INFLUENCE OF NON-IDEAL CIRCULATOR EFFECTS ON NEGATIVE-RESISTANCE AMPLIFIER DESIGN

by

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1. Introduction

It is well known that the non-ideal properties of a circulator (non-unity VSWR, non-zero insertion loss, finite isolation) have a marked effect on the design of single-stage and multi-stage negative-resistance amplifiers. These effects are due to the frequency dependence of the circulator parameters, the feedback associated with multiple reflections between circulator ports and terminations, and the possibility of spurious pass-bands in the circulator characteristics away from the desired operating frequency range. Noise degradation also occurs with a low-noise amplifier circuit.

Assessment of these effects, and design of circuits which minimize the performance degradation from non-ideal circulator properties, depends upon provision of an equivalent circuit which accurately models the device over a wide frequency range. Using such an equivalent circuit, conventional network analysis techniques can be employed to obtain information about amplifier behaviour.

Circulator models used thus far have generally been quite simple e.g. Sard[1] used a lossless network with finite frequency-independent isolation; Helszajn[2] used a parallel-resonant element in each arm of an otherwise-ideal circulator, and Okean[3] considered a combination of a parallel-resonant and a series-resonant network in each arm. The present authors have recently published[4] a narrow-band equivalent circuit, derived using a method which can be extended to encompass the broad-band case.

This paper uses a wideband equivalent circuit derived for a non-ideal circulator, from measured parameters. The derivation is equally applicable to obtaining the circuit from parameters obtained by theoretical analysis, or from parameters specified as being desired for a particular application.

Using the equivalent circuit for an X-band waveguide circulator in a negative-resistance amplifier circuit, studies are carried out to examine:

- effect of isolators before or after the circulator, on gain and input impedance characteristics; comparison between three-port and five-port circulators;
- effect of circulator properties on two-stage amplifier gain-frequency response; use of dissimilar stages to compensate for frequency variations;
- comparison of various two-stage amplifiers using circulator (C) and isolator (I) combinations in ICCI, CICI and ICIC forms.

2. Equivalent Circuit Derivation

The equivalent circuit is derived from dissection of the non-ideal circulator scattering matrix into matrices representing an ideal circulator, a lossless two-port filter-type network, and a lossy distributed two-port (realized by a series resistor and a bilaterally-matched attenuator having a complex attenuation coefficient). A typical waveguide circulator equivalent circuit shown in Fig. 1 provides good agreement between calculated and measured values of insertion loss, isolation and reflection coefficient magnitude and phase.

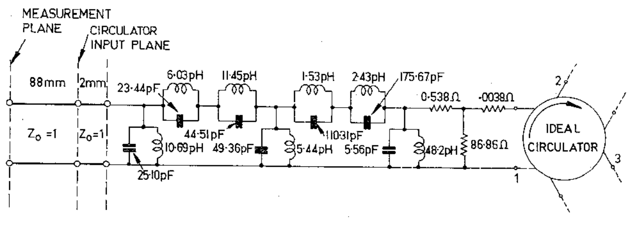

Fig. 1 Waveguide circulator equivalent circuit

3. Negative-Resistance Amplifier Studies

The investigations have shown that the non-ideal circulator introduces feedback paths that, in a broad-band amplifier, result in the gain of the amplifier exhibiting alternating maxima and minima dependent on the phase of the feedback. The most significant feedback loop is that formed by the active device, the circulator port to which it is connected, and the transmission line between the device and the circulator. The length of this transmission line controls the phase shift around the loop at a given frequency and hence determines whether the feedback is positive or negative. The magnitude of the gain variation is determined by the magnitude of the product of the reflection coefficients of the active device (Γ) and that of the remainder of the circuit attached to the device, which, for a single stage amplifier with a matched source and load, is equal to the input reflection coefficient of the circulator (γ). The ratio, G_r of maximum to minimum power gain is approximately

$$G_r = \frac{G_{max}}{G_{min}} = \left(\frac{1 + |\gamma\Gamma|}{1 - |\gamma\Gamma|}\right)^2$$

Thus for $\gamma = 0.1$ and a nominal gain of 10 dB for which $\Gamma = 3.16$, G_r is 5.7 db. A high gain amplifier therefore requires that the input reflection coefficient of the circulator be very low if the gain variation is to be kept within acceptable limits.

