Blocking and Desensitization in RF Amplifiers

Robert G. Meyer and Alvin K. Wong

***Abstract*— Blocking and desensitization in RF amplifiers is analyzed and related to second and third order intermodulation performance. Methods of predicting blocking behavior are described and used to improve the performance of an existing amplifier. Measurements are compared with theoretical predictions.**

I. Introduction

PREAMPLIFIERS in RF receivers are used to boost the incoming signal level prior to the frequency conversion process. This is important in order to prevent mixer noise from dominating the overall front-end noise performance. Important specifications of such RF amplifiers include noise figure, gain and third-order intermodulation intercept [1].

In typical applications, the RF receiver must tolerate large interfering signals emanating from users in adjacent channels, as well as from transmission sources which may be relatively far removed in frequency but whose large transmission power can cause significant interference problems. The influence of large interfering signals is manifested in several ways. One of these is third-order intermodulation in which two interfering signals at frequencies f_1 and f_2 (with $f_1 \simeq f_2$ and both close to the desired signal) combine in the amplifier third-order nonlinearity to produce an intermodulation product at $(2f_2 - f_1)$ which is again close to the desired signal. This intermodulation product is then processed by the receiver along with the desired signal. The resulting interference causes BER degradation in digital communication systems and audible or visible defects in analog communication systems. This is an example of desensitization in that the receiver sensitivity (ability to process very weak signals) is compromised by the presence of these intermodulation products. The relation between amplifier nonlinearity and intermodulation distortion is well-known and will not be considered further here.

Desensitization can also occur due to a single large interfering signal. This is called blocking and the interferer is called a blocker. In this paper the phenomenon of desensitization due to blocking is considered. The connection between blocking and amplifier nonlinearity is delineated and the results verified with experimental measurements.

II. Theoretical Analysis of Blocking and Desensitization in Amplifiers

The reduction in sensitivity in an amplifier caused by a large blocking signal can be attributed to two separate mechanisms. One of these is the gain compression caused by third-order nonlinearity in the circuit which occurs in the presence of large intefering signals, allowing existing noise sources in the amplifier (and in the mixer which usually follows it) to exert a larger influence, thus degrading the overall noise performance. The relationship between third-order nonlinearity and this gain compression can be analyzed assuming frequency independence of the nonlinearity [2] using a power series approach, or more generally for frequency dependent nonlinearities using Volterra series [3].

The second mechanism producing desensitization is caused by second-order nonlinearity in the circuit. In this case there is a mixing mechanism between (relatively) low-frequency noise sources in the amplifier and the interfering signal, which results in the low-frequency noise being up-converted to the desired signal frequency. This again degrades the circuit noise performance. Either one or both of these mechanisms may be significant in any given amplifier or receiver.

The phenomenon of gain compression caused by a large interfering signal acting on the amplifier third-order nonlinearity is well-known and the basic relations are summarized here for completeness. A power series representation is used for purposes of illustration and shows the same basic features as the more complex Volterra series approach.

Assume that the amplifier transfer function can be expanded in a power series as

$$V_o = a_1 V_i + a_2 V_i^2 + a_3 V_i^3 + \cdots \tag{1}$$

where V_o is the output signal (bias removed), V_i is the input signal and coefficients a_1, a_2, a_3 are frequency independent. Coefficient a_1 is the small-signal gain. Consider a small wanted signal $V_1 \cos\omega_1 t$ applied to the circuit together with a large interferer $V_2 \cos\omega_2 t$. Then

$$V_i = V_1 \cos\omega_1 t + V_2 \cos\omega_2 t. \tag{2}$$

Substituting (2) in (1) and collecting all terms at frequency ω_1 we have

$$V_o = a_1 V_1 \cos\omega_1 t + \frac{3}{2} a_3 V_1 V_2^2 \cos\omega_1 t + \cdots \tag{3}$$

where the second term comes from the third-order nonlinearity. Thus the apparent gain of the circuit is

$$a_1' = a_1 \left(1 + \frac{3}{2}\frac{a_3}{a_1} V_2^2\right). \tag{4}$$

A common method of characterizing this phenomenon is to specify the interfering signal level required to cause a -3 dB gain compression. For this case we set

$$20 \log_{10} \left(1 + \frac{3}{2}\frac{a_3}{a_1} V_2^2\right) = -3$$

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and assuming a_3 and a_1 have opposite signs we find

$$V_2 = 0.442\sqrt{\frac{|a_1|}{|a_3|}}. \tag{5}$$

Thus the blocking level caused by third order effects is dependent on the ratio of coefficients a_1 and a_3. This process is related to other third-order phenomena and a similar analysis to the above shows the 1 dB gain compression signal level (wanted signal only) is $V_1 = 0.383\sqrt{\frac{|a_1|}{|a_3|}}$, or about 1 dB less than (5). Similarly the third-order intermodulation (IM_3) intercept level can be calculated as $V = 1.155\sqrt{\frac{|a_1|}{|a_3|}}$, or about 8 dB more than (5).

