GAIN SATURATION IN CIRCULATOR-COUPLED REFLECTION AMPLIFIERS

Michael B. Steer

North Carolina State University
Electrical and Computer Engineering Department
Raleigh, North Carolina, NC27695-7911

ABSTRACT

In this paper we present an analytic treatment of large-signal gain saturation in reflection amplifiers and present design curves for optimizing large signal performance. General recommendations for the design of reflection amplifiers, notably of IMPATT amplifiers, are presented. The design curves are verified by comparing analytic results with large signal nonlinear numerical analyses of gain saturation in parametric amplifiers.

I INTRODUCTION

Reflection amplifiers utilize the negative resistance induced at the terminals of a one-port active device to reflect and amplify an input signal. Reflection amplifiers available at millimeter wave frequencies include IMPATT amplifiers, parametric amplifiers, and traveling-wave tube amplifiers (TWTA's) of the reflection type. Typically the reflected and incident signals are separated by a circulator and this is the form of the reflection amplifier considered here. In this paper the effect of the signal-frequency embedding circuit on large signal performance is considered analytically, and design curves are presented for optimizing the signal circuit to minimize gain compression. In particular we find that for best large signal performance, the negative resistance induced at the active device terminals should be slightly higher than the characteristic impedance of the signal-frequency circulator.

The overall large signal behavior of a reflection amplifier is determined by both the linear embedding circuit and the active, and hence nonlinear, device. While our treatment of the effect of the signal circuit on gain compression applies to all reflection amplifiers, separate investigations are required of each different type of active device. Such an investigation is performed here for a varactor diode parametric amplifier using an analytic/graphical method developed elsewhere [1, 2]. The analytic gain compression work is verified here using the results of large signal numerical analyses of a number of parametric amplifiers.

II GAIN COMPRESSION IN REFLECTION AMPLIFIERS

The signal frequency equivalent circuit of a circulator-coupled reflection amplifier is presented in figure 1, where R_{ind} is the net induced negative resistance, X_s is the steady-state reactance of the active device, $\Gamma_{in} = \rho_{in}\exp(j\phi_{in})$ is the signal-frequency reflection coefficient presented to the circulator, $\Gamma_s = \rho_s\exp(j\phi_s)$ is the reflection coefficient at the terminals of the active device, and P_{in} and P_o are the input and output powers of the amplifier. The signal circuit, which includes the parasitics of the active device, is passive, reciprocal, and has scattering parameters $S_{kl} = \rho_{kl}\exp(j\phi_{kl})$.

The gain compression performance of a reflection amplifier is normally indicated by the output power at a particular level of gain compression which can be indicated by the ratio G/G_0 where G is the transducer gain of the amplifier and G_0 is the small signal value of G. In the following we develop an expression for $P_o(G/G_0)$ in terms of G/G_0, the scattering parameters of the signal circuit, and the sensitivities of the reflection coefficient of the active device.

The dependence of the amplifier gain on the output signal level is approximated by a truncated taylor series

$$G \approx G_0 + \frac{\partial G}{\partial P_0} P_o(G/G_0) \qquad (1)$$

Since $G = \rho_{in}^2$, we can rearrange (1) as

$$P_o(G/G_0) = \left|\frac{G}{G_0} - 1\right| \frac{\rho_{in}}{2} \cdot \left|\frac{\partial \rho_{in}}{\partial \rho_s} \cdot \frac{\partial \rho_s}{\partial P_o} + \frac{\partial \rho_{in}}{\partial \phi_s} \cdot \frac{\partial \phi_s}{\partial P_o}\right|^{-1} \qquad (2)$$

In this equation the large signal behavior of the active device is described by $\frac{\partial \rho_s}{\partial P_o}$ and $\frac{\partial \phi_s}{\partial P_o}$. On the other hand, the

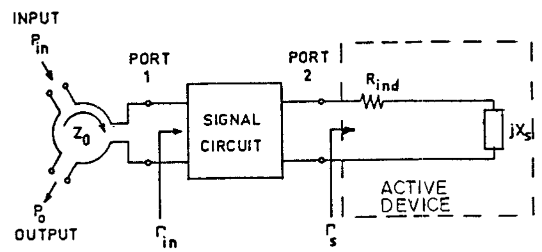

Figure 1
Signal frequency equivalent circuit of a circulator-coupled reflection amplifier.

