

Performance Advantages and Design Techniques for THz Schottky Diode Limiters

Abstract

Limiters are critical components in the front end of nearly every modern RF receiver. As system level requirements of modern transceivers become more stringent, this drives a need for RF components that can offer near ideal performance at every point along the chain. For a limiter, this means instantaneous recovery times, near-zero spike leakage and thermal properties that allow for unaltered performance in high-power pulsed conditions. In this paper we will discuss the massive performance advantages offered by THz Schottky diode-based limiters, how to optimize limiter designs, and how system level requirements are simplified through the adoption of this limiter technology.

What Is A Limiter And How Are Limiters Used?

Limiters are used to protect sensitive circuitry from high power signals. Take for example a simple radar system, which consists of a high-power pulse transmitter sharing an antenna with the Rx signal chain shown below in Figure 1.

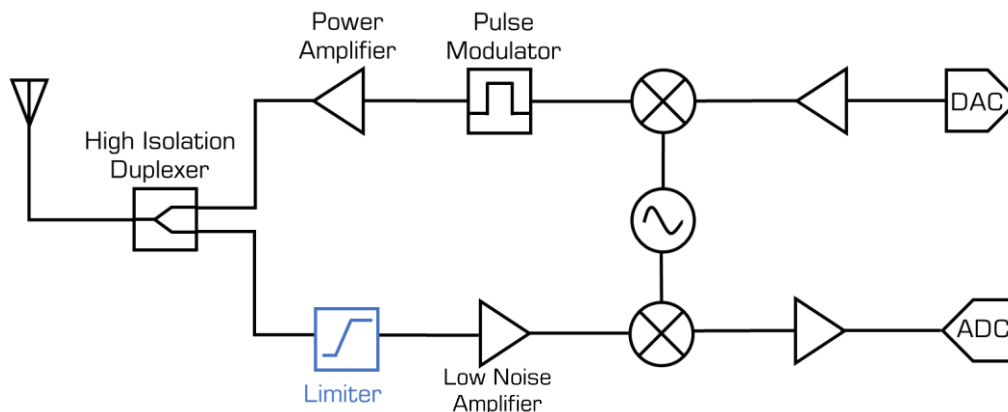


Figure 1: Simplified Block Diagram of Typical Radar

The pulse exiting the power amplifier (or any other high power pulse incident on the antenna) may be well above the damage threshold of the LNA and, depending on the isolation of the duplexer, may cause catastrophic damage to the LNA. Something needs to be placed early in front end to protect the sensitive circuitry from high powered signals and this is a limiter.

A limiter is a device commonly implemented as a set of antiparallel diodes which has a very low *small signal* insertion loss, however as the input power to the limiter increases past a critical input power level (referred to as the limiting threshold), the insertion loss begins to increase dB for dB. This limits the power out of the device to some maximum level (referred to as the flat leakage) regardless of input power. This operates on the principle that once the input to the limiter is large enough, the diodes will clamp the signal at their turn on voltage. As the instantaneous voltage on the diode increases, the diode moves along its IV curve and begins drawing more current. At high enough voltage levels, the diode appears more like a parallel short than a parallel open, leading to dissipation of the power both in the IV

current of the diode and the reflection of the incident signal. In essence, the limiter limits signal strength on the device's output by diverting excess power through the diodes allowing only a fixed RF power out when limiting. By placing a limiter before sensitive circuitry such as an LNA which can be damaged by excessive input power, one can protect that device from high signal levels by selecting a limiter with a flat leakage level below the damage threshold of the next device in the signal chain.

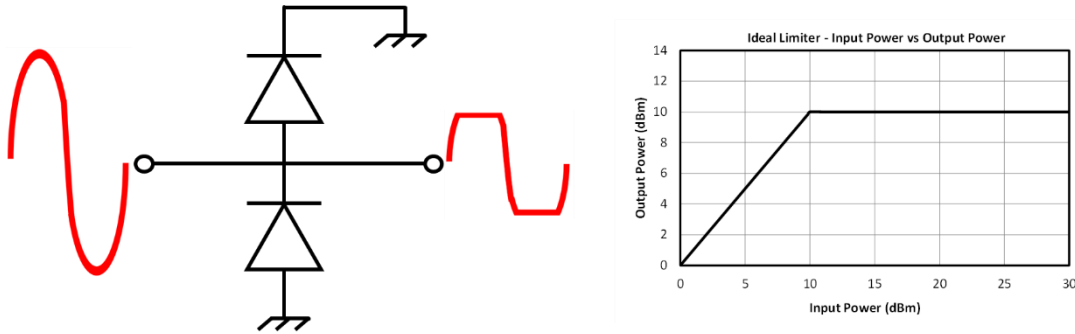


Figure 2: Simplified Limiter Circuit And Ideal Input Vs Output Power Relationship Showing +10dBm Flat Leakage and +10dBm Limiting Threshold

Figure 2 above shows a simplified limiter circuit and a plot of an ideal limiter which has a +10dBm flat leakage. Note that this plot shows the theoretical response of an ideal limiter. A real limiter has a small insertion loss associated with the device which pushes the whole curve to the right, and the flat leakage level has some slope to it which are important figures of merit in a high-performance limiter.

