary temperature coefficients of the ferrite and magnet for a circulator to operate over a wide range of temperatures. Next, a newly developed ferrite material and a new fabrication process for crossovers will be described. The ferrite is basically a GdIG which has a low temperature coefficient. The fabrication process utilizes thin-film technology which simplifies the fabrication of the air-

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isolated crossover structures of conductors and thereby thin-film circulators. Finally, the effective contribution of a radial magnetic field to the bandwidth and the results of the experimental circulators will be presented.

II. ANALYSIS

A. Equivalent Circuit and Circulator Characteristics

A three-port lumped-element circulator operates principally with the nonreciprocal couplings of three coils wound around a magnetized ferrite disk. Fig. 1 shows the basic configuration of a microstrip-type lumped-element circulator. The three coils are formed with three short coupled lines shorted at each end. To maintain electrical symmetry and insulation of the coils, the coupled lines cross each other at an angle of 120° and have crossovers at the intersections.

In the peripheral part of the ferrite disk, there are three input ports and three ground lines for the three coupled lines, respectively. The RF magnetic field induced by passing RF current through one coupled line does not link with the other coupled lines, because in the peripheral part, the coupled lines are separated from each other by a large distance. Thus the coil has a reciprocal coupling inductance (L_1 or L_2), which is equal to the self-inductance.

On the other hand, in the central part, there are the middle parts of the coupled lines including the crossovers. The RF magnetic field induced by passing RF current through one coupled line does link with the other coupled lines in this case and thus produces a nonreciprocal coupling inductance L_c.

Therefore, each coupled line on the ferrite disk has three inductances: L_1 for the input port, L_2 for the ground line, and L_c for the middle part of the coupled line. Additionally, the coupled lines have two kinds of capacitances which can be ignored in the design at low frequencies: a crossover capacitance C_c and a stray capacitance C_s.

According to the preceding discussions, an equivalent circuit of a lumped-element circulator can be described with the circuit in Fig. 2. To obtain the element values of the circuit, we have measured the S parameters of the circulator and have calculated the eigenimpedances from the S parameters. We have used an automatic network analyzer to measure the S parameters of the circulator terminated with a dummy load at one port. Fig. 3 shows the eigeninductances calculated by dividing the measured impedances by ω. According to these results, it is understood that the in-phase inductance L_0 has an almost constant value in an external magnetic field of 3100 G. On the other hand, the rotational inductances L_+ and L_- have a strong frequency dependence on the effects of the capacitances C_c and C_s. From these results, we have obtained the element values for a circulator substrate: $L_c \approx 1.6$ nH, $L_1 + L_2 \approx 1.0$ nH, $C_s \approx 0.9$ pF, and $C_c \approx 0.2$ pF.

We can calculate the circulator performance using the S parameters of the equivalent circuit. The inductances

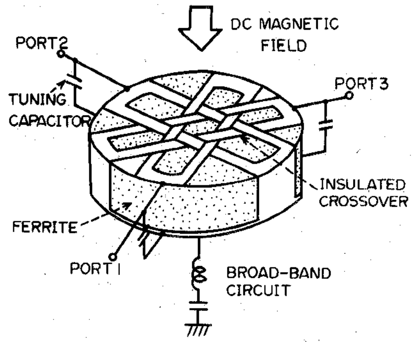

Fig. 1. Microstrip-type lumped-element circulator.

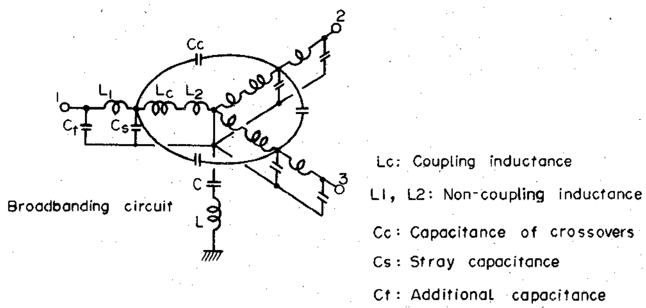

Fig. 2. Equivalent circuit of the circulator in Fig. 1.

