Noise Considerations in Broadband Microwave Power Amplifiers

Application Note

The Giga-tronics microwave power amplifiers offer linear high-power amplification over a very broad frequency range. RF/microwave power amplifiers used in test and measurement applications are typically characterized by their broadband frequency range, high gain with relatively flat frequency response, low noise and wide linear range. RF/Microwave amplifiers are characterized by their noise figure. Giga-tronics microwave power amplifiers have relatively low noise figure, ideal for applications where a combination of broad frequency range, high power and low noise are required. This application note discusses noise considerations in broadband microwave amplifiers.

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Microwave Amplifier Noise Floor

The Giga-tronics microwave power amplifiers offer linear high-power amplification over a very broad frequency range. They are used to boost signal power levels to the range of +20 to +40 dBm. However, all amplifiers amplify noise as well as the signal, raising the noise floor. And amplifiers add some amount of their own noise as well, as represented by the noise figure of the amplifier.

The noise floor power level is usually negligible at audio frequencies and in many narrowband RF applications. But at broadband microwave frequencies, the noise floor can become significant and may be the limited factor in measurement dynamic range.

The theoretical minimum noise floor is thermal noise, sometimes referred to as "white noise". Thermal noise is broadband and flat with frequency, and is expressed by the formula:

$N_T = kTB$

Where k = Boltzman's constant = 1.38×10^{-23} Joules/°K (Watt-seconds/°K), T = temperature in Kelvin and B = the frequency bandwidth (Hz).

For T = 290 °K (~ 17 °C), then N_T = -174 dBm/Hz

It is clear that for small bandwidth B, the thermal noise floor is quite low. But with wider bandwidths at microwave frequencies, the noise floor can become significant. The noise floor can be calculated by multiplying -174 dBm/Hz by the bandwidth, or adding the bandwidth in dB. For example, with a 1 MHz bandwidth (10^6 = 60 dB), N_T = -114 dBm and with a 1 GHz bandwidth (10^9 = 90 dB), N_T = -84 dBm.

The noise floor at the output of an amplifier is equal to the thermal noise increased by the amplifier gain and the amplifier's noise figure. These add when calculated in dB:

$N_o = N_T$ (dBm/Hz) + Gain (dB) + NF (dB)

With a high gain amplifier, even with low noise figure, you can see how the amplifier output noise floor can become a significant limitation in the overall dynamic range. **Table 1** shows the noise floor at the output of an amplifier with 10 dB noise figure (NF) for gain values of 25 to 40 dB, and frequency bandwidth of 10, 20, 40 and 50 GHz.

Table 1) Output noise floor (N_o) in dBm for various bandwidths and gains (dB) with NF = 10 dB.

BW (GHz)	kTB (dBm/Hz)	N_o for G = 25 NF = 10 dB	N_o for G = 30 NF = 10 dB	N_o for G = 35 NF = 10 dB	N_o for G = 40 NF = 10 dB
10	-74	-39	-34	-29	-24
20	-71	-36	-31	-26	-21
40	-68	-33	-28	-23	-18
50	-67	-32	-27	-22	-17

The Giga-tronics microwave power amplifiers were originally developed for the purpose of boosting available power from test and measurement instruments such as microwave signal generators and vector network analyzers. Microwave signal generators can provide significant power at microwave frequencies, typically up to +20 dBm (100 mW). Microwave power amplifiers are most often the best solution for increasing that available power from the signal generators.

The Giga-tronics 2520B Microwave Signal Generator combined with the GT-1000B Microwave Power Amplifier can provide +40 dBm (10 Watts) to 8 GHz and +37 dBm (5 Watts) to 18 GHz, significantly higher than from any signal generator alone.

The Giga-tronics GT-1000B microwave power amplifier is very broadband with nominal gain of 35 dB and noise figure of 10 dB.

One of the things that Giga-tronics has done to help mitigate the effect of the increased noise floor out of the GT-1000B with its high gain and 20 GHz bandwidth in applications where dynamic range is critical, is to provide remote RF on/off control directly from the 2520B microwave signal generator. Turning RF off on the 2520B signal generator will also turn RF off on the GT-1000B and the noise floor at the amplifier output will drop from approximately -26 dBm to -71 dBm as calculated for kTB with a 20 GHz noise bandwidth (see Table 1).

Figure 1) Signal generator and amplifier driving a device-under test (DUT)

An application example would be with the signal generator and amplifier providing the stimulus test signal to a device-under-test (DUT), as pictured in **Figure 1**. There are applications where the DUT is sensitive to the noise level at its input. With an amplifier that is always on, turning the test signal from the signal generator on and off provides a test signal power level at the DUT from approximately +35 dBm with the amplifier driven into saturation, to about -26 dBm for the amplifier output noise floor.

Turning the amplifier off at the same time the signal generator's output test signal is turned off provides a test signal power level at the DUT from approximately +35 dBm with the amplifier driven into saturation, to about -71 dBm for the noise floor at the input to the DUT, or an improvement in dynamic range of about 45 dB.

