Monolithic Attenuator/Limiter using Nonlinear Resistors

Scott Schafer, Michael Roberg
Qorvo, Inc. - Infrastructure and Defense Products
Richardson, Texas 75080, Email: scott.schafer@qorvo.com

***Abstract*—A novel attenuator/limiter circuit that uses nonlinear GaN epitaxial resistors is presented. The circuit is small, broadband as it does not use any reactive elements, does not use DC bias, and can be integrated on GaN or GaAs with other microwave elements and/or circuits. GaN epitaxial resistors have a saturation current limit which provides a limiting function. Resistive T- and Pi-network attenuators are implemented using GaN epitaxial resistors to limit the total power through the attenuator. A first-order equation of the trade-off between attenuation and flat leakage power is derived. Fabricated circuits show flat leakage powers 0.4 - 10 W with input powers >30 W. No noticeable spike-leakage is observed. The limiting attenuator is implemented at the input of an S-band 32 W PA for radar applications, and is shown to protect the input from overdrive while delivering consistent output power after limiter saturation.**

***Index Terms*—GaN, attenuator, high-power limiter.**

I. Introduction

Microwave amplifiers typically have maximum input power ratings. These ratings are derived based on laboratory testing which determines the maximum amount of input power the amplifier can withstand prior to the onset of damage or permanent degradation. Users of the amplifier must be careful to not provide an input power greater than this recommended level.

A well-known two-port microwave circuit is a power limiter. Limiters are used in a variety of applications, in particular for front end protection of receivers [1], [2]. At non-limiting levels of input power, the output power of the limiter is very nearly the input power. However, as the level of input power rises beyond a critical threshold, the limiter begins to limit the amount of output power (the remaining power is either reflected back to the input port or dissipated within the circuit in some manner). Microwave limiters are often realized in a technology which is not integrated in the same process as a MMIC amplifier. For instance, PIN diode limiters are not available for fabrication on GaAs or GaN MMIC processes. Additionally, many types of limiters require DC bias to provide limiting with very high levels of input power.

This paper implements a limiter using GaN epitaxial resistors (or GaN resistor) which saturate under high current. The resistors are implemented as a T- or Pi-network resistive attenuator to provide a wide band and high-power limiter with a very small footprint. While there are many examples in literature of higher power limiters [3], this is the first limiter (that the authors know of) that does not use DC bias, can be integrated with GaAs or GaN MMIC devices, can handle relatively high input powers ¿30 W (as compared to GaAs MMIC Schottky diodes) [4]–[6], and has a very small footprint.

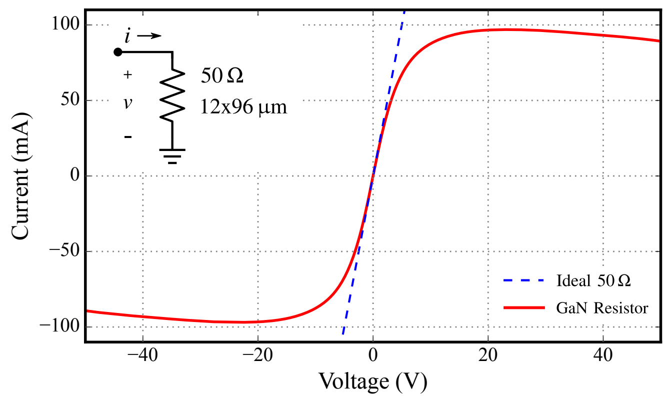

Fig. 1. Typical DC-IV of a measured shunt GaN resistor. The resistor is highly nonlinear and limits the total current that it can pass. The size of the resistor is 12x96 µm (length x width) which gives a saturation current of approximately 1 A/mm. As comparison, the dashed blue line is the current through an ideal 50 Ω resistor.

The limiter implemented as a T- or Pi-attenuators can provide a dual usage in microwave systems for a variety of reasons, including buffering poor return losses and reducing system gain levels. Basic design equations for the limiter are derived and a limitations of a minimum attenuation versus limiting power are explored. Limiting powers from 0.4 W up to 10 W (defined as the maximum output power from the attenuator) with various attenuations are demonstrated using Qorvo's GaN 0.25 µm process. The limiters are shown to have no spike leakage as they are resistive in nature. Finally, a limiter implemented at the input of an S-band 32 W PA for radar applications is shown to protect the input from overdrive while delivering consistent output power after limiter saturation.