Limiter Figures of Merit

This standard use case of limiters gives rise naturally to one of the most important figures of merit for a limiter which is the flat leakage level, however there is much more to consider when selecting or designing a high-performance limiter than the leakage alone. For a limiter, it is simplest to break the specifications into two categories: Typical RF Specifications, and Limiter Specific Specifications. The typical RF specifications are parameters like insertion loss, return loss, compression and IP3. These are things that you are used to seeing in two port RF component datasheets. In a limiter these specs are important to consider, however they are not the most critical specs which make or break a limiter design. These are typically the limiter specific specifications which are defined below and shown graphically in Figure 3.

Flat Leakage – Flat leakage is a parameter expressed in dBm and is typically characterized at a given input power level and frequency. Flat leakage describes the absolute output power exiting the limiter when in its limiting regime. This figure of merit tells the RF designer whether this limiter will be able to protect the signal chain under maximum input levels.

Flatness – Flatness goes hand in hand with flat leakage and describes the deviation from the flat leakage level as you increase to higher input power levels. This figure of merit comes from the fact that no limiter will be completely flat and there is always going to be some slope to the limiting curve. Flatness describes the deviation from ideal flat leakage and in a high-performance limiter, it is ideally very low. Typically, this parameter is defined as the difference in flat leakage from the 0.1dB compression point at some defined higher input level.

Recovery Time – The recovery time of a limiter is one of the most important specifications for modern high-performance receivers because it directly impacts receiver sensitivity and if not optimized *will* create blind spots in your receiver. The recovery time is defined as the amount of time it takes for the limiter to relax to a low insertion loss state after being jammed by a high-power signal causing high insertion loss.

Spike Leakage – Spike leakage can be thought of as recovery time in reverse. If recovery time describes how long it takes for a limiter to relax back to a low insertion loss state, spike leakage describes how much of a high-powered signal can transmit through the limiter before it clamps down and begins to limit. This is typically characterized in terms of energy (power x time). If a high-power pulse is incident on the input even with a very short duty cycle, if the limiter exhibits high spike leakage it may allow too much energy from this pulse through the limiter causing catastrophic damage.