(i) Gain with a single-tuned negative resistance

A suitable representation of a negative-resistance diode device is obtained by a single-tuned resonant circuit added to a constant negative resistance, giving the equivalent circuit (including tuning inductance) shown in Fig. 2. The small series resistance is added to ensure that the two-port coupling network has a Y-parameter representation and has the effect of reducing the effective negative resistance and thus the gain of the amplifier.

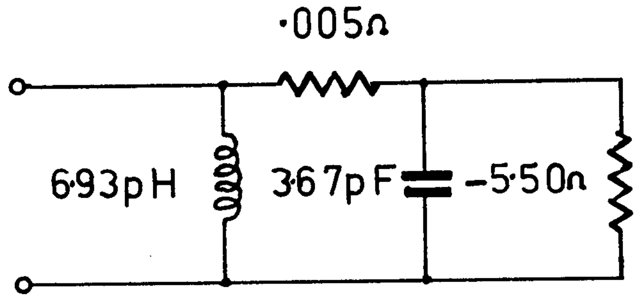

Fig. 2 Assumed negative-resistance device equivalent circuit

The gain is shown in Fig. 3 for two different values of the line length connecting a 3-stage quarter-wave transformer to the circulator. Also shown is the gain obtained with an ideal circulator. It is evident that the bandwidth obtainable with the non-ideal circulator is less than obtainable with an ideal circulator.

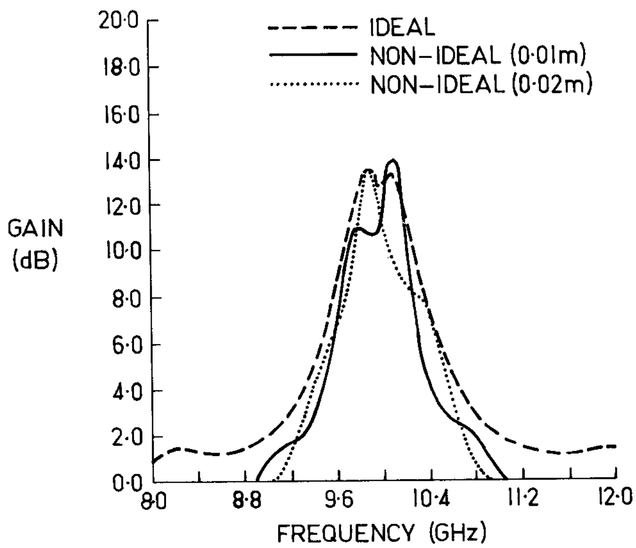

Fig. 3 Single-stage circulator-coupled amplifier gain

Closer examination of the two curves obtained with two different line lengths suggests that there should be a length somewhere in between these two values of 10 mm and 20 mm that would give a double-peaked response with peaks of equal magnitude. With a 16 mm line length, the bandwidth at the 3 dB points is 0.60 GHz, compared with 0.56 GHz in the ideal case and approximately 0.26 GHz for the 10 mm line length case; the maximum gain is 12 dB. Note that although the bandwidth is greater than in the ideal case, it is at reduced gain and so the gain bandwidth product is diminished.

This phenomenon may be explained in terms of positive feedback compensating for the reduction in gain due to off-resonance operation.

(ii) The five-port circulator

A common module used in circulator coupled amplifiers is the so-called five-port circulator consisting of three circulators connected as shown in Fig. 4. Ports 2 and 4 are terminated in $\Gamma = 0.01$ loads while the negative resistance is attached to port 3 with $\Gamma = 3.162$ and 180° phase. Ports 1 and 5 become the input and output respectively, with $\Gamma = 0.01$. There is 10 mm linelength between circulator ports and terminations, and 50 mm linelengths between circulators.

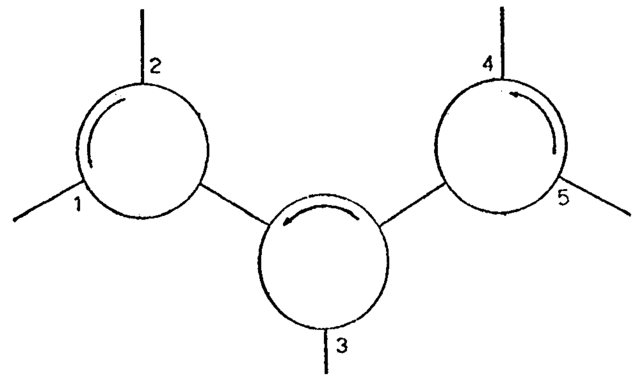

Fig. 4 Representation of five-port circulator module

Fig. 5 shows the gain of the single stage amplifier incorporating a five-port circulator in the designated amplifier circuit.