II. Design Equations

DC-IV measurements of a GaN resistor were taken. A typical curve of a 50 Ω (12x96 µm) GaN resistor is shown in Fig. 1 (solid) as compared to an ideal 50 Ω resistor (dashed). The resistance is highly nonlinear and saturates at approximately 97 mA. The width is 96 µm, giving an I_{max} of 1 A/mm, which is also typical of a saturated FET in the process. The decrease in I_{max} beyond 24 V applied to the resistor is likely due to thermal heating of the resistor; power dissipation still increases when current limited because of the increasing voltage.

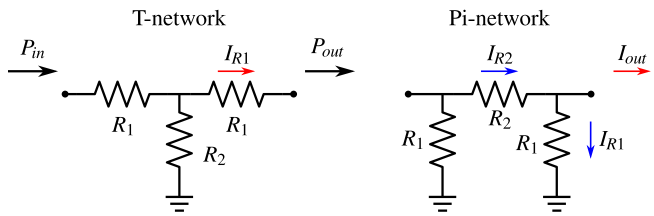

Fig. 2. T- and Pi-network attenuators. Limiting power, P_{out} is determined by the series resistor in the T-network case. The pi-network limiting power is primarily determined by the series resistor, however, there is a small amount of current that passes through the shunt resistor.

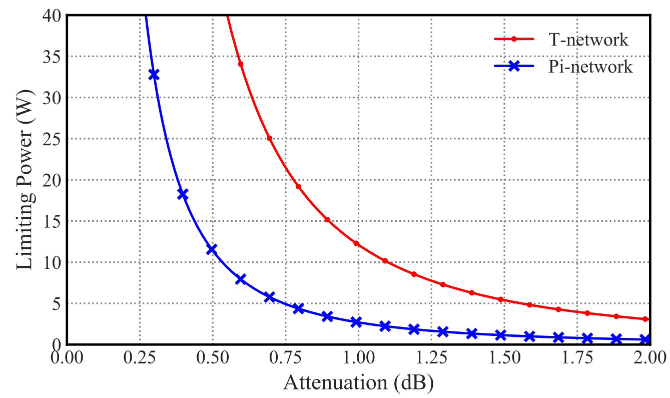

Fig. 3. Minimum limiting power possible with a desired attenuation. The line denotes an attenuator designed with the minimum length of $l = 5\,\mu$m and a saturation current of $I_{sat} = 1$ A/mm. Any point *above* the line ($l = 5\,\mu$m) is realizable in the GaN process being used in this paper.

The design equations for a T- and Pi-network resistive attenuators are well known. For a T-network (see Fig. 2) they are,

$$R_1 = Z_0 \frac{10^{dB/20} - 1}{10^{dB/20} + 1}, \tag{1}$$

$$R_2 = 2Z_0 \frac{10^{dB/20}}{10^{dB/10} - 1}, \tag{2}$$

where R_1 and R_2 are the series and shunt resistors respectively, Z_0 is typically 50Ω, and dB is the desired attenuation value in dB. For both attenuators, minimum attenuation is achieved by the series resistors approaching 0 Ω and the shunt resistors approaching infinity. Due to process limitations in the Qorvo 0.25 µm GaN process, the minimum dimension length of a resistor is 5 µm. This effectively puts a limit on the minimum attenuation that a GaN resistor network can have in order to limit at a particular power level. To explain more clearly, a limiter is desired to have a small insertion loss, especially at higher powers where additional tenths of dB in power may be very costly. To approach 0 Ω for the series resistors, the implemented GaN resistor width must be very wide or the length must approach 0 µm. However, making the resistor wider increases the saturation current thereby increasing the power the attenuator would limit at. The minimum attenuation value versus limiting power is derived in the following paragraphs. The limiting power is defined as the maximum output power from the attenuator (assuming a 50Ω system).

The peak current through a resistor is

$$I_{pk} = I_{sat} w, \tag{3}$$

where w is the width of the resistor (perpendicular to current flow), and I_{sat} for the process used is 1 A/mm. The resistance of a sheet resistor is given by

$$R = \frac{l}{w} R_s, \tag{4}$$

where l is the length (parallel to current flow) of the resistor and R_s is the resistance in Ω per square. The peak current through the resistor will determine the power that can be passed to the output of the attenuator.

$$I_{pk} = I_{sat} \frac{l}{R} R_s \tag{5}$$

For the T-network attenuator, the limiting resistor is the second series resistor (Fig. 2) assuming the physical size of the first series resistor is much larger so that there is no significant limiting effect. The limiting power is easily found as

$$P_{out}^{T} = \frac{1}{2} I_{out}^2 Z_0 = \frac{1}{2} I_{pk}^2 Z_0 = \frac{Z_0}{2} \left(\frac{l R_s I_{sat}}{R_1} \right)^2. \tag{6}$$

where Z_0 is the system impedance. R_1 can be found by the design equations for the T-network resistive attenuator.