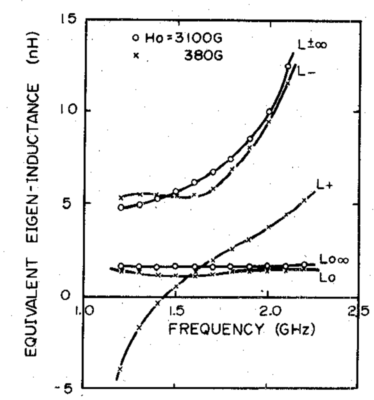

Fig. 3. Equivalent eigenimpedances as a function of frequency for the circulator substrate. Inductances L_+ and L_- are rotational inductances and L_0 is in-phase inductance. H_0 is external magnetic field.

L_c, L_1, and L_2 are calculated from considerations of a nonreciprocal filling factor K_f [10], and are affected by the permeabilities ($\mu_\pm$ and μ_{eff}), including the geometrical effects of the ferrite and the conductors. Fig. 4 shows the calculated relationship between the saturation magnetization $4\pi M_s$ of ferrites and the internal magnetic field H_i with a 20-dB-isolation bandwidth $\Delta\omega$ as a parameter, each normalized to the operation frequency ω for a lumped-element circulator. For simplification, we have assumed that L_1 and L_2 are equal to zero and the broad-banding circuit is not applied. As a result, we can predict the realization of a lumped-element circulator which has about a 10-percent bandwidth and 0.5-dB loss.

Adding an appropriate broad-banding circuit, we have calculated the broad-band characteristics. The added circuit was an LC series circuit inserted between the common conductor on the back surface of the ferrite

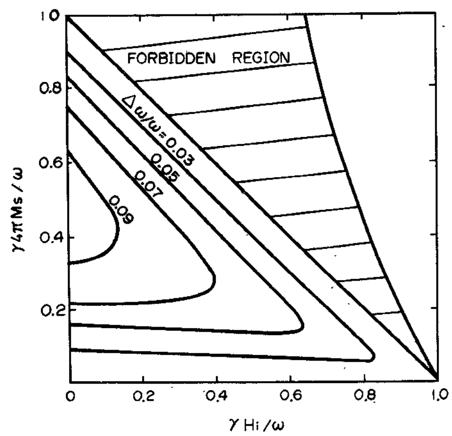

Fig. 4. Saturation magnetization as a function of the internal magnetic field normalized with the resonance field corresponding to the operating frequency for the below-resonance operations. $\Delta\omega$ is the 20-dB isolation bandwidth. When $\gamma H_i/\omega = 0$, the ferrite is magnetized just to saturation, and when $\gamma H_i/\omega = 1$, it is magnetized to the magnetic resonance.

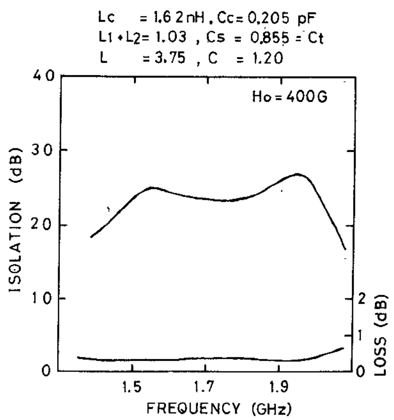

Fig. 5. Calculated circulator performance using the equivalent circuit in Fig. 2.

substrate and the ground conductor of the case. The circuit influences only the in-phase eigenimpedance of the circulator and thus the broad banding can be easily adjusted.

Fig. 5 shows the calculated broad-band performance with $K_f = 0.7$. From the simulation results, we have concluded that an L-band lumped-element circulator with a 30-percent bandwidth can be realized even in the case of nonperfect coupling ($K_f < 1$), if the circuit elements and the broad-banding circuit are chosen appropriately.

