RF/Microwave Equalizers: An Essential Ingredient for the Modern System Designer

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The need for equalization has become commonplace throughout the RF/microwave/millimeter wave frequency ranges. Modern military, satellite and wireless communications systems transmit and receive signals with relatively high instantaneous bandwidths. Gain variation across the signal bandwidth induces distortion in the transmitted or received signal because not all frequency components are amplified equally[1]. In other words, for multi-phase, multi-amplitude-level-modulated systems, unintended amplitude differences (i.e. due to gain changes) over the occupied bandwidth introduce errors, leading to incorrect interpretation of the signal and an increase in system bit error rate (BER)[2]. A 5G system, for example, may operate in FR1 (3.3-4.2 GHz) with a bandwidth of 100 MHz or in FR2 (24-54 GHz) with an aggregate contiguous bandwidth of 1.2 GHz[3]. 5G signals utilize quadrature amplitude modulation (QAM)[4], a multi-phase, multi-amplitude-level modulation scheme that is susceptible to amplitude (gain) variation over its occupied bandwidth. Consequently, gain flatness specifications have become more demanding for receiver and transmitter chains operating across wider bandwidths.

Most transmitter and receiver systems experience decreasing gain and increasing losses at progressively higher frequencies. The equalizer is a component designed specifically to compensate for this natural tendency toward roll-off exhibited by these systems. Mini-Circuits' equalizers extend from DC to 45 GHz. In combination with Mini-Circuits' family of ZEQ and VEQY connectorized components, the EQY-series SMT and die devices provide the designer great latitude in the selection of an equalizer to fit any application. These equalizers are offered in many different attenuation levels and in bandwidths ranging from DC to 6 GHz, 20 GHz, 28 GHz, and 45 GHz.

What is an Equalizer?

An equalizer, sometimes referred to as a “lossy equalizer,” is essentially an attenuator placed in a circuit or system that exhibits an *insertion loss* that is at its *maximum* at the *lowest* operating frequency and at its *minimum* at the *highest* operating frequency. A complementary statement is that the equalizer exhibits *minimum gain* at the lowest operating frequency and *maximum gain* at the highest operating frequency. Placing the equalizer in a system cascade “tilts” the gain response in a positive direction. The magnitude by which the equalizer tilts the system gain response from minimum to maximum operating frequency is called its equalization value or “slope.”

Although far less common, some equalizers tilt gain in a negative direction. This type of equalizer is suitable in applications requiring waveguide components, for example. Additionally, parabolic equalizers have long established a niche in the area of traveling-wave tube (TWT) amplifiers. Regardless of the shape of the equalizer response, the end goal is to flatten or “equalize” the gain of a system over a relatively wide bandwidth.

Figures 1 and 2 show frequency response curves for three SMT devices in Mini-Circuits’ line of 45 GHz equalizers, the EQY-3-453+, EQY-6-453+ and EQY-10-453+. Each equalizer in Figure 1 has a different slope, or magnitude of monotonic decrease in attenuation from DC to 45 GHz. The slope of each model may also be interpreted as the magnitude of monotonic increase in gain from DC to 45 GHz, as shown in Figure 2. It is easier to visualize how the equalizer compensates for gain roll-off when the frequency response is viewed from a gain perspective, as in Figure 2. Mini-Circuits’ family of 45 GHz equalizers includes a unique model for each 1 dB increment in slope from 3 to 10 dB. Additionally, every equalizer in the 45 GHz line is available in die form.