For the Pi-network, there is a small adjustment due to the current that passes through the shunt resistor. The output current is related to the current through the series resistor as

$$I_{out} = \frac{R_1}{R_1 + Z_0} I_{R2} \tag{7}$$

and so the limiting power is

$$P_{out}^{Pi} = \frac{Z_0}{2} \left(\frac{l R_s I_{sat}}{R_2} \right)^2 \left(\frac{R_1}{R_1 + Z_0} \right)^2. \tag{8}$$

A similar equation can found for the T-network if the second series resistor is the limiting component. Fig. 3 shows the limiting power versus attenuation for T- and Pi-network resistive attenuators with the minimum length of $l = 5\,\mu$m. One may note that the Pi-network allows lower attenuation values for a given limiting power.

III. Implementation and Measurements

Various attenuators were designed with differing limiting powers and attenuation levels and tested. Fig. 4 shows a 10 dB attenuator that was designed to limit at 26 dBm of maximum output power. Multiple resistors were used in parallel for the first series and shunt resistor to keep the layout symmetric. The red rectangular shapes are vias to the backside ground metal. The size of the attenuator is very small at ≈200*500 µm; the largest part of the layout is the RF input pad where two bondwires would be located. Fig. 5 shows the measured input/output power of the attenuator with a CW 1 GHz tone.

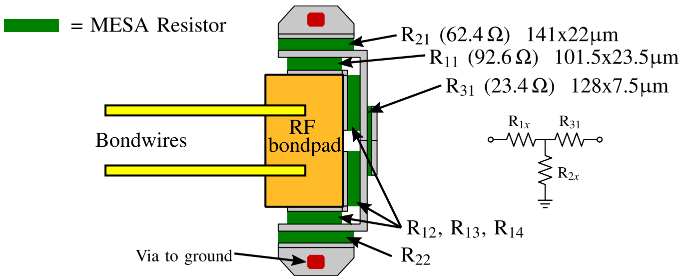

Fig. 4. Layout of 10 dB "T"-attenuator. The first series resistor (R_{1x}) was split in to 4 and the shunt resistor was split into 2 parallel elements to keep symmetry. The size of the shown layout is 202x497 μm.

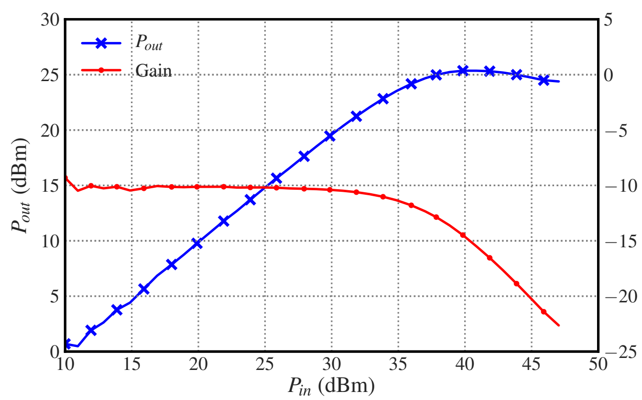

Fig. 5. CW measurements of "T"-attenuator on fixture. The attenuator/limiter has 10 dB of attenuation and limits to just over 25 dBm at 40 dBm input.

The maximum measured output power is 26 dBm with a corresponding input power of 10 W (40 dBm). Compression of the nonlinear resistors is apparent with a sharply increasing attenuation (decreasing gain) through the network after 30 dBm.

A. Spike-leakage

Spike-leakage was measured on a limiter with an attenuation of 3 dB. The pulse width was set to 1 μs and 1% duty cycle with an RF frequency of 1 GHz. A detector was used at the output with an oscilloscope to measure the time domain pulse response through the attenuator/limiter. A single measured pulse is shown in Fig. 6 for three different input powers. At any input power there is no spike seen at the rising edge of the pulse. However, thermal heating can be seen decreasing the I_{sat} of the GaN resistors decreasing the allowed power through the element giving a peaking shape to the beginning of the pulse. The spike at the falling edge of the spike for all input powers was due to the test set; it was present with a thru line replacing the attenuator/limiter.