B. Necessary Temperature Coefficient

For practical use of the circulators, changes in the circulator characteristics due to temperature variations must be taken into consideration. The circulators must have a broad-band performance over a wide range of temperatures. In general, the saturation magnetization of ferrite as well as the magnetic field of magnets change due to temperature variations, and consequently the center frequency and the bandwidth change with the temperature. The necessary temperature coefficients of the ferrite and the magnet can be calculated so that the changes are kept within the desired limits.

We reported previously a center frequency shift due to temperature variations on the assumption that the shift is equal to half the sum of the rotational frequency shifts [12]. In this paper, we will calculate the shift more precisely.

Let us assume that the circulator is an ideal circulator which has perfectly coupled inductances ($K_f = 1$) and uses a thin ellipsoidal ferrite disk (demagnetizing factor $N_z = 1$). From the latter assumption, the rotational permeability $\mu_\pm$ is calculated in the following equation [11]:

$$\mu_\pm = 1 + \frac{4\pi M_s}{H_0 - 4\pi M_s \mp H} \tag{1}$$

where $4\pi M_s$ is the saturation magnetization, H_0 the external magnetic field, and H the electron spin resonance magnetic field of the operation frequency. The change of $\mu_\pm$ due to temperature variations $\delta\mu_\pm$ is derived by differentiating (1) as follows:

$$\frac{\delta\mu_\pm}{\mu_\pm} = \frac{p}{(s \mp 1)(s \mp 1 + p)} \cdot \left((s + p \mp 1)\frac{\delta 4\pi M_s}{4\pi M_s} - (s + p)\frac{\delta H_0}{H_0} \pm \frac{\delta f}{f}\right) \tag{2}$$

where s and p are the normalized internal magnetic field and the saturation magnetization with the resonance magnetic field, respectively. In the former assumption, the in-phase eigenimpedance is equal to zero for any given frequency and therefore the rotational eigenimpedances must be kept at constant values against temperature variations. From the representation of the circulator condition in admittance,

$$(\omega + \delta\omega)C - \frac{1}{(\omega + \delta\omega)L(\mu_\pm + \delta\mu_\pm)} = \mp \frac{1}{\sqrt{3}Z_0} \tag{3}$$

where ω is the operation frequency, $\delta\omega$ the frequency shift, L and C the inductance and the capacitance of the circulator, and Z_0 the characteristic impedance. Using these equations and neglecting the term $(\delta\omega/\omega)(\delta\mu_\pm/\mu_\pm)$ ($\ll 1$), we can obtain the frequency shift:

$$\frac{\delta f}{f} = \tfrac{1}{2}(1 - t^2)\frac{\delta 4\pi M_s}{4\pi M_s} + t^2\frac{\delta H_0}{H_0} \tag{4}$$

where $t = s + p$. Bandwidth B is related to VSWR, γ, and κ/μ [13], i.e.,

$$B/f = \sqrt{3}\,\frac{\kappa}{\mu}\,\frac{\gamma - 1}{\sqrt{\gamma}}. \tag{5}$$

Differentiating (5) and inserting (2), we have

$$\frac{\delta(B/f)}{B/f} = \frac{1}{st - 1}\left((t^2 - 1)\frac{\delta 4\pi M_s}{4\pi M_s} - t(s + t)\frac{\delta H_0}{H_0} + (st + 1)\frac{\delta f}{f}\right). \tag{6}$$

Inserting (4) into (6), we get the bandwidth shift

$$\frac{\delta(B/f)}{B/f} = \tfrac{1}{2}(1 - t^2)\,\frac{\delta 4\pi M_s}{4\pi M_s} + \left(t^2 + \frac{tp}{st - 1}\right)\frac{\delta H_0}{H_0}. \quad (7)$$