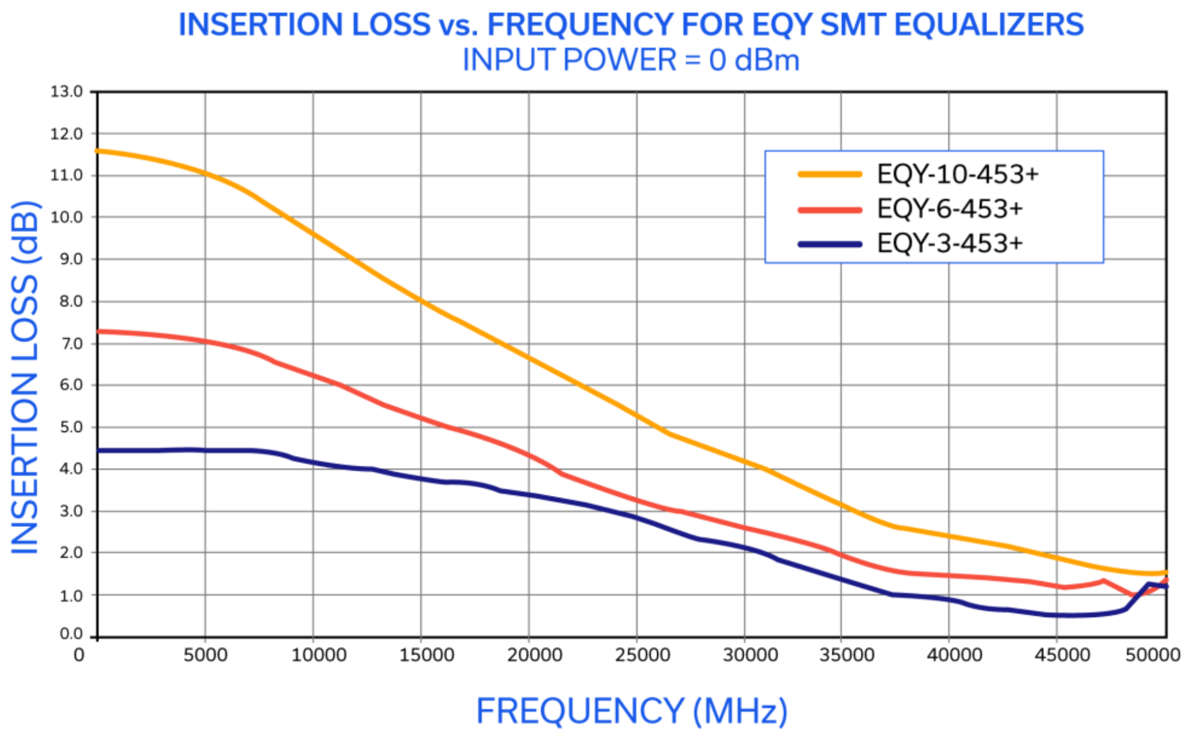

Figure 1: EQY-3-453+, EQY-6-453+ and EQY-10-453+ MMIC SMT equalizer IL vs. frequency.