B. Limiter at PA input

The 10 dB attenuator with 26 dBm of flat-leakage shown in Fig. 4 was implemented on the input of an S-band 32 W power amplifier designed for pulsed radar applications. Without any protection, this PA's performance typically degrades with input

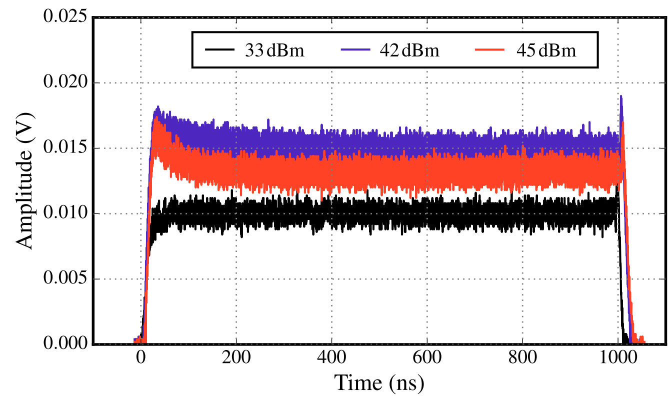

Fig. 6. Time domain at various input powers of a 3 dB attenuator with 1 μs pulse at 1 GHz carrier frequency. The thermal heating of the attenuator is evident at the beginning of the pulse. The oscilloscope used has enough sampling bandwidth to catch the RF sinusoid making the traces seem noisy.

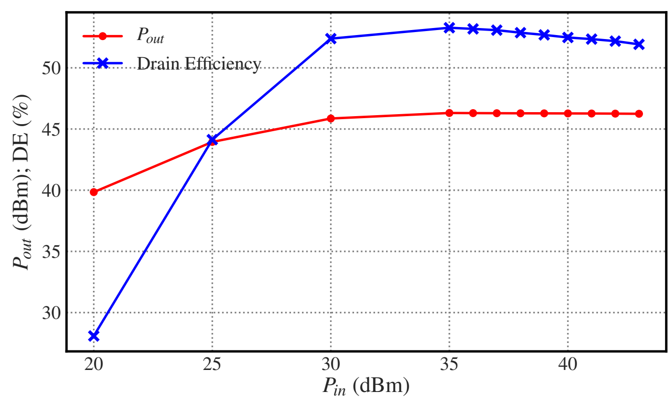

Fig. 7. Input power sweep up to 43 dBm input power (20 W) at 3.1 GHz. The PA saturates above ≈ 35 dBm without output power decreasing and small decreases in the drain efficiency.

powers $> 28\,dBm$. With the GaN limiter at the input, the PA is protected from damage due to input over-drive. Measured output power and efficiency versus input power at 3.1 GHz (midband of the device) is shown in Fig. 7. Driving the PA at up to 43 dBm (20 W) input power shows nearly flat output power and drain efficiency performance after hard saturation at P_{in}=35 dBm.

IV. Conclusion

This paper explored the concept of using nonlinear elements for a limiting effect. The particular implementation and measured results shown are as a resistive attenuator. Limiting output powers of 0.4 - 10 W are shown with input powers >30 W. These limiter/attenuators could be used to reduce system gain while reducing return loss at the same time. A limiter is implemented on the input of a PA and is shown to successfully protect the PA up to 43 dBm input power, increasing the robustness greatly. They could also be used as a rough high power limiter with a lower flat leakage output power limiter following, implemented as diodes or another topology. The effect of self-heating was not discussed here and is a potential avenue for further research.

REFERENCES

[1] I. J. Bahl and P. Bhartia, *Microwave Solid State Circuit Design*. John Wiley & Sons, 2003.

[2] N. Billstrm, M. Nilsson, and K. Estmer, "Gaas mmic integrated diode limiters," in *Microwave Conference, 2010. 5th European*, Sept 2010, pp. 126–129.

[3] J. Bouchez *et al.*, "A 2-5ghz 100w cw mmic limiter using a novel input topology," in *Compound Semiconductor Integrated Circuit Symposium (CSICS)*, Oct 2013, pp. 1–4.

[4] A. P. M. Maas, J. P. B. Janssen, and F. E. v. Vliet, "Set of x-band distributed absorptive limiter gaas mmics," in *2007 European Radar Conference*, Oct 2007, pp. 17–20.

[5] M. van Wanum, T. Lebouille, G. Visser, and F. E. van Vliet, "Suitability of integrated protection diodes from diverse semiconductor technologies," in *2009 European Microwave Integrated Circuits Conference (EuMIC)*, Sept 2009, pp. 294–297.

[6] D. G. Smith *et al.*, "Designing reliable high-power limiter circuits with gaas pin diodes," in *Proc. IEEE MTT-S Int. Microwave Symp. Digest*, vol. 2, June 2002, pp. 1245–1247 vol.2.