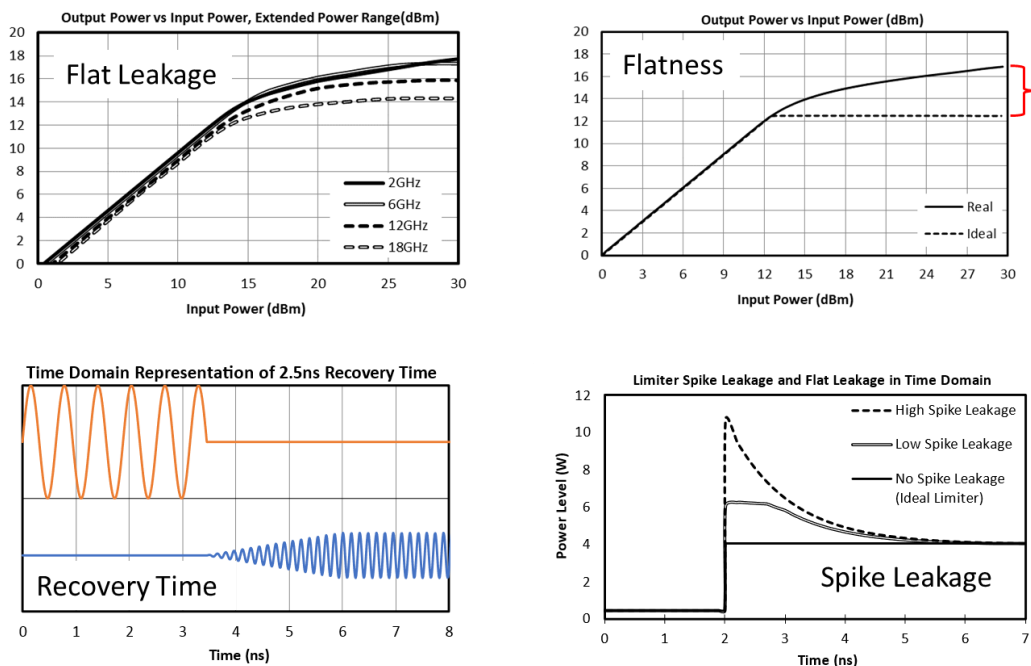


Figure 3: Graphical Depiction of Limiter Specific Specifications

While the typical RF specs are still important to optimize, without optimizing these limiter specific specifications, the limiter could never be adopted by modern receiver systems since it cannot do its job of protecting from high powers in all environments modern receivers find themselves in. In the subsequent sections of this paper, we will outline why there is a market need for a new limiter technology, and then we will go over design techniques to optimize the typical RF specifications as well as how adopting a THz Schottky diode process can allow for unparalleled performance in the key limiter specific areas.

Does The Market Need a New Limiter Technology and How are People Implementing Limiters Today?

Before diving into design techniques and the performance advantages one can obtain with a THz Schottky process, it is essential to examine the current state of limiter technology and understand the

distinctions between existing limiter designs and the novel THz Schottky designs we will discuss in this paper. As the operating frequency and transmit power levels of state-of-the-art transceiver systems increase, there is a pressing demand within the RF community for innovative limiter technologies capable of meeting the evolving requirements imposed by these advancements. The advancements of these systems call for a limiter which can exhibit incredibly high linearity with low loss, a near instantaneous limiting response to stimuli, and thermal properties that allow for unaltered performance in high-power pulsed conditions. Meeting all these specifications simultaneously in a broadband limiter is no simple task, however we will make a case for the adoption of a THz Schottky process to offer unparalleled performance required of these state-of-the-art systems. Today's limiter implementations can be categorized into three main approaches: omitting the use of a limiter altogether, utilizing an in-house limiter design tailored to the specific application, and the conventional practice of procuring a COTS PIN diode limiter.

Omitting a limiter from the system involves relying solely on the power-handling capabilities of the LNA, demanding trust in both the LNA's datasheet and the end user's ability to not place the receiver in an environment with conditions that could harm the LNA. This approach often requires the use of a GaN LNA due to its high power-handling characteristics, albeit at the cost of increased DC power consumption and higher expenses. These drawbacks frequently render this strategy impractical for state-of-the-art transceiver designs, as it lacks any protective measures.

The next commonly employed approach is the in-house design of a limiter tailored to the specific system requirements. This method, while offering flexibility, carries inherent risks, notably the potential failure of the custom-designed limiter to function effectively within the system. Moreover, if the in-house limiter proves functional in laboratory settings, the absence of long-term reliability studies introduces uncertainty in its longevity within the system. It is also worth noting that the development of a custom solution demands substantial engineering resources, making it less preferable than implementing established solutions with known performance characteristics.

This brings us to the most common method implemented today which is to use a COTS PIN diode MMIC, by far the most common implementation of limiters today. This method has been sufficient for many legacy designs; however, it falls short in meeting the demands of state-of-the-art transceiver systems. PIN diode limiters are simply too narrow band and exhibit long recovery times and high spike leakages. This means that PIN diode MMICs are unable to react to stimuli instantaneously and, depending on the conditions the limiter finds itself in, the limiter may not protect the receiver. This drawback is too detrimental for most systems being designed today since these systems find themselves in environments where low loss, high linearity, and instantaneous reaction times are all required to be met simultaneously in a single limiter.

The shortcomings of the modern approach are made clear in table 1 below which compares the legacy method of limiter design with the modern THz Schottky approach used at Marki Microwave. This table clearly elucidates the massive performance advantages of the THz Schottky process in the limiter specific parameters (flatness, spike leakage, and recovery time). Here we see comparable performance between the technologies for all the typical RF specifications, however when we compare the limiter specific figures of merit, there is virtually no comparison. The legacy method is outdated and cannot compete with the THz Schottky approach when it comes to creating a high-performance limiter. As

experts in broadband diode-based component design, Marki Microwave decided to put considerable effort into solving this problem for our customers to create our line of THz Schottky diode limiters.