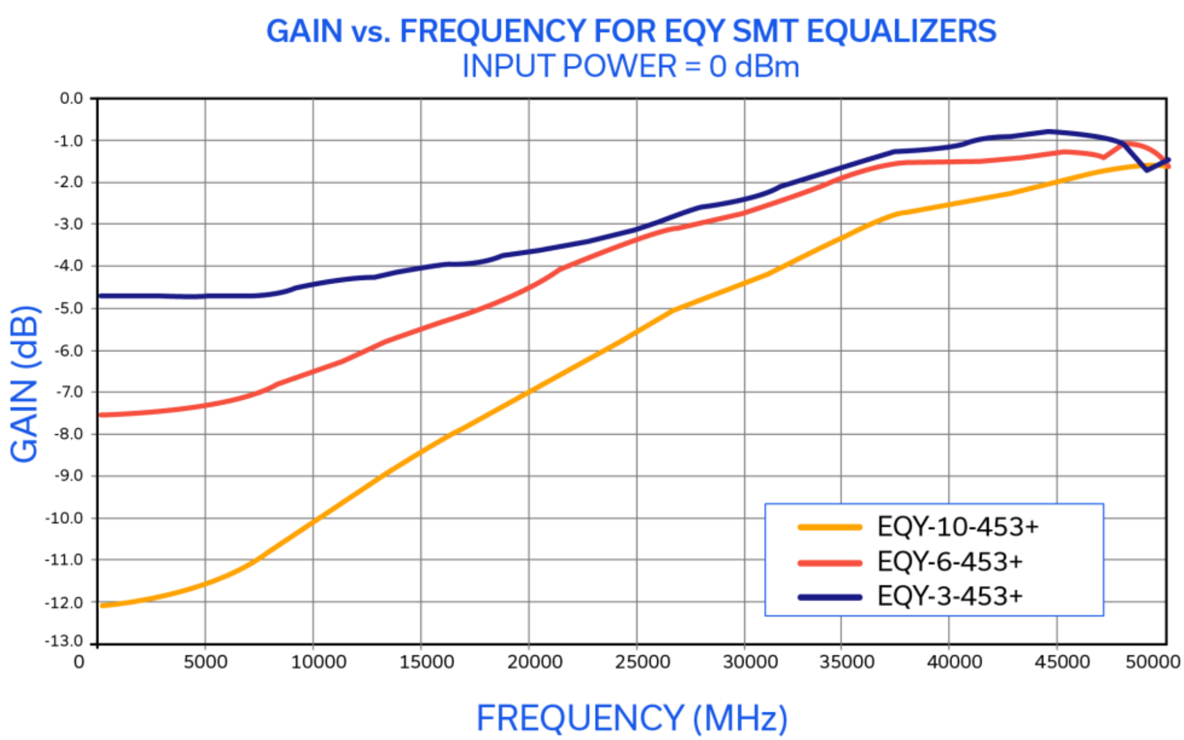

Figure 2: EQY-3-453+, EQY-6-453+ and EQY-10-453+ MMIC SMT equalizer gain vs. frequency.

When is an Equalizer Required?

Generally, equalizers are necessary in any wideband system in which elements of gain and insertion loss are cascaded in series. Examples of systems that require equalizers are wideband receivers and transmitters, where typically quite a number of gain and insertion loss elements are cascaded together, and where flat system frequency response is often desired. In most cases, the gain of the amplification stages declines with increasing frequency, and the insertion loss of the lossy elements increases, leading to significant roll-off in overall cascaded system gain. The equalizer provides a *negative* insertion loss slope to the system (*less* insertion loss at *higher* frequencies), and when chosen properly, may reduce or even eliminate frequency-dependent system gain roll-off.

How Much Equalization is Necessary?

It is possible to determine the correct amount of equalization by examining the characteristics of the discrete system components for a small system. However, even cables, circuit board traces and the mismatch of connector transitions constitute additional losses with frequency that are difficult to predict. So in reality, it is therefore most often necessary to perform simulations on a well-modeled system to determine the correct amount of equalization. Even with precise modelling, designers often need to evaluate multiple slope values at the prototyping stage to achieve measured performance that matches the requirements. Mini-Circuits' designer kits avail the designer of a multitude of slope values in small quantities for evaluation and prototyping, ensuring that optimum performance can be achieved in practice.

If the system consists of just a handful of components, however, it is quite possible to achieve a reasonable estimate of the required equalization using system calculations associated with simple cascade analysis, which we utilize for the following hypothetical system for illustration.

Equalization Yields Flat Gain in a Two-Stage Wideband LNA

An example of a two-stage, 400 to 6000 MHz LNA for which equalization is required is shown in the block diagram in Figure 3 below. The aggressive performance goals for the design are:

- Frequency Range: 400-6000 MHz
- Gain: 30 dB min.

- NF: 1dB max.
- Output P_{1dB}: +15 dBm min.
- Output IP3: +25 dBm min.

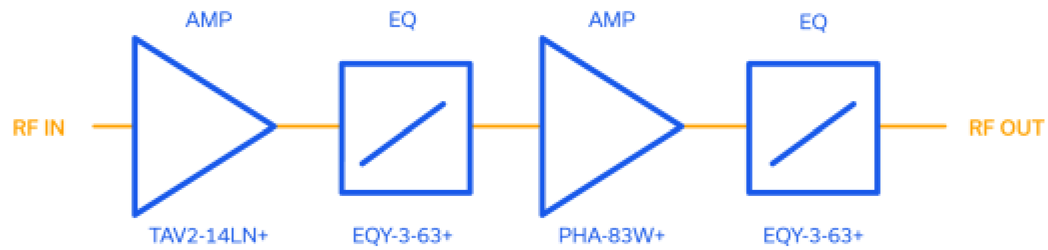

***Figure 3: Two-stage* 400-6000 MHz LNA block diagram.**

The input stage is the Mini-Circuits TAV2-14LN+. This choice was made based on its very low noise figure (NF). When operated at V_d = 2V, this device maintains a NF of 0.69 to 0.75 dB over the 400-6000 MHz band. The TAV2-14LN+ also exhibits relatively high gain (16-22 dB) over the band of interest, although its gain slope will necessitate equalization. The amplifier for the final stage is the PHA-83W+, selected predominantly since it performs quite well in the linearity category, boasting 25 dBm OP_{1dB} and 36 dBm OIP3 at 400 MHz and V_d = 9V. Not only do OP_{1dB} and OIP3 of the PHA-83+ remain strong to 6000 MHz and beyond, but its total gain flatness across the 400-6000 MHz band is only ±1 dB.

