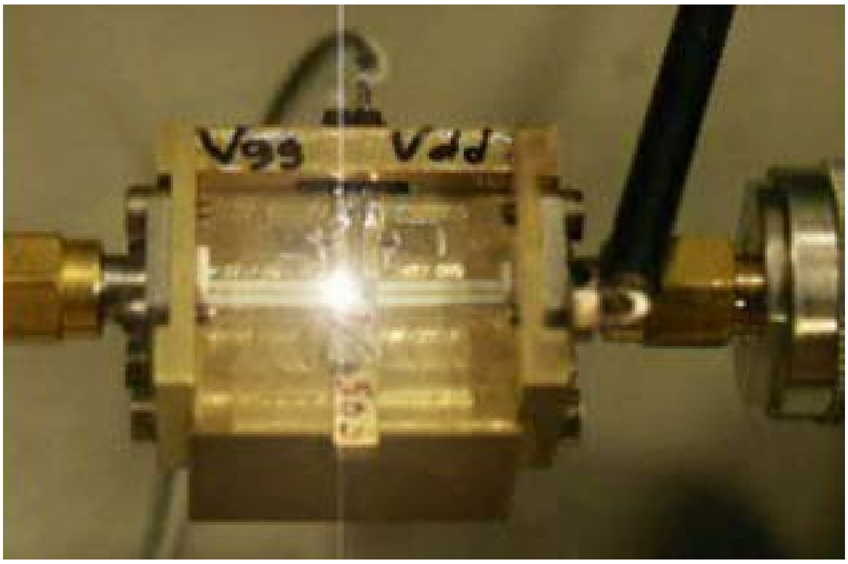
Investigation of HPM Front-door Protection Devices and Component Susceptibility

Tony Nilsson, Rolf Jonsson



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Technical report

November 2005

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Report title

Investigation of HPM Front-door Protection Devices and Component Susceptibility

Abstract

An extensive investigation of front-door protection devices i.e. limiters has been made. The report contains both new results and summarizes results from previous measurements done on limiters. Both HPM and UWB measurements on various limiters have been done in order to characterize the limiters. The measurements show that not all limiters are suitable as protection against HPM and UWB pulses. The limiters that were found to provide the best protection are limiters based on diode technologies. PIN- and Schottky-diodes generally shows very good performance and they fulfil many parameter restrictions that have been set by FOI.

This report also includes initial results from LNA (Low Noise Amplifier) susceptibility testing. HPM injection measurements have been done on one type of LNA. The destruction levels of the LNAs were investigated by changing different input parameters, such as pulse width, biasing etc. The result shows that there are up to 9 dB in difference between destruction levels, depending on the input parameters. A further study on LNAs will be done, the study will also be expanded, and in total about 150 LNAs from three different types of LNAs will be tested.

Keywords

HPM, UWB, Front-door protection, Limiter, LNA

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Rapportens titel

Undersökning av HPM framvägskopplingsskydd och komponenttålighet

Sammanfattning

En omfattande studie av framvägskopplingsskydd, dvs. *limiters* har gjorts. Rapporten innehåller både nya mätresultat och sammanfattande resultat från tidigare mätningar. Både HPM och UWB mätningar har gjorts på olika limitrar för att karaktärisera deras prestanda. Av resultaten från mätningarna kan man se att alla limitrar inte passar som skydd mot HPM och UWB pulser. De limitrar som tillhandahöll det bästa skyddet var baserade på olika diodtekniker. PIN- och Schottky dioder visade sig överlag ha väldigt goda prestanda och de uppfyllde även många av de parameter gränser som bestämts av FOI.

Rapporten innehåller även resultat ifrån inledande tålighetsmätningar på lågbrusförstärkare (LNA). HPM injektionmätningar har gjorts på en typ av LNA. Nivåer för permanent förstörelse av lågbrusförstärkare har undersökts genom att ändra olika in-parametrar som, pulslängd, biasering etc. Resultaten visar att det är upp till 9 dB i skillnad mellan olika förstörelsenivåer, beroende på in-parametrarna. Studien kommer att fortsätta och även utvidgas, totalt kommer testerna att omfatta omkring 150 lågbrusförstärkare av tre olika typer.

Nyckelord

HPM, UWB, framvägskopplingsskydd, Limiter, LNA

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1 Background

The threat from high power microwaves (HPM and UWB) and other high power electromagnetic sources is today a reality. These sources can be military sources with high performance or laboratory sources used for research. The second can be bought by anyone from retailers, and can with relatively little knowledge be put together to functional improvised HPEM weapons. In order to prevent interference and destruction, the electronic equipment needs to be hardened, i.e. to be protected against HPM and UWB. This constitutes a threat to the modern society, which is very dependent on the function of electronics in various electrical systems. If these systems are exposed to high EM-fields, it could lead to loss of function, degradation or even permanent physical damage. A common way to handle this threat is to shield the electrical systems from the EM-environment. The trend in todays society seem also to increase the number of wireless devices, also in military applications a wireless trend can be seen. Wireless devices cannot be completely shielded, as they have an antenna that is intended to interact with the EM-environment. The limiters can be used in both military and critical civil wireless applications, it is installed to protect the front-door path of electronic equipment from permanent damage, caused by high power pulses by absorbing, reflecting or diverting them to ground. However, since it is in practice unfeasible to protect wireless systems from interference (jamming), it is recommended to keep wired connections in important and critical applications. Wired systems are easier to protect against HPM and UWB.