Parameter	Marki HLM-20PSM	Competitor 1	Competitor 2
Frequency Coverage	DC – 20 GHz	100 MHz – 20 GHz	10 MHz – 20 GHz
Package	Surface Mount	Surface Mount	Surface Mount
Technology	THz Schottky Diode	V-PIN Diode	Unlisted
Max Insertion Loss	1.5 dB	1.2 dB	2.0 dB
Typical Return Loss	15 dB	17 dB	10 dB
Flatness	2.5 dB	9.0 dB	Unlisted
Spike Leakage	Nearly zero	20.5 dBm	Unlisted
Recovery Time	Nearly Instantaneous	40 nS	100 nS

Table 1: High Level Spec Comparison of Marki Microwave THz Schottky Diode Limiters vs Industry Standard PIN Diode Limiters

Limiter Design Techniques for Optimal Performance

A Marki Microwave Schottky limiter design is based on a similar idea to a distributed amplifier. It uses a Schottky diode to clip the signal (as has been done many times before). However, to achieve higher power handling and linearity we use some other design tricks that we have access to when designing a MMIC. Specifically, we can use the ‘stack height’, or number of diodes in series, to increase the power handling and linearity. The cost is the limiting threshold which increases with stack height, something most system designers do not want. One can also use the diode area, or the size and total number of diodes in parallel to increase the power handling, at the expense of added capacitance and thus a lower cutoff frequency for the circuit. So, an actual ‘diode’ will look more like an array of diodes in a limiter, similar to how a distributed power amplifier has an array of transistors. On the actual MMIC, a small amount of inductance is added to the capacitive diodes to provide a broadband 50Ω match which is shown as the 50Ω unit cell in Figure 4. This effectively creates a synthetic transmission line where the small inductance is the series L and the diodes to ground act as the shunt C.

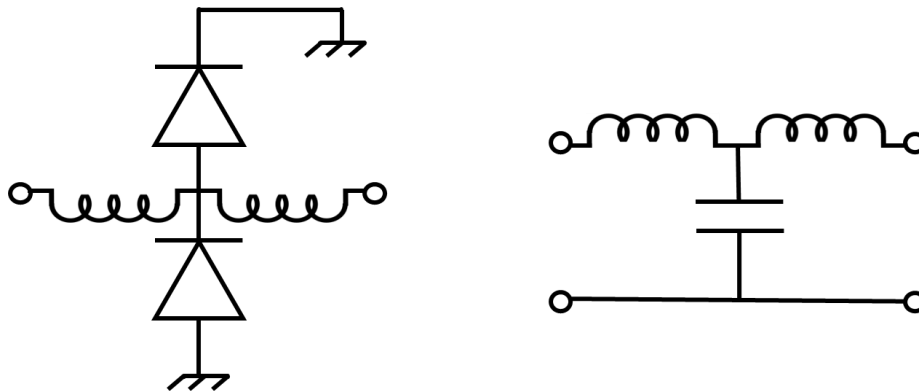


Figure 4: Limiter with Inductance Creating Synthetic Transmission Line To Provide Broadband 50Ω Match.

Then we combine stages with different power handling values and limiting thresholds to make a complete limiter. In general, the higher power handling sections are closer to the input, and the lower limiting or ‘clean up’ cells are towards the output. For this reason, these limiters behave identically

forwards and backwards in small signal, but they have different power handling one way versus the other. Figure 5 below shows what these cells may look like, however only half of the cell is being shown in this figure. In reality each diode array is an antiparallel set of diode arrays.

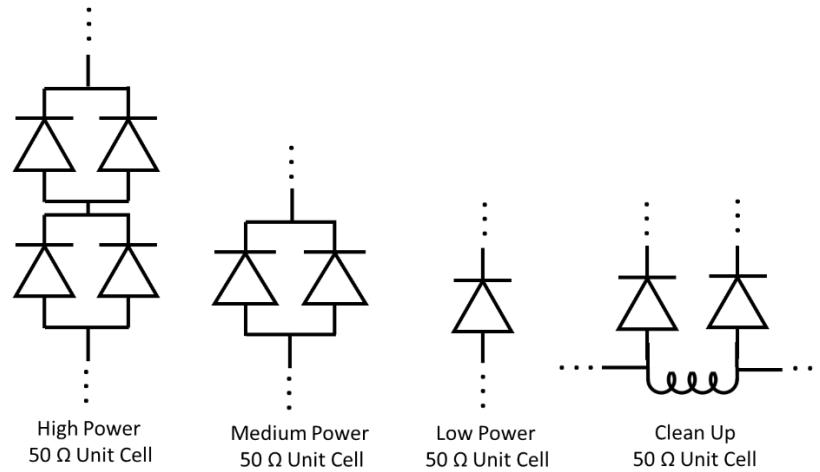


Figure 5: Diode stacks and diode arrays for various power handling and leakage levels

