A 1.7GHZ LUMPED-ELEMENT CIRCULATOR STABLE OVER A WIDE RANGE OF TEMPERATURE

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Abstract

This paper describes a broadband thin-film lumped-element circulator stabilized over a wide range of temperatures using a newly-developed ferrite material with a low temperature coefficient. The experimental circulator exhibits a bandwidth of about 420MHz over a wide temperature range of from -10°C to 60°C, in which VSWR and loss are less than 1.2 and 1.0dB, respectively.

Introduction

To realize a small circulator at low microwave frequencies, R. H. Knerr recently developed a thin-film lumped-element circulator at L-band with a 20dB bandwidth in excess of 30% using a unique broadbanding technique [1].

Several papers dealing with lumped-element circulators have been published, but these papers have only lightly touched upon variations in the characteristics due to temperature changes. These variations however are very important considerations in practical application situations.

We have calculated the variations of the bandpass performance due to temperature changes and have obtained the necessary temperature coefficients of ferrite and magnet for a circulator to operate efficiently over a wide range of temperatures. Based on these results, we have developed a new ferrite with a low temperature coefficient and a magnetically-shielded case with a magnet which is compensated for temperature. Additionally we have developed a new fabricating process for making a circulator utilizing IC techniques. Using these materials and processes, we have obtained a thin-film lumped-element circulator which operates over the wide temperature range which is necessary for practical use.

This paper describes a circulator which operates in a temperature range of from -10°C to 60°C at 1.7GHz and has a bandwidth of 420MHz in which VSWR and loss are less than 1.2 and 1.0dB, respectively.

Analysis

Equivalent Circuit

We have derived an equivalent circuit of a lumped-element circulator from theoretical considerations and verified it experimentally.

The circuit can be represented by coupling inductances, non-coupling inductances, and capacitances, as shown in Fig. 1.

The scattering parameters of the circulator have been calculated from the eigen-impedances of the equivalent circuit, assuming a non-reciprocal filling factor [2] including geometrical effects. After calculating the bandpass performance of the circulator using the S-parameters, we have proven the possibility of a 1.7GHz lumped-element circulator with about 30% bandwidth.

Temperature Dependence

The center frequency fo and the bandwidth B vary with the temperature, since both the saturation magnetization of ferrite 4 Ms and the magnetic field of magnet Ho change. We have calculated the necessary temperature coefficients for a circulator to operate over a wide range of temperatures.

The variations of the center frequency and bandwidth are calculated as follows in cases where a circulator operates below the resonance field ($\sigma=0$) and uses a elipsoidal thin ferrite disk (Nz=1),

$$\frac{\delta fo}{fo} = \frac{-p^2}{4-p^2}\left(\frac{\delta 4\pi Ms}{4\pi Ms} - 2\frac{\delta Ho}{Ho}\right) \quad (1)$$

$$\frac{\delta(B/fo)}{B/fo} \doteqdot \left(1-p^2+\frac{p^2}{4-p^2}\right)\frac{\delta 4\pi Ms}{4\pi Ms} + p^2\left(1-\frac{2}{4-p^2}\right)\frac{\delta Ho}{Ho} \quad (2)$$

where, p is a magnetization normalized with the resonance field.
In the calculations, we used the following equations,

$$\mu_{\pm} = 1+p/(\sigma \mp 1) \quad (3)$$

$$\frac{\delta fo}{fo} \doteqdot \frac{1}{2}\left(\frac{\delta\omega-}{\omega-}+\frac{\delta\omega+}{\omega+}\right) \quad (4)$$

$$B = \sqrt{3}\,\frac{\kappa}{\mu}\,\frac{\gamma-1}{\sqrt{\gamma}} \quad (5)$$

Applying these equations to a 1.7GHz circulator with characteristics of B/fo=0.2, $\gamma=1.2$, $\delta fo/fo<1.5\%$, $\delta(B/fo)/(B/fo)<5\%$, and an operating temperature range of from -10°C to 60°C, we can obtaine necessary temperature coefficients of the ferrite and magnet as follows,

$$|\delta 4\pi Ms/4\pi Ms| < 0.06\%/°C \quad (6)$$

$$|\delta Ho/Ho| < 0.04\%/°C \quad (7)$$

Experimental Result

Newly-Developed Ferrite

Many commercially available ferrite materials are not suitable for use in a lumped-element circulator which has a stable operation with a broad bandwidth over a wide range of temperatures, because the ferrites depend heavily on the temperature as to saturation magnetization and therefore the temperature variation affects the bandwidth.