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effect of the signal circuit on gain compression is described by $\frac{\partial\rho_{in}}{\partial\rho_s}$ and $\frac{\partial\rho_{in}}{\partial\phi_s}$. Now G, ρ_{in} and ρ_s are related by the characteristics of the signal circuit

$$G = |\rho_{in}|^2 = |S_{11} + S_{12}S_{21}\Gamma_s/(S_{22}\Gamma_s - 1)|^2 \qquad (3)$$

and for high gain $\rho_{in} >> 1$ so that S_{11} (≤ 1) can be neglected. Equation (2) can be further simplified using (3) and noting that the signal circuit is reciprocal ($S_{12} = S_{21}$). This yields

$$P_o(G/G_0) = \left|\frac{G}{G_0} - 1\right| \left[A.\frac{\partial\rho_s}{\partial P_o} - B\frac{\partial\phi_s}{\partial P_o}\right] \qquad (4)$$

where

$$A = \frac{1}{\rho_s} + \frac{\rho_{in}^2}{\rho_s^3\rho_{12}^4}(1-\rho_{22}^2\rho_s^2) \qquad (5)$$

and

$$B = \frac{\rho_{in}^2\sin(\phi_{22}+\phi_s)}{\rho_s^2\rho_{12}^4} \qquad (6)$$

The output power at which gain compression begins to occur can therefore be set to a very high value by choosing A and B so that the expression in square brackets in (4) is negligible. While this may be possible at a single frequency, it cannot be achieved even over a small frequency range without detailed knowledge of the large signal behavior of the active device. Alternatively, a high gain compression level can be obtained by minimizing A and B separately. By determining the requirements for minimum A and B we obtain the conditions for good gain compression performance.

For optimum noise performance the signal circuit must be lossless, $S_{12}^2 = 1 - S_{22}^2$ and from (3) we see that for high gain $S_{22} \approx 1/\Gamma_s$ so that $\rho_{12}^2 \approx |1 - 1/\Gamma_s^2|$ Thus (5) and (6) can be rewritten as

$$A = \frac{1}{\rho_s} + D.(1 - \rho_{22}^2\rho_s^2) \qquad (7)$$

$$B = D.\rho_s.\sin(\phi_{22}+\phi_s) \qquad (8)$$

where

$$D = \frac{G\,\rho_s}{\rho_s^4 - 2\rho_s^2\cos(2\phi_s) + 1} \qquad (9)$$

Since the steady state reactance of an active device is usually appreciable , ρ_s can never be very large. Also, for unconditional stability $\rho_{22}\rho_s < 1$ and so $A > 1/\rho_s$. Hence the output power at which gain compression begins to occur, peaks for minimum D and thus optimum ρ_s. This is investigated in figure 2 where D/G and $1/\rho_s$ are plotted as functions of $|R_{ind}/Z_0|$ for various normalized device reactances X_s/Z_0. Figure 2 indicates that the optimum R_{ind} for good large signal performance (small D) is minimum for R_{ind} slightly greater than Z_0, and thus for large ρ_s. An important point illustrated by figure 2 is the dramatic effect that X_s has on the gain compression performance of the amplifier.