The high-power cells find themselves at the front of the limiter and their job is to absorb most of the incident power. This cell does not do much limiting as that is handled by subsequent cells. This cell is implemented using a high diode area (parallel diodes) and many of these diode arrays in a stack. The parallel diodes offer higher power handling, and the series diodes offer some small amount of limiting. Next, medium-power cells are used to step down the flat leakage while retaining high power handling. This is achieved by reducing the number of series diodes in the stack while adding additional diodes in parallel. Increasing diode area while simultaneously reducing the series diodes reduces flat leakage while retaining high power handling. Lastly, we have low power cells which are used to set the final flat leakage level and improve flatness. At this point in the limiter, the power handling has been taken care of by the high power and medium power cells, however the flat leakage is not optimized. The goal of the low power cells is to add or remove series diodes to vary the final flat leakage level for the specific limiter design. These low powered cells flow into what we call cleanup cells. These cells do not have a major affect on the power handing and typically are designed to have the same leakage level as the low powered cells. These cleanup cells have a direct impact on the flatness of the limiter and allow for extremely flat leakage levels out to very high incident powers. In the next section we will go over how these design techniques affect limiter performance, as well as how adopting a THz Schottky process will improve the limiter specific figures of merit.

Performance Advantages of THz Schottky Diode Limiters

Having explored limiter specifications and key design techniques, we can now delve into the performance benefits of these techniques, particularly when implementing a THz Schottky diode process. The previous section outlined design methods which primarily impact insertion loss, return loss, flat leakage level, and flatness. The limiter specific specifications of spike leakage and recovery time are dominated by the switching speed of the diodes and are optimized through manufacturing process.

Below is a list of key limiter specifications and the performance advantages one can achieve through design tricks and process technology.

Typical RF Figures of Merit

Insertion Loss and Return Loss – Given that the limiter typically precedes the LNA, it is important that a limiter has low insertion loss and high return loss to minimize its impact on the signal path during non-limiting conditions. Using the synthetic transmission line technique outlined above of adding a small amount of inductance to cancel out the capacitance of the diodes allows for a broadband match and maximum power transfer when not limiting. At Marki Microwave, we have shown losses as low as 1.5dB out to 40GHz by implementing this design technique.

Flat Leakage Level – The flat leakage level is decided by the limiter designer and is varied through the careful selection of diode stacks in the medium and low powered cells. Through the careful selection of series and parallel stacks, one can create arbitrary limiting thresholds. At Marki Microwave we have been able to use this to design limiters with a wide variety of flat leakage levels from +7dBm to +18dBm.

Limiter Specific Figures of Merit

Flatness of Limiting Curve – The flatness of the limiting curve, defined as the deviation from flat leakage at high incident power levels, is dominated by the low power and cleanup cells in the design techniques outlined above. By simply adding more cleanup cells to the output, one can flatten out the response at the expense of some added insertion loss. We have used this technique at Marki Microwave to design limiters with industry leading flatness using carefully selected low power and clean up cells.

Spike Leakage – Spike leakage is the first limiter specific metric which we have not yet discussed how to optimize. This is because optimizing this parameter requires optimizing the diode you are using, typically changing from the industry standard PIN to a faster THz Schottky diode. To understand why this simple change optimizes this parameter, it requires an understanding of why spike leakage exists at all.

When the input signal exhibits a rise time faster than the diodes' switching speed, a portion of the input signal leaks through the limiter, resulting in potentially catastrophic damage. Additionally, PIN diode limiters are engineered to switch to high resistance when in the 'off' state, whereas Schottky diodes switch open. The PIN diode limiter's reliance on current flow to facilitate switching introduces an inherent time delay during the activation and deactivation processes. This all comes together to generate a much slower switching speed in current state-of-the-art PIN limiters versus what is achievable in a THz Schottky diode limiter. Comparing it to the rise time of a 1GHz signal in Figure 6, it becomes evident that the PIN technology switches too slowly, indicating a potential for significant spike leakage.

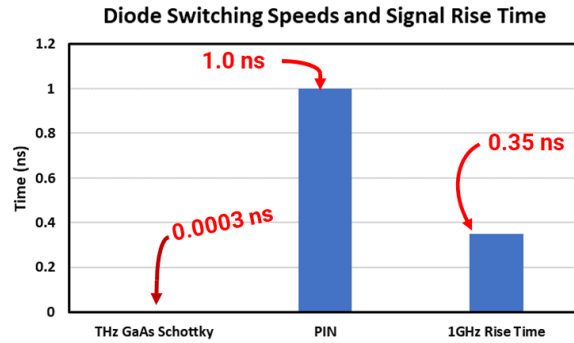


Figure 6: Switching Speed of THz Schottky Diodes, PIN Diodes, and Switching Speed of a 1GHz Signal.