Amplifier Noise Figure, Noise Factor and Residual Phase Noise

Electronic noise[1] is a random fluctuation in an electrical signal, an unavoidable characteristic of all electronic circuits generated by the random thermal motion of charge carriers, usually electrons, inside an electrical conductor or by a number of other mechanisms and variety of effects. Noise is an error or undesired random disturbance or summation of unwanted or disturbing energy. The noise level is typically measured as an electrical power in Watts or dBm. Noise may also be characterized by its noise spectral density in Watts/Hz or dBm/Hz.

A noise signal is typically considered as a linear addition, in opposition, to a useful information signal. The typical signal quality measure involving noise is signal-to-noise ratio (SNR or S/N). Communication systems strive to increase the ratio of signal level to noise level in order to effectively transmit data. In practice, if the transmitted signal falls below the level of the noise, called the noise floor, in the system, then data can no longer be decoded at the receiver. While there are exceptions, such as spread spectrum where signal processing can recover the signal from below the noise floor, it is still desirable to minimize the noise floor.

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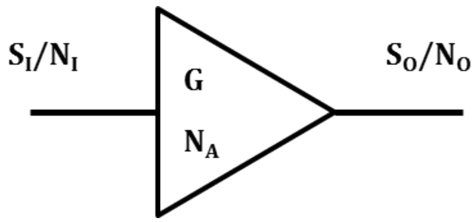
[1] http://en.wikipedia.org/wiki/Noise_(electronics)

Amplifiers are one of the most basic electrical elements in any electronic system. They amplify noise as well as the signal and amplifiers add some amount of their own noise as well. The added noise is characterized by noise figure, noise factor and/or residual phase noise.

Noise factor (F) is the deterioration of the signal-to-noise ratio due to noise from the amplifier as defined by the ratio of the signal-to-noise ratio at the input to the signal-to-noise ratio at the output.



$$\mathbf{F = (S/N)_{IN} / (S/N)_{OUT} = (S_I/N_I) / (S_O/N_O) = S_I N_O / S_O N_I}$$

For an amplifier with gain G and noise N_A, the signal is increased by the gain G so that $\mathbf{S_O = GS_I}$ and the noise is increased by both the gain and the amplifier noise so that $\mathbf{N_O = GN_I + N_A}$.

$$\mathbf{F = S_I (GN_I + N_A) / GS_I N_I = (GN_I + N_A) / G N_I = 1 + (N_A/GN_I)}$$

Note that the result is independent of the signal and approaches unity as N_A approaches zero.

$$\mathbf{F \geq 1}$$

In engineering, it is often more convenient to work in decibels and the term noise figure (NF) is the decibel expression of noise factor (F), defined as:

$$\mathbf{NF = 10 \log_{10} (F)}$$

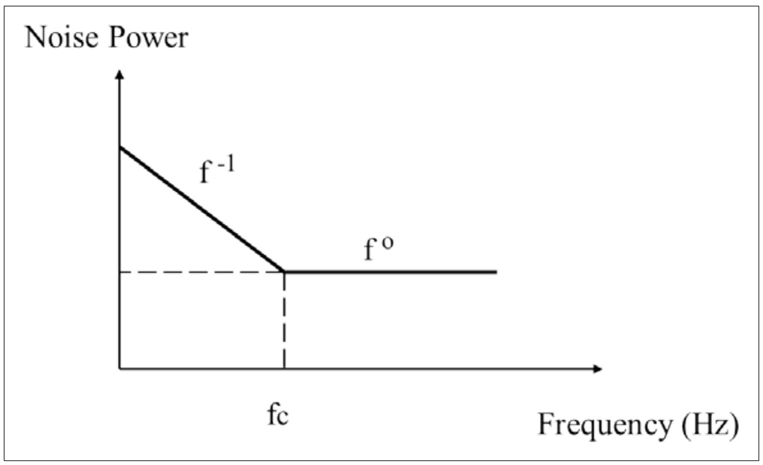
Note that for an ideal noise factor of unit (F = 1), the noise figure is zero (NF = 0 dB). A few values are shown in Table 2.

Table 2) Examples of conversion of noise factor (F) to noise figure (NF)

F	NF
1	0 dB
2	3 dB
4	6 dB
10	10 dB
100	20 dB

Given an amplifier's frequency range (noise bandwidth), gain, noise factor or noise figure, and the amplifier's temperature if substantially different from room ambient, then the noise floor at the output of the amplifier can be calculated.

The level of the noise floor calculated using thermal noise (kTB) and noise figure represents the noise at frequencies away from the signal (far from carrier). Thermal noise is flat (f^0) with frequency. In the presence of a carrier signal, the noise level near the carrier is no longer constant, but is increased[2,3]. Random noise in electronic systems exhibits the characteristic of increasing near the carrier. "Flicker" noise or "pink" noise has a slope of f^{-1} versus frequency. This "1/f" or "one over f" noise is attributed to electron motion caused by the signal.