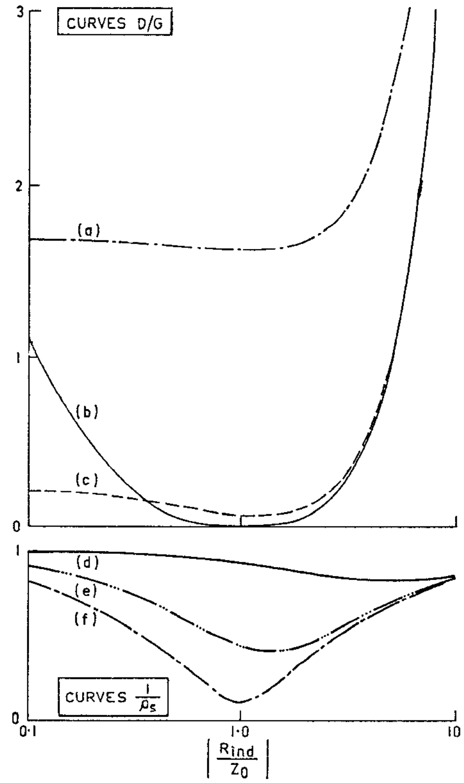

Figure 2
Design curves for optimizing the gain compression performance of reflection amplifiers. Curves (a), (b) and (c) are plots of D/G for $|X_s/Z_0| = 5$, 0.2, and 1 respectively. Curves (d), (e) and (f) are plots of $1/\rho_s$ for $|X_s/Z_0| = 5$, 0.2, and 1 respectively.

III GAIN COMPRESSION IN PARAMETRIC AMPLIFIERS

The gain compression performance of a reflection amplifier is determined by the large signal performance of the active device as well as the large signal effects of the linear embedding circuit. Thus before we can validate the design curves presented above we must consider one type of reflection amplifier in detail. In this section we present an algebraic treatment of the large signal effects of the active device of a parametric amplifier.

Gain is obtained in a parametric amplifier when a large pump signal mixes, in the active region of a reverse biased diode, with a smaller and lower-frequency input signal. The active region is modeled as a nonlinear capacitor defined by $C_j = C_{j0}/(1-\frac{v}{\phi})^\gamma$ (C_{j0} is the zero bias capacitance of the junction, v is the voltage across the junction, ϕ is the contact potential, and γ is the capacitance index of nonlinearity) as, to a first approximation, the nonlinear conductance of the active region is negligible when it is reverse biased. In [1] an analytic treatment of gain compression in diode mixers was developed. Specifically a sensitivity function, S, for the sensitivity of the signal-pump intermodulation in a mixer was developed. Mixer and parametric amplifier operation is similar and so S is an indication of the effect of the varactor diode junction on gain compression with low S indicating good gain compression performance. After eliminating terms related to the nonlinear junction conductance (as this is negligible in parametric amplifiers) S is given by [1]

$$S = \frac{2\zeta}{V_p} + \left\{ \frac{\displaystyle\sum_{\sigma=1}^{\infty} \left[\frac{(2+2\sigma)!}{2^{(2+2\sigma)}} \left\{ \frac{(V_p)^{2\sigma}}{\sigma!(1+\sigma)!} \right\} \left\{ \frac{2\sigma}{V_p} \right\} \left\{ \frac{A.a_{2+2\sigma}}{(\phi - V_d)^{2+2\sigma}} \right\} \right]}{\displaystyle\sum_{\sigma=0}^{\infty} \left[\frac{(2+2\sigma)!}{2^{(2+2\sigma)}} \left\{ \frac{(V_p)^{2\sigma}}{\sigma!(1+\sigma)!} \right\} \left\{ \frac{A.a_{2+2\sigma}}{(\phi - V_d)^{2+2\sigma}} \right\} \right]} \right\} \tag{10}$$

where

$$A = \frac{j\omega C_{j0}\phi^{\gamma}(\phi - V_d)^{1-\gamma}}{\gamma - 1}$$

$$a_l = \begin{cases} \dfrac{(1-\gamma)(-\gamma)\ldots(1-\gamma-l+1)}{l!} & l = 1, 2, \cdots \\ 1 & l = 0 \end{cases}$$

In (10) S is only a function of V_p (peak pump voltage at the junction), ϕ (contact potential), V_d (dc bias), the pump embedding circuit through ζ and, through the power series coefficients A and a_l, γ (capacitance index of nonlinearity), C_{j0} (zero bias capacitance), and frequency.

We can now determine the effect of the diode junction on gain compression by investigating the behavior of S. S is plotted as a function of γ and normalized pumping level, $V_p/(\phi - V_d)$, in figure 3. We see that for larger pumping level, S reduces and so the large signal performance of the diode improves. Generally, for fixed V_p, γ has little effect on large signal behavior.