With source and load mismatches of 0.1, the gain is only very slightly affected, and the input and output reflection coefficients are increased from an average value of approximately 0.05 up to 0.1. The five-port circulator arrangement is thus relatively insensitive to the source and load terminations and is an attractive circulator-coupled amplifier module.

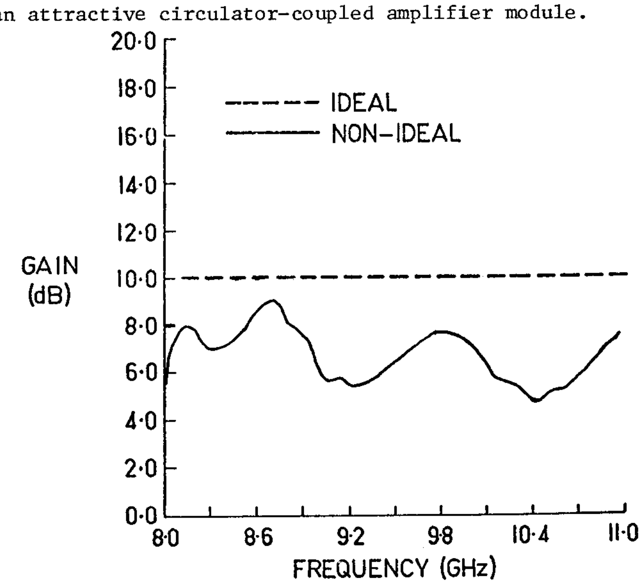

Fig. 5 Single-stage amplifier gain using five-port circulator module

(iii) Gain compensation

As has been shown in the single stage investigations, the gain at a particular frequency depends on the length of transmission line between the circulator and the negative resistance, designated here as D_{cd}. If, for a particular choice of D_{cd}, the gain is a maximum, then changing D_{cd} by $\lambda_g/4$ where λ_g is the guide wavelength at the frequency of interest, will result in a gain minimum at that frequency. At a frequency of approximately 9.9 GHz, at which $\lambda_g/4$ equals 10 mm, an amplifier formed from a device having $\Gamma = 3.162$ at 180° phase gave a gain maximum of 9.6 dB while a 20 mm D_{cd}

gave a minimum of 7.6 dB. Thus, if these two amplifiers are cascaded, it is expected that the resultant amplifier will have a flat gain in an interval around 9.9 GHz of approximately the sum of the maximum and minimum gains; in this case 17.2 dB. Fig. 6 shows a comparison between the gains obtained by cascading two identical stages and that obtained by cascading two stages for which D_{cd} equals 10 mm for the first stage and 20 mm for the second stage. Isolators were added to the input and the output to make the amplifier more realistic; these have the effect of increasing the gain variations slightly and reducing the overall gain by about 1.8 dB. As can easily be seen, over the interval surrounding 9.9 GHz, the gain is very flat, while over the entire 8.0 to 11.0 GHz interval, the variation is less than 3 dB compared with the 9 dB variation obtained when two identical stages are cascaded. The smaller the length of D_{cd}, the larger the frequency interval over which satisfactory compensation is possible.