To mitigate spike leakage effectively, it is imperative that the diodes respond instantaneously to incoming pulses, initiating the limiting action as soon as a pulse enters the system. This immediate response ensures minimal spike leakage, even when dealing with signals of low duty cycles where the pulse is incident for only a small amount of time. The presence of high spike leakage introduces discrepancies between the pulsed and CW characteristics of PIN diode limiters, especially when operating at low duty cycles. This inconsistency can pose challenges for system designers who aim to maintain consistent limiter performance across a range of input powers and duty cycles.

In order to verify the performance advantage of a faster switching diode in the lab, we use the experimental setup in Figure 7 below and take advantage of the fact that as you reduce the duty cycle, the energy that makes it through the limiter should also go down if the limiter exhibits high spike leakage.

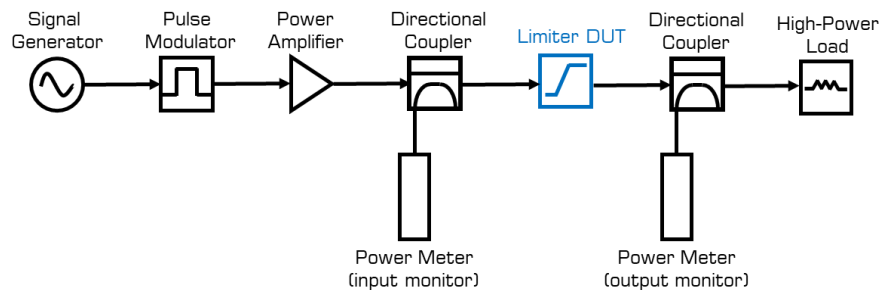


Figure 7: Experimental Setup to Measure Limiter Spike Leakage

In this experimental setup, high-power couplers are positioned at both the input and output of the limiter with power meters connected to the coupled ports to track the power entering and exiting the limiter. A high-power load is affixed to the output of the final coupler. To assess spike leakage performance, a high-power pulsed signal is introduced at the input of the initial coupler. The pulsed input power level is gradually increased while simultaneously monitoring the corresponding output power to obtain plots of output power vs input power over varying duty cycles.

This is the experimental setup we use in our lab at Marki Microwave to characterize spike leakage with Figure 8 showing the results of our testing. The first objective was to examine the correlation between pulsed and CW input versus output power relationships. To investigate this, we employed a 1% duty cycle and determined the input versus output power relationship at three different frequency points

within the limiter's operational range. The results revealed a substantial overlap between the pulsed measurements and the anticipated CW measurements. Then, with our initial assumptions validated, we decided to characterize the spike leakage over more stringent conditions. Up to this point, the measurements have been taken with a very low duty cycle of only 1%, however it's important to note that modern receivers often expect high powered pulses with much longer duty cycles. With this in mind, we proceeded to investigate the limiter's performance across a spectrum of duty cycles, progressively increasing the duty cycle during each test iteration. Our findings demonstrate that regardless of pulse conditions, the leakage remains consistent. This is illustrated in the figure below, encompassing four duty cycles of 1%, 5%, 15%, and 30% as well as the CW case.

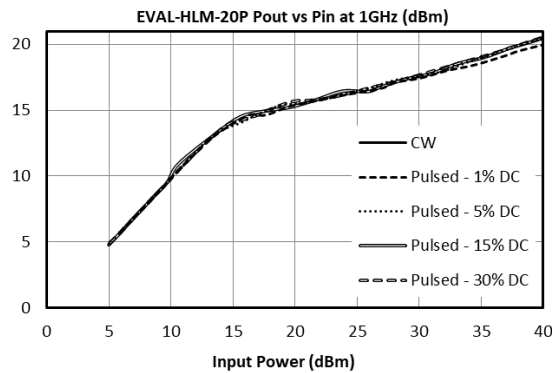


Figure 8: Spike Leakage Test Results on Marki Microwave HLM-20PSM

Figure 8 shows a near perfect overlap of limiter response across duty cycles. This impressive result is attributed to the limiter's ability to respond almost instantaneously to stimuli, initiating the limiting action the moment a pulse reaches the diodes. This highlights the ability to obtain near-zero spike leakage through the adoption of a THz Schottky diode process. This result, illustrating instantaneous turn-on speeds, naturally leads to an inquiry regarding the limiter's turn-off speed. This is what is known as recovery time in limiters.