Here, it should be kept in mind that the shifts become small when the changes in the ferrite and the magnet show the opposite temperature tendencies. Applying these equations to a circulator which operates in a temperature range from −10 to 60°C and has the following characteristics: $\delta f/f < 1.5$ percent, $\delta(B/f)/(B/f) < 1$ percent, VSWR < 1.2, $B = 0.1$, $s = 0$, $\kappa/\mu = p$, we can obtain the necessary temperature coefficients of ferrite materials and magnets:

$$| \delta 4\pi M_s/4\pi M_s | < 0.03\%/°\mathrm{C} \quad (8)$$

$$| \delta H_0/H_0 | < 0.04\%°/\mathrm{C}. \quad (9)$$

III. EXPERIMENT

A. Newly Developed Ferrite

As shown in Fig. 4, a ferrite material for 1.7-GHz broad-band lumped-element circulators operating in a below-resonance magnetic field must have a saturation magnetization of about 400 G. Moreover, to operate in a wide range of temperatures, the magnetization must have a low temperature coefficient as shown in (8).

YAlIG [11], [14], CVB garnet [15], CaV garnet [16], and GdIG show relatively low magnetization compared with other microwave ferrite materials. However, no suitable material with the low temperature coefficient was commercially available.

We have developed a new ferrite material for 1.7-GHz lumped-element circulators, taking into account that a GdIG ferrite material can be controlled to have a maximum magnetization near room temperature and a low loss factor by the substitution of Gd with the appropriate materials [11], [14].

Changes in the magnetization due to temperature variations are shown in Fig. 6 in comparison with those of a conventional YAlIG. The total change in magnetization in a temperature range from −10 to 60°C is only 7 percent in the case of the newly developed ferrite, while it is 20 percent for the YAlIG. As a result, it has been confirmed that the new ferrite has the necessary temperature coefficient for a circulator to operate over a wide range of temperature.

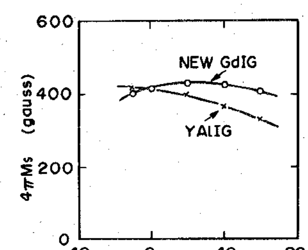

Fig.6 . Saturation magnetization as a function of temperature for the new ferrite, represented as NEW GdIG, and a conventional YAlIG.

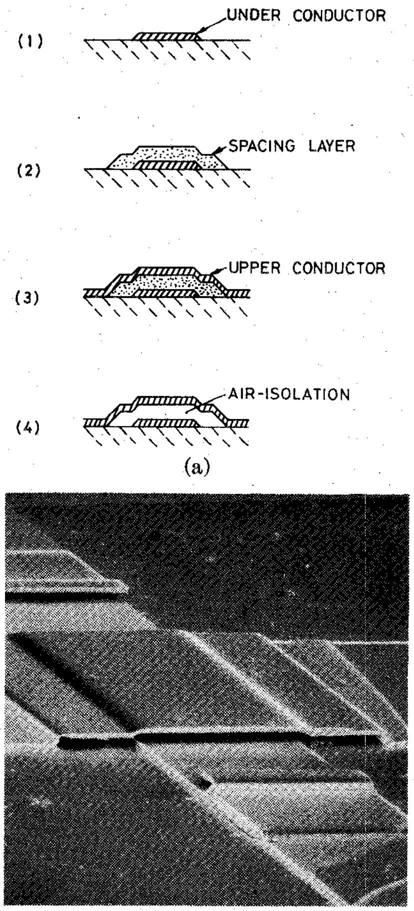

Fig. 7. (a) Illustrative sequence of the new fabrication process for the air-isolated crossover structures. (b) Magnified view of the crossover in which the conductor is 300 μm in width and the air gap is 20 μm in height.

B. New Fabricating Process for Air-Isolated Crossovers

We have developed a simple process to fabricate the crossover structures of the circulator. Fig. 7 shows the illustrative sequence and the air-isolated crossover. At first, the under conductor segments at the crossovers are formed by the first three steps: flash evaporating, electroplating, and photolithographic etching [Fig. 7(a)-(1)]. Then, the spacing layers of copper are formed by the second three steps [Fig. 7(a)-(2)], and the upper conductors at the crossovers, as well as the ground conductors on the back and side surface of the ferrite substrate, are formed by the third three steps [Fig. 7(a)-(3)]. Finally, the spacing layers are etched to make the complete crossover structures isolated with air [Fig. 7(a)-(4)].