Desensitization can also occur from phenomena involving the second-order term in (1). Consider the small wanted signal $V_1 \cos\omega_1 t$ applied to the amplifier together with a large interferer $V_2 \cos\omega_2 t$ and a small interfering signal $V_3 \cos\omega_3 t$. Further assume that ω_2 is close to ω_1 and that $\omega_3 \ll \omega_1$. In practice, filters connected in front of the amplifier will usually ensure that practically no external signals at ω_3 (including external noise sources) are present at the amplifier active input node. However the amplifier itself has internal noise sources which act as unwanted signal inputs and are represented by $V_3 \cos\omega_3 t$. Thus

$$V_i = V_1\cos\omega_1 t + V_2\cos\omega_2 t + V_3\cos\omega_3 t. \tag{6}$$

Substituting in (1), neglecting powers beyond the second and collecting the relevant terms we find

$$V_o = a_1 V_1 \cos\omega_1 t + a_2 V_2 V_3 \cos(\omega_2 \pm \omega_3)t + \cdots \tag{7}$$

Since noise is present in the circuit at all frequencies, ω_3 can always be chosen so that the term generated at $(\omega_2 \pm \omega_3)$ falls in the band occupied by the wanted signal at frequency ω_1. This interference can thus be identified as a second-order intermodulation (IM_2) effect with the amplifiers own internal noise acting as one input. The effect occurs for any values of ω_2 and ω_3 as long as $(\omega_2 \pm \omega_3) \simeq \omega_1$. However the worst case is usually found for $\omega_2 \simeq \omega_1$ and $\omega_3 \ll \omega_1$. Excessive $1/f$ noise levels in the circuit will also tend to make this phenomenon more pronounced.

From (7) the ratio of the interference to the amplitude of the wanted signal is $\frac{|a_2|}{|a_1|}\frac{V_2 V_3}{V_1}$. The second-order intermodulation intercept is $V = \frac{|a_1|}{|a_2|}$, and thus the desensitization produced by this blocking mechanism is directly related to the second-order intermodulation performance of the amplifier

III. Measurement

The theory developed above was prompted by measurements on an existing RF amplifier described elsewhere [4]. A schematic is shown in Fig. 1. This is a 2-stage amplifier (Q_1 and Q_2) with overall dc feedback via Q_6 used to stabilize the bias point. The feedback is decoupled in the kilohertz range by R_{14} and C_3. Bias currents are $I_{C1} = 2.5$ mA, $I_{B1} = 25$ μA, and $I_{C2} = 5.5$ mA with a supply voltage of 5 V. Peak process f_T is 10 GHz with base resistance for the large area input device Q_1 of 11 Ω. The input blocking signal power level

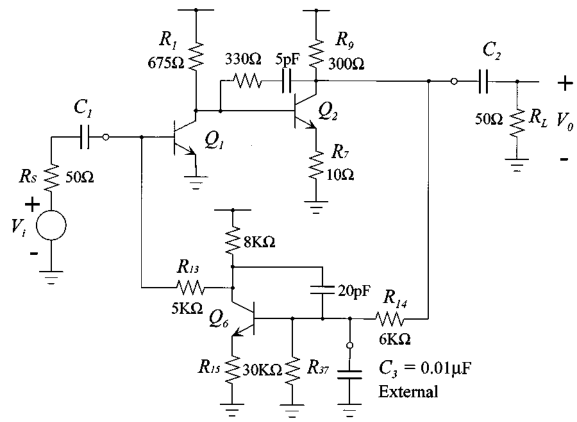

Fig. 1. RF amplifier schematic.

required to cause a -3 dB gain compression in the amplifier at 950 MHz was measured as -20 dBm at the input. The 1 dB gain compression level was also about -20 dBm and the third-order intercept was -10 dBm. These results agree closely with the theoretical predictions above for third-order blocking.

Blocking due to second-order effects was also observed in that large interfering signals at 950 MHz (offset by 3 MHz from the desired channel) representing adjacent channels caused significant increases in the background noise of the amplifier at 947 MHz. In order to predict these effects analytically, information is needed on both the noise generators of the amplifier at 3 MHz and the value of IM_2 for $f_2 = 950$ MHz and $f_3 = 3$ MHz. Equivalent input noise generators for the amplifier are conveniently generated using SPICE. Noise from all generators in the circuit is first calculated at V_o and then referred back to the input as a current generator across the base-emitter of Q_1. At 3 MHz this gave an equivalent input noise current spectral density of 25.4 pA$/\sqrt{\text{Hz}}$.