In order to determine the required equalization in this example, it is first necessary to determine the frequency response of the system gain without the use of an equalizer. Since the gain is in dB, the cascaded gain is simply the sum of the gain of the two stages. Figure 4 shows that the gain without equalization exhibits a significant roll-off of 7 dB, 6 dB from the TAV2-14LN+ plus 1 dB from the PHA-83W+. The biggest contributor to negative gain slope, the TAV2-14LN+ input stage, will be equalized, and the results examined.

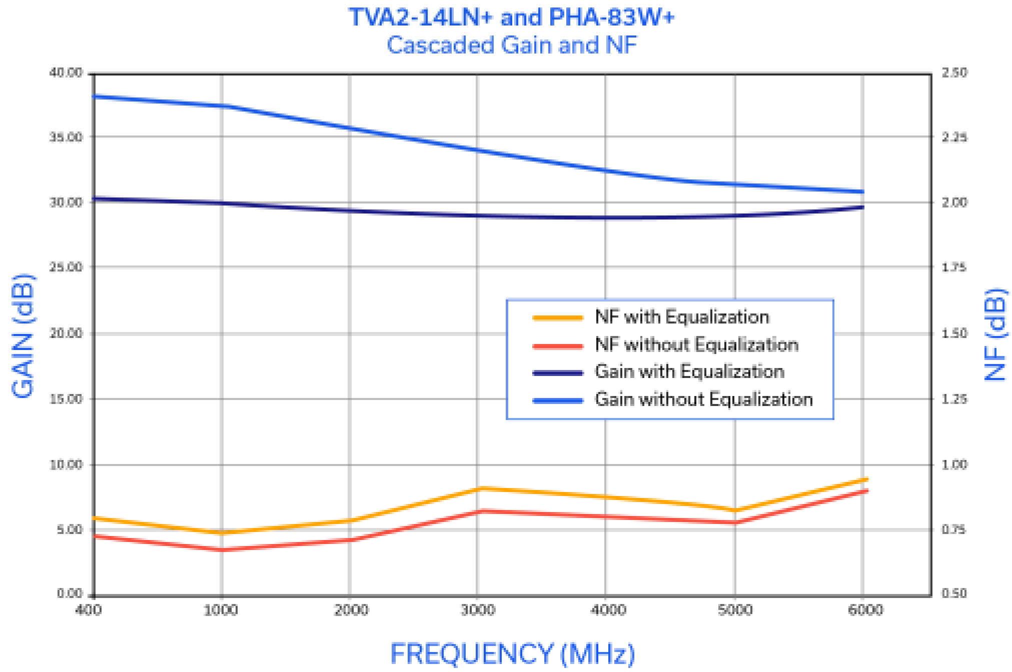

Figure 4: Gain and NF with and without equalization for two-stage LNA system.

The system is an LNA requiring very low NF (< 1 dB). Therefore, no attenuation should be added to the input. Integrating a single equalizer that has steep slope into the cascade is often not the best way to correct system gain roll-off. It is generally better to distribute equalization throughout the cascade. An arbitrary decision was made to split the required amount of equalization between two identical SMT equalizers, the EQY-3-63+, for which the frequency response is shown in Figure 5. The first of the two 3-dB equalizers is placed on the output of the first stage amplifier which greatly reduces its effect on overall NF (since a gain element precedes it). A collateral benefit of splitting the equalization in the LNA of Figure 3 is that the first equalizer serves as a low value attenuator, improving the interstage 50Ω match and mitigating VSWR interactions between stages.