Based on GdIG, we have developed a new ferrite material which has a low temperature coefficient, less than the necessary value 0.06%/°C, and a maximum magnetization of 430 gauss at 20°C. Figure 2 compares the temperature dependences of saturation magneti zation of the newly-developed material and a conventional YAlIG. The change in magneti zation due to temperature variation is 20%/ -10°C 60°C for YAlIG, but only 7% for the new material.

The ferrite substrate used in the circulator is 7mm in diameter and 2mm in thickness.

New Fabricating Process

The center conductors of the lumped--element circulator have twelve crossovers at the intersections. We have developed a new process for fabricating the crossover structures, which requires only three main steps using three different masks.

Figure 3 is a photograph of a crossover made by this process. We have confirmed that the crossovers have enough mechanical strength for practical use.

Broadbanding Circuit

Broadbanding has been attained by insert ing a LC series circuit between the common conductor back on the circulator substrate and the earth conductor of the case. The LC circuit was made by combining a spiral inductor with a silica substrate (7^{ϕ}x0.6^{t}) and a parallel plate capacitor, using the silica for dielectric.

Compact Magnetically-Shielded Case

Experiments have indicated that the characteristics of microstrip-type lumped-element circulators can be improved especially with regard to loss and bandwidth by magnetizing the ferrite with a radial magnetic field. The magnetic field diverges from the upper side to the lower side of the ferrite substrate, on which the center conductors are fabricated. The radial magnetic field can be realized by arranging one magnet over the upper side of the substrate.

Taking the effectiveness and the magnetic shield into consideration, we have designed an iron case measuring 18x16x9 mm^3 for the T-type and $12mm^{\phi}$x$9mm^{t}$ for the plug-in type circulators. A SmCo magnet (6^{ϕ}x1^{t}) coveres with an appropriate ring of Fe-Ni alloy is used for the magnet. The ring acts as a compensator for changes in the magnetic field due to temperature variations.

Circulator Characteristics

The experimental circulators are shown in Fig. 4 and are smaller by a factor of 5 ~ 10 than a conventional distributed-element circulator at L-band.

Figure 5 and 6 show the typical bandpass characteristics of the circulator using a conventional YAlIG and the newly-developed ferrite, respectively. At 20°C, both circulators exhibit VSWR's of less than 1.2 and losses of less than 1.0dB over a bandwidth of 420MHz. However, comparing changes in the bandpass performances due to temperature variations, the YAlIG shows a strong temperature dependence and shows suitable performance characteristics (VSWR < 1.2, loss < 1.0dB over 420MHz) only over a temperature range of from 10°C to 30°C. On the other hand, the new ferrite one shows no remarkable changes over a wide temperature range of from -10°C to 60°C.

Conclusion

In order to offset the effects of the temperature coefficients of ferrite and magnet on the circulator performance, we have developed a new ferrite material based on GdIG and a compensating method for the magnet. The experimental 1.7GHz thin-film lumped-element circulator has shown a 20dB isolation bandwidth of over 420MHz over a wide range of temperarure of from -10°C to 60°C.

Acknolegement

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References

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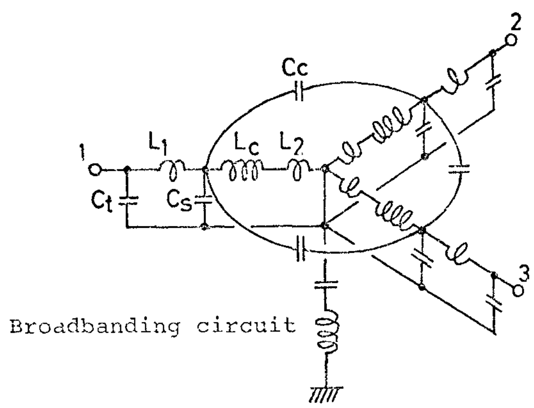