(F_c is called the corner frequency and varies depending upon the technology)

The phase noise of a signal through an amplifier is increased by the flicker noise, referred to as the amplifier's residual phase noise. This is an interesting result, in that it means that not only is the noise floor is increased by gain and noise figure of an amplifier, but that the phase noise of a signal through the amplifier is also increased.

Note that there may be other undesired energy in the spectrum of the signal due to interference, intermodulation frequency products (both active and passive) or various spurious signals coupled through power supplies, cross-talk or radiation. The presence of this unwanted energy may be detrimental to the performance of the system, and generically called "noise", but are separate phenomena, and can be removed or mitigated by filtering, shielding and isolation techniques.

Giga-tronics microwave power amplifiers have lower noise figure than most other microwave power amplifiers in their class, and with the GaAs parallel-MMIC technology, the root mean square (RMS) residual phase noise is less than that of cascaded single device designs.

[2] "Noise Figure vs. PM Noise Measurements: A Study at Microwave Frequencies" by Hati, Howe, Walls and Walker, NIST, Proc IEEE Intl Frequency Control Symposium, 2003

[3] AN-GT140A, Introduction to Phase Noise in Signal Generators, Giga-tronics Incorporated

Due to careful design and construction, the use of the highest quality cables and connections along with well-filtered power supplies, Giga-tronics amplifiers exhibit low spurious and excellent immunity to interference.

Using Preamplifiers to Reduce System Noise Figure

The low noise figure, high gain and flat frequency response of the Giga-tronics amplifiers allow them to be used as preamplifiers for high noise figure spectrum and signal analyzers. The Giga-tronic amplifiers used as a preamp can help bring low level signals above the noise floor of the analyzer.

The approximate formula[4] for noise figure of cascaded amplifiers is calculated in linear terms of noise factor (F):

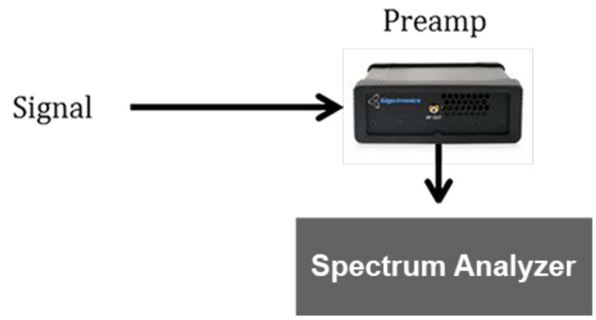
$$F_{total} = F_1 + (F_2 - 1)/G_1$$

Where F_1 is the noise factor of the first amplifier, G_1 is the gain of the first amplifier, and F_2 is the noise factor of the second or following amplifier. Note that in the exact formula, there may be additional terms for additional amplifiers following the first two, but these terms are negligible if the gains are reasonably high, since the gains multiply in the denominator of additional terms.

This can be written in terms of a preamp and analyzer:

$$F_{system} = F_{amplifier} + (F_{analyzer} - 1)/GAIN_{amplifier}$$

For example:



$NF_{amplifier}$ **= 6 dB (F = 3.98)**

$NF_{analyzer}$ **= 20 dB (F = 100)**

$GAIN_{amplifier}$ **= 40 dB (10,000)**

F_{system} **= 3.99**

And finally:

NF_{system} **= 6.1 dB**

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[4] http://en.wikipedia.org/wiki/Noise_figure

Note that the system noise figure is greatly reduced by the preamplifier and for a high gain preamplifier is essentially the noise figure of the preamplifier.

In this way, adding a preamplifier increases the sensitivity of the analyzer by decreasing the displayed average noise level (DANL) or noise floor of the analyzer.

There are a couple caveats to be aware of when using an amplifier as a preamp for spectrum and signal analyzers. First, it is assumed that the noise figure of the amplifier is lower than that of the analyzer. Second, if the amplifier gain is high, it may be necessary to adjust the analyzers input attenuator to maintain the signal in the analyzer's "sweet spot", where the power level at the analyzer's mixer is at an optimum level for the best analyzer performance. The "sweet spot" mixer power level is a tradeoff between the analyzer's sensitivity and distortion products.

Note that while manufacturers of spectrum and signal analyzers recommend you use their own high-priced amplifiers as preamps for their analyzers, there is no absolute requirement to do so. Compare specifications for frequency range, gain, gain flatness, noise figure, harmonics and spurious, and the Giga-tronics amplifiers will very likely offer higher performance at a lower cost.

The broad frequency ranges of the Giga-tronics amplifiers, from 100 MHz to 20 GHz, 40 GHz and 50 GHz, well match the frequency range of the majority of spectrum and signal analyzer applications. The Giga-tronics parallel-MMIC design provides wide linear range and a sharp saturation knee. The result is outstanding performance when used with signals having high peak to average ratios. The broad frequency range provides excellent pulse performance preserving the fast rise and fall times of high speed signals and narrow pulses.

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