The Swedish Armed Forces aim to increase their participation in international peace-promoting and humanitarian operations. The Nordic Battle Group is a concept where Sweden has a leading role for an EU-based fast-reaction-force. When our armed forces are deployed in foreign battle theaters, a more extensive threat picture becomes a reality. It is conceivable that the troops will be exposed to foreign RADARs, EW (Electronic Warfare) and other more or threatening EM (Electromagnetic) environments such as HPM. As the warfare becomes more sophisticated and advanced, the need for HPM and UWB protection of military equipment used in such operations is increased.

2 Introduction

This report is intended to be a continuing part of the work done on HPM front-door protection devices and it is also a mile stone report for the project HPM protection methods for the network centric defence (E3031) from the Swedish Armed Forces (FM). This work is also to some extent sponsored by the project HPM protection technique (E3954) from the Swedish Defence Material Administration (FMV).

In this report we have characterized a number of limiters in order to investigate their response to both UWB and HPM pulses. The ideal limiter should pass a low-level signal without changing it, and clamp the signal when high-level pulses occur, Figure 2.1 show the placement and function of the limiter in a front-end structure. The measurements are done to further characterize or verify the limiter performance.

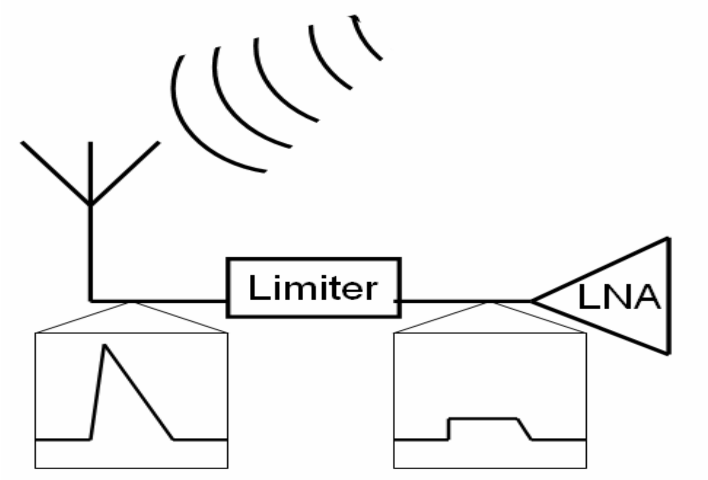


Figure 2.1 Schematic of the location and the function of a limiter.

The report mainly contains characterizing measurements of limiters, which can be used as front-door protection devices. The report also includes results from HPM measurements on one type of low noise amplifiers (LNA) have been done in order to determine the destruction levels of common front-door circuits. This has increased our knowledge of the LNA susceptibility to HPM pulses.

3 Threat definition

Most of the limiters have been tested with respect to both HPM and UWB-pulses. The different properties of these two types of HPEM pulses will be briefly described in this chapter. However, a more detailed description can be found in [1]. Figure 3.1 show the spectrum of both HPM and UWB signals.

3.1 HPM

HPM or High Power Microwaves is more or less microwave pulses with very high peak power level. One of the characteristics for HPM-signals is that the frequency content of the pulse is typically very narrow, less than 10 % instantaneous bandwidth [1]. Two parameters also of importance are the rise time and the pulse width, which usually are 5-10 ns and around 100 ns respectively. The PRF (Pulse Repetition Frequency) of a HPM-signal is typically 1 kHz or less which gives a duty cycle of about 1e-4.

3.2 UWB

The characteristics of the UWB (Ultra Wide Band) pulse are somewhat different compared to the HPM-pulse. The frequency content of the UWB-pulse is very broadband for the pulses we consider here, it can range from below 0.3 GHz up to several GHz, with an instantaneous band width of at least 25 %. The UWB-pulses also have a very short rise time and pulse width, in the order of hundreds of picoseconds and a few nanoseconds respectively. The PRF can be varied from single-pulse up to tens of kHz.