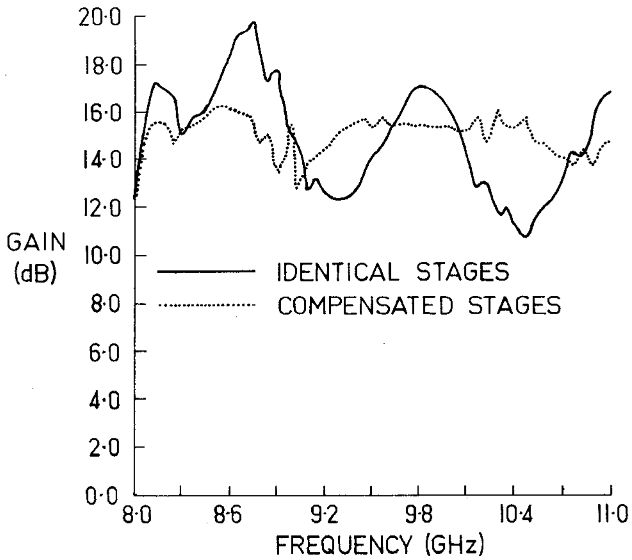

Fig. 6 Two-stage circulator-coupled amplifier gain

(iv) Effect of isolator positioning

Out of the six possible combinations of two amplification stages (denoted by C) and two isolation stages (denoted by I), only three are of any practical significance, namely ICCI, CICI and ICIC. The ICCI configuration has already been briefly considered in the previous section. The same amplifier modules are used for investigations of the other configurations; i.e. D_{cd} = 10 mm for the first amplification stage and D_{cd} = 20 mm for the second amplification stage.

With matched terminations at the load and source, it is expected that the gain of three configurations will be similar but, as indicated by the single stage investigations, the CICI case will have superior noise performance to the other two due to the absence of an input isolator.

Fig. 7 shows a comparison between the gains of the ICCI and the CICI amplifiers. The ICCI gain shows more ripple due to the interaction of the two adjacent amplification stages. The ICIC gain (not shown) is almost identical to the CICI gain and would be identical if the first and second stages were identical.

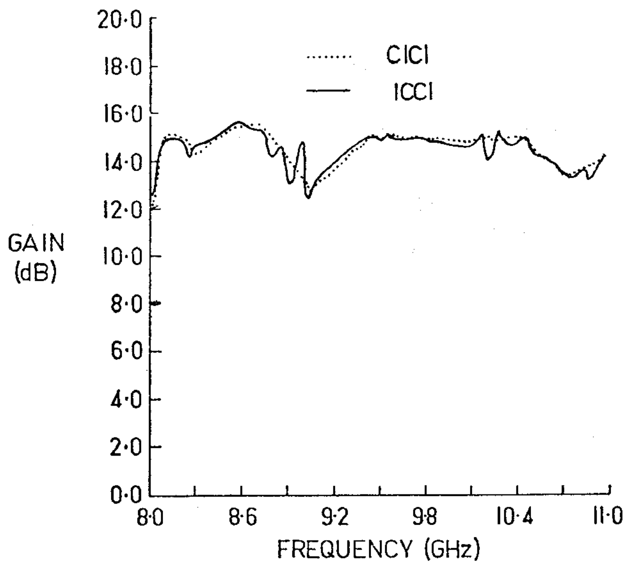

Fig. 7 Two-stage amplifier gain for differing circulator-isolator configurations

4. Conclusions

The investigations reported here have demonstrated the importance of feedback phenomena in controlling the shape of the gain-frequency response of a circulator coupled amplifier. The dominant feedback loop is that formed by the active component and the circulator port to which it is attached. Amplifier gain and circulator properties determine the magnitude of the "open loop gain" of this loop but its phase (and hence the sign of the feedback) may be controlled at a particular frequency by varying the length of the transmission line which forms part of this loop.

Appropriate choice of this line length can lead to amplifier broadbanding. In the narrow-band amplifier, bandwidth maximization is achieved by applying maximum negative feedback at the band centre and maximum positive feedback at the band edges. In the broadband case, two stages of amplification of approximately equal gain are necessary, so that the gain variations of the second stage cancel those of the first stage.

Acknowledgement

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References

[1] E.W. Sard, "Analysis of a Negative Conductance Amplifier Operated with a Non-Ideal Circulator", IRE Trans. on Microwave Theory Tech., Vol. MTT-7, pp 288-293, April 1959.

[2] J. Helszajn, "A Simplified Theory of the Three-Port Junction Ferrite Circulator", The Radio and Electronic Engineer, Vol. 33, pp 283-288, May 1967.

[3] H.C. Okean, "Synthesis of Negative Resistance Amplifiers employing Band-Limited Circulators", IEEE Trans. on Microwave Theory Tech., Vol. MTT-14, pp 323-337, July 1966.

[4] B.D. Bates and P.J. Khan, "An Equivalent Circuit for Narrow-Band Non-Ideal Circulators", Proc. IEEE, Vol. 67, pp 1560-1562, November 1979.