IV VALIDATION OF DESIGN CURVES - GAIN COMPRESSION IN PARAMETRIC AMPLIFIERS

In this section we present data verifying the design curves presented in the previous section. The verification is achieved using large signal numerical simulation [3] of a variety of circulator-coupled parametric amplifier circuits. (Elsewhere [4] the numerical technique has been successfully compared to the experimental performance of an experimental parametric amplifier.) All the parametric amplifier circuits use the crossed waveguide mount of figure 4 where the varactor diode is a typical GaAs X-band device pumped with available pump power P_{pA}. The numerical results are summarized in table 1 where it can be seen that the calculated gain compression responses presented in table 1 are consistent with the behavior of S (figure 3, in which the loci of the parametric amplifiers are superimposed on the sensitivity function diagram), and D/G and $1/\rho_s$ (figure 2).

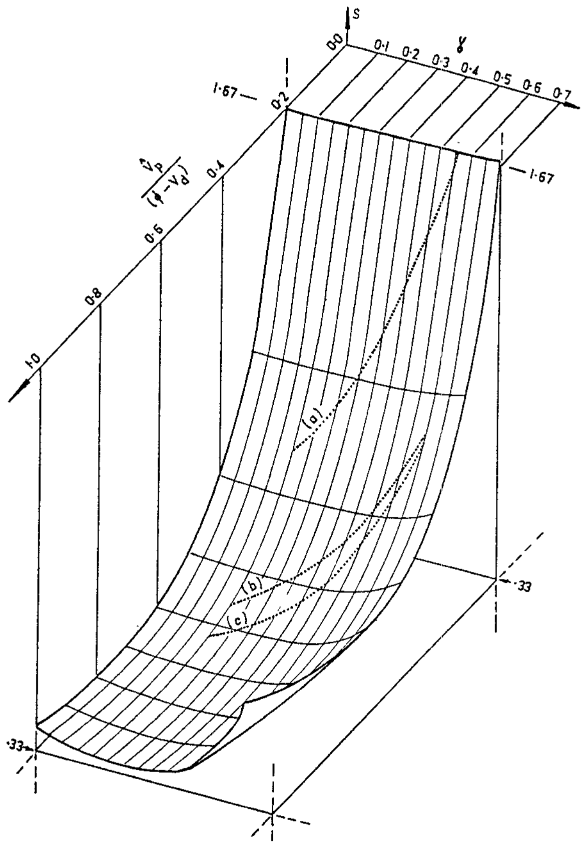

Figure 3
S as a function of capacitance index of nonlinearity, γ, and normalized pumping level, $V_p/(\phi - V_d)$. Curves (a), (b) and (c) are loci for parametric amplifiers of table 1.

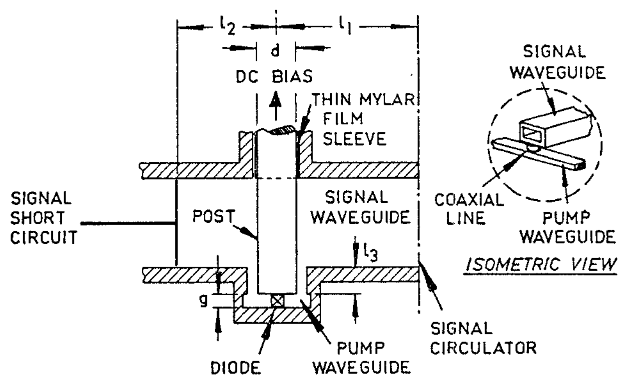

Figure 4
Crossed-waveguide parametric amplifier.