The new process is simplified by eliminating the steps to form the pedestals which were used in the published processes [17]–[20]. The crossover structures formed by the new process, shown in Fig. 7(b), were proved to show enough strength for practical uses.

C. Broad Banding

From the results of computer simulations and experiments, the phase differences between the rotational eigenvalues have maintained a value of about 120° over a wide range of frequencies but the phase differences between

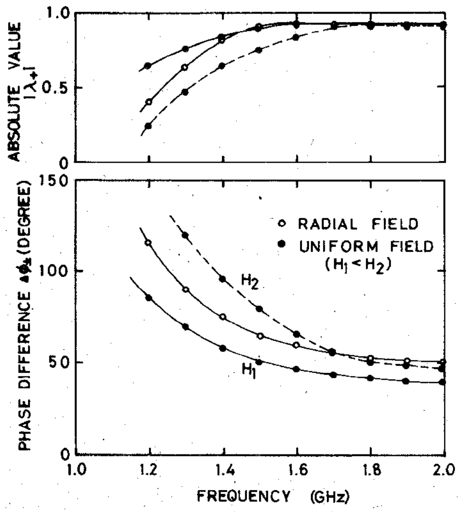

Fig. 8. Influence of the magnetizing field shape on the phase differences of the S-parameter eigenvalues and the absolute eigenvalues.

the in-phase and the rotational eigenvalues have a value far from 120°.

Hence, we have chosen an LC series circuit for a broad-banding circuit, which is inserted between the common conductor of the ferrite substrate and the ground conductor of the case.

Moreover, we used a radial magnetic field for magnetizing the ferrite substrate. The radial magnetic field diverges from the surface side of the ferrite substrate to the back side and can be produced by setting a magnet over the ferrite substrate. Fig. 8 shows the effectiveness of the radial magnetic field for the rotational eigenvalues in comparison with that of the uniform magnetic field. It is obvious that the radial magnetic field improves the magnitudes of the eigenvalues and contributes to broad-band and low-loss performance of the circulators.

We have proposed the following tentative reasons as to why it does. The RF magnetic field of the microstripline links the center conductor with an elipticlike circle and therefore a uniform magnetizing field does not cross at right angles everywhere. However, a radial magnetic field improves the crossing to a point where it comes closer to 90°. In other words, the nonreciprocal filling factor K_f becomes large, and this condition of the magnetic fields contributes to an effective circulation action.

D. Experimental Circulator

All conductors including crossovers of the lumped-element circulator were formed on the newly developed ferrite substrate (with dimensions of 7 mm$^\phi$ × 2 mm^t) by the new thin-film process for fabricating the air-isolated crossovers. In addition, the use of an LC series circuit for a broad-banding circuit was integrated on a silica substrate (7 mm$^\phi$ × 0.6 mm^t).

We have designed a compact magnetically shielded case (12 mm$^\phi$ × 9 mm^t) in the consideration of the effect of the radial magnetic field. It is an iron case in which a magnet and a compensator ring are installed as shown in

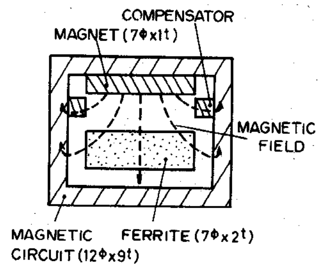

Fig. 9. Configuration of the compact magnetically shielded case.