The additional equalization needed is provided by a second EQY-3-63+ equalizer placed at the output of the final stage of the LNA. The cascaded system gain both with and without equalization is shown in Figure 4. The overall LNA with equalization has a gain vs. frequency slope that is now just slightly negative. The choice of equalization was sufficient to compensate for the vast majority of the gain roll-off for the LNA's 400-6000 MHz operating range. Additionally, the absolute gain is just slightly lower than the design goal of 30 dB min. in the center of the band, which is a rather successful outcome, given this gain flatness was achieved over more than a decade of bandwidth.

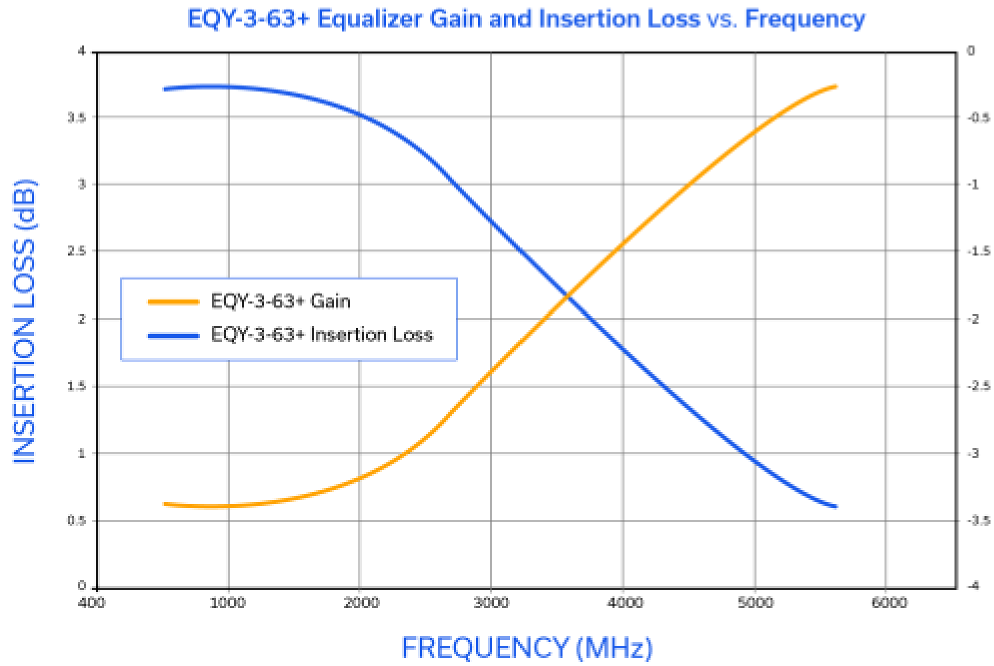

Figure 5: EQY-3-63+ equalizer gain and insertion loss vs. frequency.

The Equalizer and its Influence on Noise Figure

When an equalizer is introduced into a system, it is important to examine its effect on system noise figure (NF) over frequency since the equalizer is essentially a frequency-dependent attenuator. The effects of equalization on system performance parameters NF, P_{1dB}, and IP3 can often be quite involved, particularly as the complexity of the system grows.

In the relatively simple example discussed above, it is first necessary to take the inverse log of each of the components' respective noise figures (NF_1, NF_2, NF_3, …(dB)) and Gains (dB) to determine individual noise factors (F_1, F_2, F_3, …) and linear gains (G_1, G_2, G_3, …). Next, the two-stage LNA requires Friis' formula to cascade the respective, individual noise factors and to compute system noise factor (F). System noise factor is then converted back to system noise figure (NF) in dB. Sample calculations are shown below for cascaded system F and NF at 400 MHz, with equalization:

F_n = 10^(NF_n/10) = $10^{(NFn/10)}$

F_1 = 10^(0.69/10) = 1.17, F_2 = 10^(3.77/10) = 2.38, F_3 = 10^(2.96/10) = 1.98, F_4 = 10^(3.77/10) = 2.38

(Gn(dB)/10)