Recovery Time – Recovery time is important in limiters since it can create blind spots in your receiver. In something like a radar which transmits high powered pulses, we are faced with what is typically referred to as the self-jamming problem. To describe this problem, Figure 9 below shows the input power vs output power and input power vs insertion loss plots for an ideal limiter.

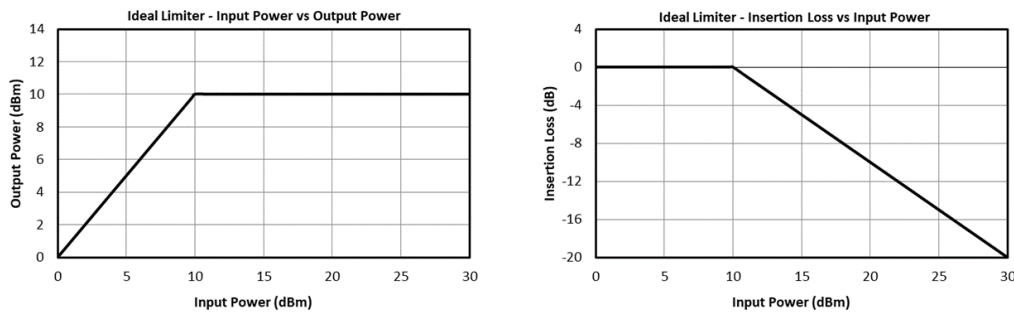


Figure 9: Ideal Limiter Input Power vs Output Power and Input Power vs Insertion Loss Response

The left plot illustrates how an ideal limiter safeguards sensitive circuitry against high-powered signals, while the right plot, depicting insertion loss versus input power, reveals a potentially adverse impact on your system. In the radar example, engaging the limiter during signal transmission (self-jamming) minimizes receiver sensitivity, blocking detection due to its high insertion loss. This disrupts communication creating a blind spot until the self-jamming signal ceases and the limiter relaxes to a low insertion loss state. In that time delay between high insertion loss and low insertion loss, you are temporarily disabling your system and, in a radar, limiting the proximity at which objects can be detected. In cases where returning pulses have short time delays (as with nearby objects), a limiter in a high insertion loss state prevents returned pulse detection entirely, making close in objects completely invisible.

To characterize this parameter in lab, it is important to accurately recreate the self-jamming problem and monitor the small signal information's recovery. Figure 10 below shows the experimental setup, as well as some time domain representations of long and short recovery times. In the time domain plots, the orange signal is the self-jamming tone, the blue signal is the small signal information of interest, and the recovery time is highlighted in red. *These plots do not display measured data and are only used to give an example of what the time domain representation of recovery time typically looks like.*

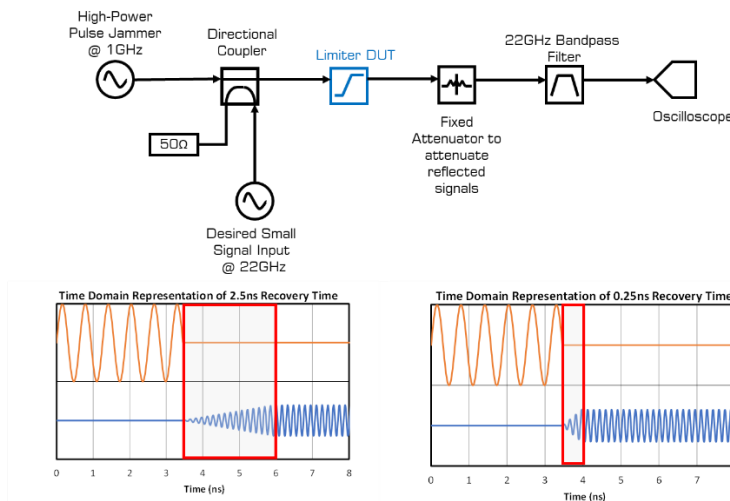


Figure 10: Recovery Time Experimental Setup and Theoretical Time Domain Representations for 2.5ns and 0.25ns recovery times

In the experimental setup above, a small signal CW tone representing the signal of interest, and a high-power pulsed tone simulating a jamming signal are injected into a coupler which feeds into the limiter. The objective is to observe the signal of interest in the time domain the instant the high-power pulse turns off, and measure the time it takes for the signal of interest to return to its full power level. This time delay is the definition of recovery time. In our laboratory setup, we utilized a Marki Microwave C13-0140 directional coupler to combine the high-power jammer and the low-power input signals. The output of this coupler was then fed into an HLM-40U, a THz Schottky limiter designed using the techniques outlined above. A Marki Microwave FB-2250 bandpass filter was used to select the 22GHz signal of interest, and to mitigate high-power reflections from the jammer signal, we placed a 10dB attenuator between the DUT and the filter. Finally, the output was connected to an oscilloscope to capture and analyze the measured output, allowing us to measure the limiter's recovery time. Based on

our findings when measuring spike leakage, we expect that the recovery time of the limiter will be nearly instantaneous and behave close to the bottom right of Figure 10. What we found in lab when measuring this parameter is shown below in Figure 11.