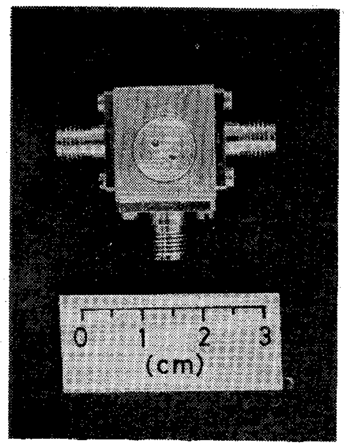

Fig. 10. External view of the 1.7-GHz lumped-element circulator.

Fig. 9. Considering a low temperature coefficient and a high magnetic energy to be useful in the miniaturization of the magnet, we have used a SmCo magnet and a NiFe alloy ring. The ring acts as a compensator for changes in the magnetic field induced in the magnet by temperature variations.

Fig. 10 shows an experimental circulator with dimensions of 16 × 18 × 9 mm^3 without the connectors and which is smaller than the conventional distributed-element circulator by a factor of about 10.

E. Circulator Characteristics

Figs. 11 and 12 show the bandpass characteristics of the experimental circulator using a conventional YAlIG and the newly developed ferrite, respectively. The circulator performance using the YAlIG changes with temperature variations because the YAlIG magnetization has a strong temperature dependence as shown in Fig. 6. The temperature range in which stable performance is possible with this material is from −10 to 30°C. In this case, the circulator exhibits VSWR < 1.2, and loss < 1.0 dB over a bandwidth of 450 MHz centered at 1.7 GHz.

On the other hand, the new ferrite has very little temperature dependence and thus the circulator exhibits a temperature stabilized performance. Over a wide temperature range from −10 to 60°C, the circulator shows the following characteristics: VSWR < 1.2, loss < 1.0 dB, and isolation > 20 dB over the bandwidth of 450 MHz centered at 1.7 GHz.

We are now attempting to reduce the size as much as possible in order to realize a compact circulator which can be attached directly to an MIC.

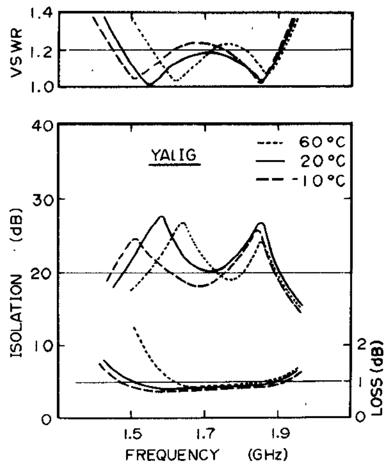

Fig. 11. Bandpass characteristics of the circulator utilizing a conventional YAlIG.

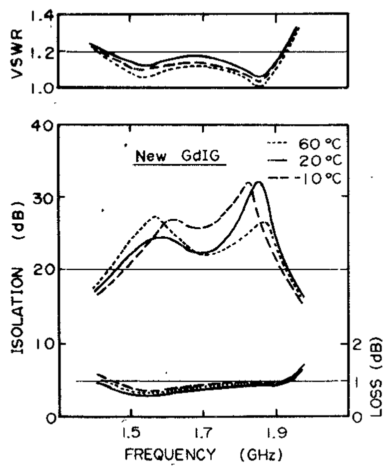

Fig. 12. Bandpass characteristics of the circulator utilizing the newly developed GdIG ferrite material.

IV. CONCLUSION

An equivalent circuit of a microstrip-type lumped-element circulator has been derived. Using the equivalent circuit which includes the stray reactances, we have calculated the circulator performance and suggested the possibility of a broad-band circulator with a 30-percent bandwidth. Further, we have calculated the necessary temperature coefficients of the ferrite and the magnet so that the circulator operates over a wide range of temperatures with broad-band characteristics. The results show the necessity of a ferrite and a magnet with a very low temperature coefficient.

A new ferrite material has been developed based on a GdIG for use in a 1.7-GHz circulator. Using the new ferrite and a new fabricating process for the air-isolated crossovers, we have produced a thin-film lumped-element circulator experimentally. The experimental circulator has a compact magnetically shielded case and exhibits suitable characteristics over a wide range of temperatures.

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