Lc: Coupling inductance

L1, L2: Non-couping inductance

Cc: Capacitance of crossovers

Cs: Stray capacitance

Ct: Additional capacitance

Fig. 1 Equivalent circuit of a lumped-elment circulator

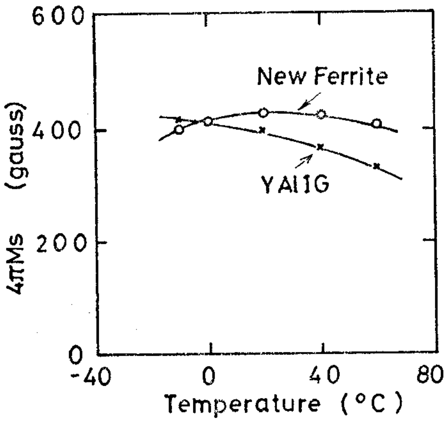

Fig. 2 Changes of magnetization due to temperature variations

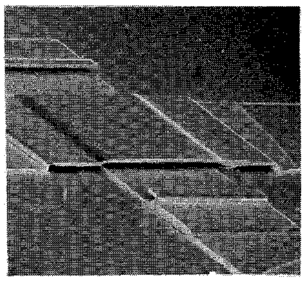

Fig. 3 Photograph of the crossover structure

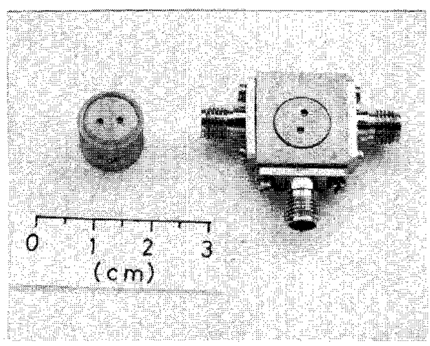

Fig. 4 Photograph of the experimental circulators

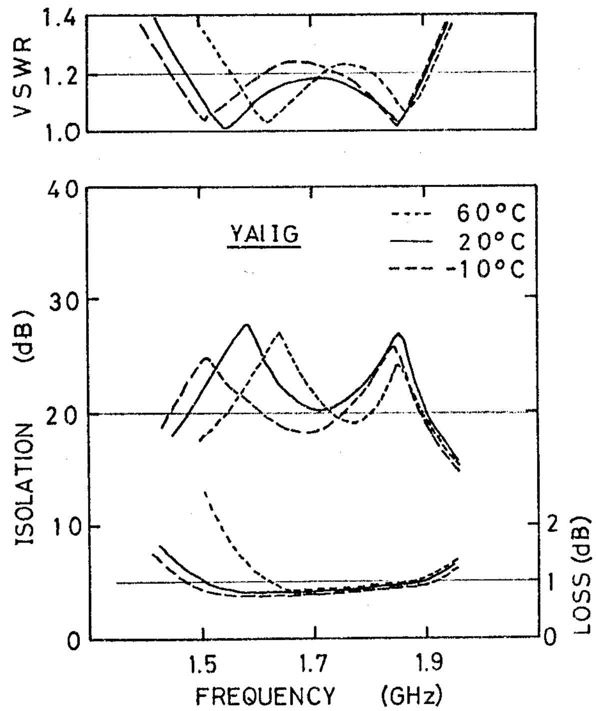

Fig. 5 Bandpass characteristics of the circulator using a YAlIG

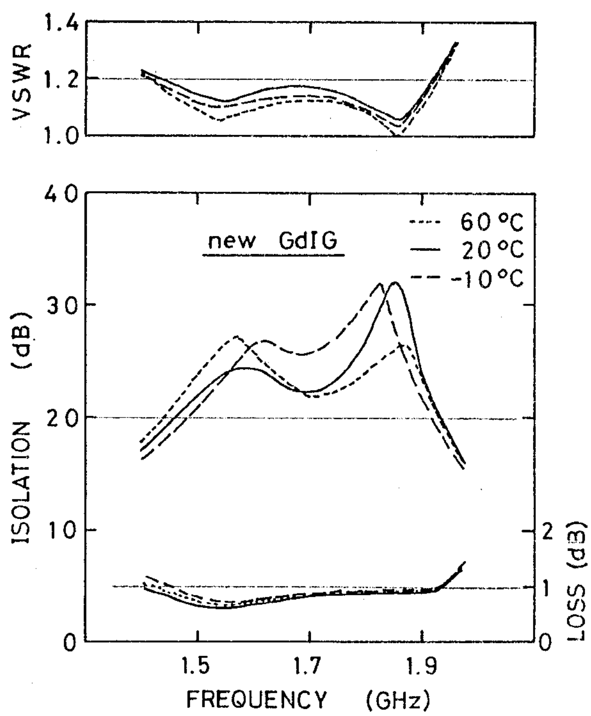

Fig. 6 Bandpass characteristics of the circulator using the new ferrite