P_{pA} (dBm)	γ	R_s (Ω)	B (MHz)	P_o(1dB) (dBm)	R_{ind} (Ω)	$\left\lvert \frac{R_{ind}}{Z_0} \right\rvert$	X_s (Ω)
Set (a)							
0	0.20	0.38	67	-20.4	-20.3	0.41	-60.5
0	0.33	0.38	123	-21.9	-70.2	1.4	-67.9
0	0.38	0.38	142	-22.6	-99.6	2.0	-71.4
0	0.42	0.38	161	-22.9	-131	2.6	-71.3
0	0.46	0.38	174	-23.6	-172	3.4	-75.8
0	0.50	0.38	207	-24.4	-225	4.5	-80.3
0	0.60	0.38	253	-27.4	-421	8.4	-93.9
Set (b)							
0	0.20	2	-	-	-1.2-	0.02	-53.8
0	0.33	2	36	-29.0	-3.5	0.07	-53.7
0	0.38	2	57	-26.5	-4.6	0.09	-53.9
0	0.42	2	78	-25.7	-5.6	0.11	-53.7
0	0.46	2	98	-25.2	-6.8	0.14	-54.2
0	0.5	2	117	-24.2	-8.1	0.16	-53.4
0	0.6	2	167	-23.2	-11.8	0.24	-54.8
Set (c)							
10	0.2	2	63	-11.6	-5.7	0.11	-61.2
10	0.33	2	120	-11.8	-21.5	0.43	-70.0
10	0.38	2	150	-11.5	-31.7	0.63	-74.0
10	0.42	2	185	-11.1	-41.4	0.83	-86.3
10	0.46	2	217	-10.9	-59.4	1.2	-82.4
10	0.5	2	245	-10.9	-80.8	1.6	-88.2
10	0.6	2	306	-12.5	-179	3.5	-112

Table 1

Table of amplifier 1 dB bandwidth, B, output signal power at 10 GHz resulting in 1 dB gain compression, P_o(1 dB), and induced signal frequency negative resistance, R_{ind}, for various indices of nonlinearity of the junction capacitance, γ, diode spreading resistance, R_s, and available pump power, P_{pA}.

In table 1 two different types of varactor diodes are considered. The first type of diode is typical of readily available varactor diodes which have zero bias cutoff frequencies, f_c, of 250-500 GHz The first type of diode has $C_{j0} =$ 0.3 pF and bulk resistance $R_s = 2\ \Omega$ and so $f_c =$ 265 GHz. Varactor diodes with cutoff frequencies as high as 1400 GHz have been fabricated with $R_s = 0.38\ \Omega$ and $C_{jo} = 0.3$ pF [5] and this is the other type of diode considered. An important feature to note from table 1 is that even though a diode with higher cutoff frequency leads to greater root-gain bandwidth product, it can seriously degrade the large signal performance of a parametric amplifier. This is also true of diodes with large capacitance index of nonlinearity.

V AMPLIFIER DESIGN RECOMMENDATIONS

General recommendations for the design of reflection amplifier can be made with the aid of the design curves presented in figure 2. These curves indicates that the optimum R_{ind} for good large signal performance (small D) is minimum for R_{ind} slightly greater than Z_0, and thus for large ρ_s. An important point illustrated by figure 2 is the dramatic effect that X_s has on the gain compression performance of the amplifier.

Specific recommendations for the design of IMPATT amplifiers can be made with the help of figure 2. Millimeter wave IMPATT amplifiers must be constructed in rectangular waveguide and so the characteristic impedance of the signal circuit is several hundred ohms. However the negative impedance that can be induced at the terminals of an IMPATT diode will be only a few ohms. Thus the normalized impedance R_{ind}/Z_0 is always less than unity. This corresponds to the extreme left-hand-side of figure 2. Thus of the three amplifiers described by curves (a), (b) and (c) (with normalized reactances $|X_s/Z_0|$ of 5, 0.2, and 1 respectively), the best gain compression performance (corresponding to smallest D/G) will be obtained with the amplifier corresponding to curve (c).

VI CONCLUSION

This paper presented analytic and graphical design tools for the design of circulator-coupled reflection amplifiers with optimized large signal performance. It was shown that optimum performance is obtained when the reflection coefficient (with respect to the characteristic impedance of the signal circulator) of the active device is high. This occurs when the negative resistance induced at the diode terminals of the active device is slightly greater than the characteristic impedance of the coupling circulator. While it is possible to obtain large negative resistances in parametric amplifiers, negative resistances of only a few ohms can be achieved in IMPATT amplifiers. In the case of IMPATT amplifiers the analytic tools also indicate that gain compression performance can be improved by minimizing the reactance of the IMPATT diode. As verification of the analytic technique presented here, we numerically investigated a large number of varactor diode parametric amplifiers. It was seen that gain compression performance can be degraded by a varactor diode with high cutoff frequency or large capacitance index of nonlinearity.

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