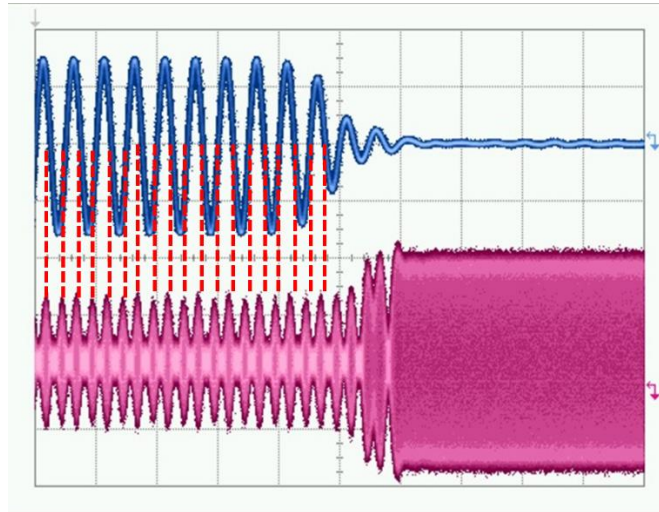


Figure 11: Recovery Time Measured Results on THz Schottky Diode Limiter

Upon immediate inspection, it is clear that the pink trace differs significantly from the expected recovery time responses in figure 10. Notably, the measured waveform exhibits distinct peaks while the high-power jammer tone is still active. A closer analysis of this plot reveals a noteworthy pattern: these peaks coincide precisely with the zero crossing points of the large signal tone representing the jammer. What this behavior implies is that the HLM-40U responds to the jammer's zero crossing as if there were no jammer present at all, instantaneously transitioning to a low insertion loss state. This result is not entirely unexpected since in a way, spike leakage and recovery time can be considered as inverses of each other. Recovery time describes how long it takes a limiter to turn off, and spike leakage is a measure of how long it takes to turn on with the caveat that spike leakage is a measurement of energy (power x time). This result makes even more sense when considering that the limiters tested employ Schottky diodes manufactured using a terahertz (THz) process, enabling them to switch on and off at exceptionally high speeds and offer near instantaneous recovery times.

Conclusion

In conclusion, this paper has emphasized the vital role of limiters in modern RF receivers, emphasizing the need for higher-performance limiters than the solutions commonly implemented today. We discussed the significance of limiters in protecting sensitive circuitry from high-power signals, using a radar system as a prime example. We explored key figures of merit for limiters, distinguishing between typical RF specifications and limiter-specific specifications like flat leakage, flatness, recovery time, and spike leakage. We discussed the current landscape of limiter technologies, categorizing modern approaches into three distinct categories. Our analysis underscored the limitations of existing methods and presented a compelling case for the adoption of THz Schottky diode technology, owing to its remarkable performance advantages.

Our discussion of limiter design techniques revealed the potential engineering tricks involved in optimizing parameters like low loss and high flatness by utilizing stack height, diode area, and series inductance. Moreover, we discussed how THz Schottky diode technology revolutionizes limiter design, benefiting limiter-specific figures of merit like spike leakage and recovery time. This process exhibits incredibly fast switching speeds in the diodes, ensuring minimal spike leakage and recovery times even under the stringent conditions modern receivers find themselves in today.

Future progress in limiter development will encompass comprehensive exploration of reliability considerations, including characterizing the lifetime vs. pulsed power performance under various operational parameters. Additionally, research and development efforts may focus on advancing high-power limiters, addressing the evolving demands of modern RF applications. These advancements are crucial to ensure that limiters continue to meet the ever-expanding requirements of today's dynamic RF landscape.

In summary, THz Schottky diode limiters offer a transformative solution to meet the rigorous demands of modern RF receivers. They strike a balance between low loss, high linearity, and instantaneous response, enhancing receiver sensitivity and performance across various applications. As the RF landscape evolves, THz Schottky diode limiters stand as a compelling choice for protecting sensitive circuitry while maintaining system performance.