Levels of IM_2 in the circuit can be determined from simulation or from measurements. Since the measurements are quite straightforward whereas the simulation is dependent on the fine detail and accuracy of the large-signal device models, the IM_2 data was generated by measurement in the circuit shown in Fig. 2. A small signal V_{i2} at 3 MHz representing circuit noise is injected into the input via a 2 KΩ resistor. A large blocking signal V_{i1} at 950 MHz is injected at the input and the IM_2 product at V_o measured on a spectrum analyzer. For a power level of -54 dBm delivered to the circuit from V_{i2} and -23 dBm (the blocking level specification of interest) the measured IM_2 product at V_o was -60.1 dBm. The IM_2 product varied approximately 1 dB per dB variation in V_{i1} or V_{i2}, as predicted by theory. The power level of -54 dBm at 3 MHz represents 0.446 mV rms delivered to 50 Ω. Taking a Norton equivalent at the amplifier input through the 2 KΩ resistor gives an input current $I_i = 0.446$ mV/2 K$\Omega = 0.223$ μA rms. This gave a measured output from the amplifier at 947 MHz of -60 dBm, which is 223 μV rms. Thus the transfer function of the amplifier from noise current input at 3 MHz to voltage out at 947 MHz in the presence of a -23 dBm blocker at 950 MHz is

$$\frac{V_o}{I_i} = \frac{223 \times 10^{-6}}{0.223 \times 10^{-6}} = 1K\Omega. \tag{8}$$

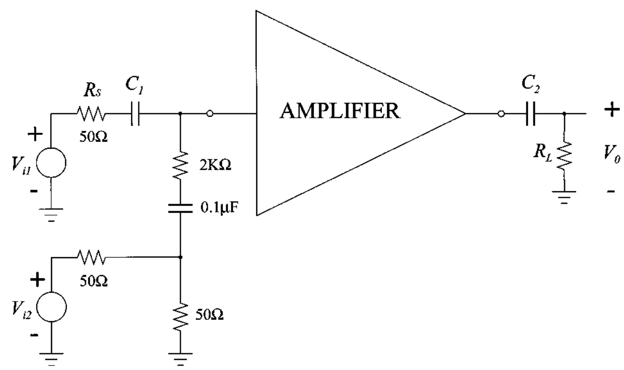

Fig. 2. Test circuit for IM_2 measurements.

Thus the SPICE simulated equivalent input noise current density of 25.4 pA/$\sqrt{\mathrm{Hz}}$ at 3 MHz should give an output noise voltage density of 25.4 nV/$\sqrt{\mathrm{Hz}}$.

The desensitization caused by second-order blocking can now be calculated. First, the noise floor of the amplifier with no blocker can be calculated from the measured gain (15.5 dB) and noise figure (2.4 dB) at 947 MHz. This gives an output noise 17.9 dB above the input noise in 50 Ω (which is $\sqrt{kTR} = 0.445$ nV/$\sqrt{\mathrm{Hz}}$). Thus the output noise from the amplifier at 947 MHz is 3.5 nV/$\sqrt{\mathrm{Hz}}$ or -156 dBm/$\sqrt{\mathrm{Hz}}$ with no blocker present. In the presence of the 950 MHz blocker at -23 dBm the output noise is increased by the 25.4 nV/$\sqrt{\mathrm{Hz}}$ calculated above. This is added to the amplifier output noise which is itself compressed somewhat by the third order blocking effect to 3 nV/$\sqrt{\mathrm{Hz}}$. The rms combination of these two gives a predicted output noise of 25.6 nV/$\sqrt{\mathrm{Hz}}$ which is -138.8 dBm/$\sqrt{\mathrm{Hz}}$. The measured output noise under these conditions was -139.1 dBm/$\sqrt{\mathrm{Hz}}$, a very close agreement. Note that the noise floor has risen 17 dB from the value with no blocker present.

The theoretical understanding of the blocking phenomenon described above allows investigation of methods of improving blocking performance. The equivalent input noise of the amplifier is not easily decreased but the IM_2 performance can be enhanced in several ways. One of these is to increase the bias current in Q_2 by adding a 1 kΩ pull-up resistor from the collector of Q_2 to V_{CC}. This increases the output stage bias current by several mA and improves the large signal handling capability of the amplifier. The measured IM_2 product at 947 MHz was then reduced by 10 dB to -70.0 dBm for V_{i1} of -23 dBm and V_{i2} of -54 dBm in the test described previously. A similar calculation to that described previously predicts that the noise output of the amplifier is increased by 8.0 nV/$\sqrt{\mathrm{Hz}}$ due to second-order blocking, and that the total output noise should be -148.4 dBm/$\sqrt{\mathrm{Hz}}$. The measured noise was -148.1 dBm/$\sqrt{\mathrm{Hz}}$ with this modification.

The IM_2 performance can be further improved by reducing the low-frequency gain of the amplifier. This reduces the signal level in the circuit at frequency f_3 and can be accomplished by adding a bypassed resistor in series with R_7 in Fig. 1. A parallel RC network consisting of 10 Ω in parallel with 390 pF added in this way further reduced the measured IM_2 product in the circuit at 947 MHz to -78 dBm. The added noise output of the amplifier caused by second-order blocking is then predicted to be 3.2 nV/$\sqrt{\mathrm{Hz}}$ and the total output noise -153.4 dBm/$\sqrt{\mathrm{Hz}}$. The measured noise was -152.1 dBm/$\sqrt{\mathrm{Hz}}$ with these modifications.

IV. Conclusions

Blocking and desensitization in RF amplifiers can be predicted from second and third order intermodulation performance and amplifier noise parameters. Good agreement is obtained between measured and predicted blocking performance in a practical amplifier, and circuit modifications to improve performance are described.

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