$G_n = 10$^$(G_{n(dB)}/10) = 10^{(Gn(dB)/10)}$

G_1 = 10^(22.0/10) = 158.9, G_2 = 10^(-3.77/10) = 0.42, G_3 = 10^(6.59/10) = 45.6, G_4 = 10^(-3.77/10) = 0.42

$F = F_1 + (F_2 - 1)/G_1 + (F_3 - 1)/G_1G_2 + (F_4 - 1)/G_1G_2G_3 + \ldots$

F = 1.17 + (2.38 − 1)/158.9 + (1.98 − 1)/(158.9)(0.42) + (2.38 − 1)/(158.9)(0.42)(45.6) = 1.196

NF = 10*log(F) = 10*log(1.196) = 0.78 dB

The results of these calculations for cascaded system NF are shown for the entire frequency range in Figure 4. Without the additional attenuation of the equalizers, the NF of the system is naturally lower, and with equalization it is higher. Even with equalization, however, system NF remains below 1 dB, meeting one of the key design goals for the LNA.

LNA System Linearity Parameters: Output P_{1dB} and Output IP3

The results of performing a cascade analysis for OP_{1dB} and OIP3 are shown in Figure 6. Both parameters meet their respective design goals of +15 dBm and +25 dBm with a good amount of margin. Naturally, the amount of performance margin at the low end of the band (400 MHz), where the equalizer exhibits maximum attenuation, is lower than the margin at the high end of the band. This particular LNA has nearly flat gain and is capable of providing increasing OP_{1dB} and OIP3 with frequency. Generally, most system components will exhibit a subtle roll-off in linearity with increasing frequency, making these positively-sloping linearity characteristics potentially useful were this LNA to be designed into a larger, more complex system.

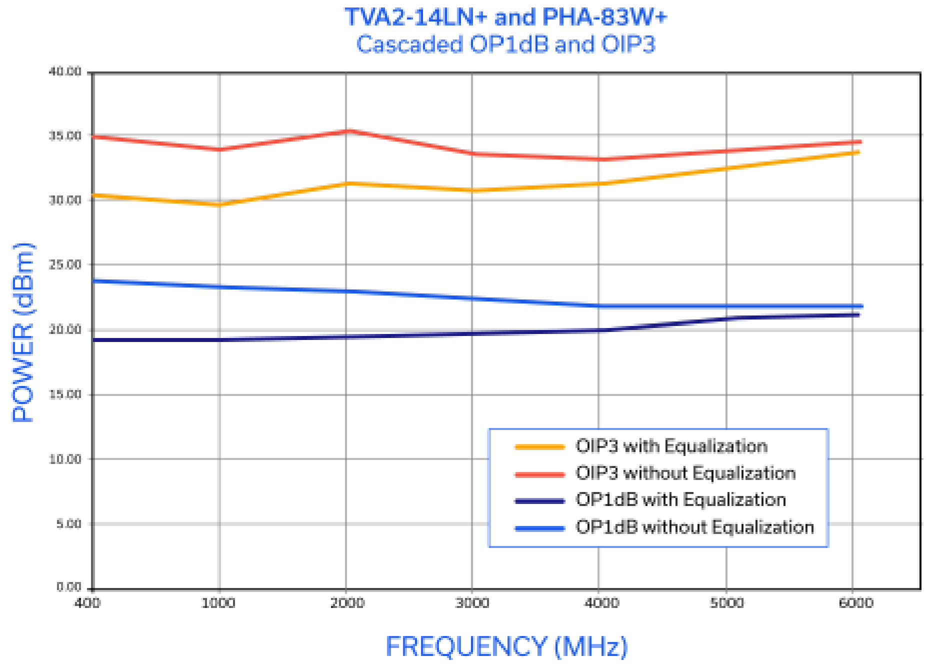

Figure 6: Output P1dB and output IP3 with and without equalization for two-stage LNA system.

Equalizers Ready for System Integration

Equalizers are an essential part of any wideband system for which flat gain response is required. Passive or "lossy" equalizers tend to reduce overall gain but may often have minimal effect on NF as shown in the two-stage LNA example. Additionally, when utilized between amplifier stages, VSWR interaction will be mitigated and 50Ω matching will improve along with gain flatness. While linearity experiences a slight reduction with equalization, it is possible to achieve increasing linearity with frequency. Mini-Circuits has over 70 unique equalizer models in stock with slope values from 1 to 15 dB and operating frequency ranges spanning DC to 45 GHz, including voltage variable equalizers.

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References

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