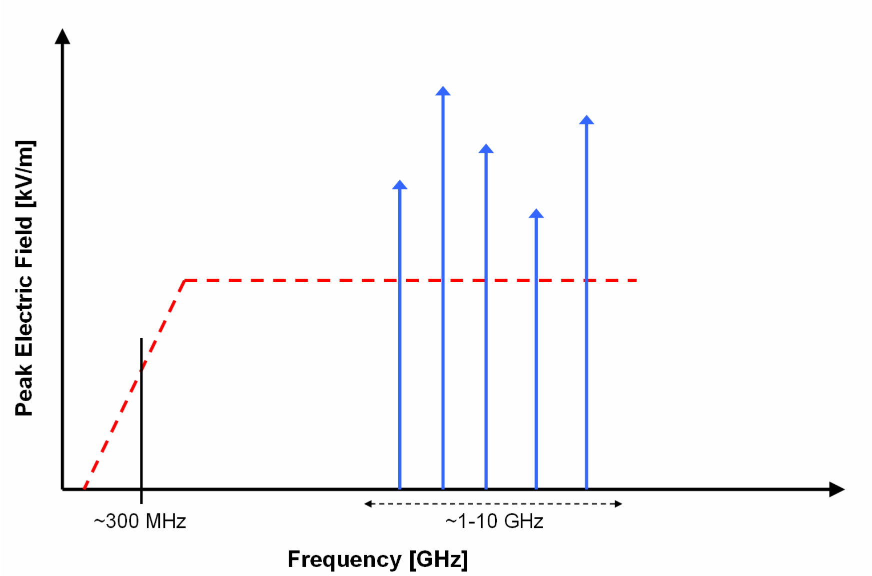


Figure 3.1 Frequency spectrums of expected HPM and UWB signals.

4 HPM and UWB Limiter Measurements

A large variety of limiters based on different technologies have been tested with both HPM and UWB pulses. All the results are not shown in this report, but all of the most recent results and a summary of results from previous reports. All these older measurement results can be found in the reports “HPM Front-door Protection Progress Report 2003” [3] and “Limiter Characterization” [2]. The older results are included to demonstrate the performance of different technologies in general. Description and schematics of the measurement set-ups is also found in the references mentioned above.

4.1 Measurement Uncertainty

The measurement uncertainty for the HPM measurement set-up has been estimated. Several parameters have been taken into account, for example losses in cables, connection and switches etc. The estimated uncertainty for the HPM power levels is 0.5 dB. The oscilloscope has about 1 % in measurement uncertainty. The detectors used for the measurements have finite rise time, 3.5 ns, which may change the shape of the pulse. Further investigation of the measurement uncertainty will be done.

The dominating uncertainty in the UWB measurements is believed to be due to the use of attenuators to regulate the power to the limiter and the power to the oscilloscope. The uncertainty of the specified attenuation of the attenuator and the real attenuation is estimated to 0.1 dB. The uncertainty due to loss in coaxial transitions is estimated to 0.1 dB at the relatively low frequencies used here. A maximum of 4 attenuators was used between the pulse source and limiter and not more than 2 attenuators were used between the limiter and the oscilloscope.

This gives a possible uncertainty of 0.1 dB in (4+5)·2 = 18 instances which yields an uncertainty of $\sqrt{18} \cdot 0.1 = 0.43$dB for the signal at the limiter input, (4 attenuators and 5 transitions). The factor of 2 at the end is due to the fact that one reference measurement of the pulse is used to calculate the input pulse of all subsequent measurements, this measurement is then scaled with the used value of attenuation to calculate the real input power, both the reference measurement and the scaling is subject to errors in the attenuators and loss in coaxial transitions.

The uncertainty for the output pulse becomes $\sqrt{2+3} \cdot 0.1 = 0.23$ dB (2 attenuators and 3 transitions).

The uncertainty of the oscilloscope is estimated to be negligible in comparison to the uncertainties in attenuators and transitions discussed above, although at very low signal level this might not be true.

4.2 Multilayer Metal Oxide Varistor (MLV), EV18N0402L

This protection device from Maida (USA) is designed to be used as a protection from electrostatic discharge (ESD) and other high voltage surges. The EV18N0402L is basically a metal oxide varistor (MOV) designed in a special way, to enable it to be used at higher frequencies. According to the specification the EV18N0402L has a maximum clamping voltage of 55 V and a maximum peak current of 1 A. The nominal working voltage is 26.5 V. This component is designed for surface mounting. To measure this component it was mounted in a fixture with female SMA connections for both input and output seen in Figure 4.1.

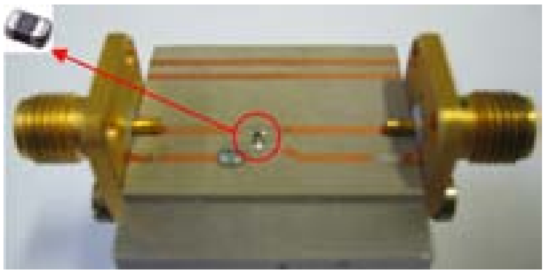


Figure 4.1 Picture of the EV18N0402L, Multilayer metal oxide varistor from Maida.

4.2.1 HPM measurement results

The HPM measurements were done at 2.4 GHz, with a PRF of 1 kHz and a pulse width of 100 ns. The frequency was selected to get a high input power. The input power was increased stepwise until the maximum output of 36.5 dBm (~4.5 W) was reached. The measurement results are shown in Figure 4.2, which contains the transmitted and the reflected power levels as a function of the input power, the input power is also plotted for reference. However the results of the measurements show that the MLV doesn't limit the transmitted power at all. The insertion loss of approximately 3 dB is constant throughout the measurements and no limiting is observed. This result is expected and due to the fact that the threshold voltage of the MLV is much higher than the voltage of the injected signal.

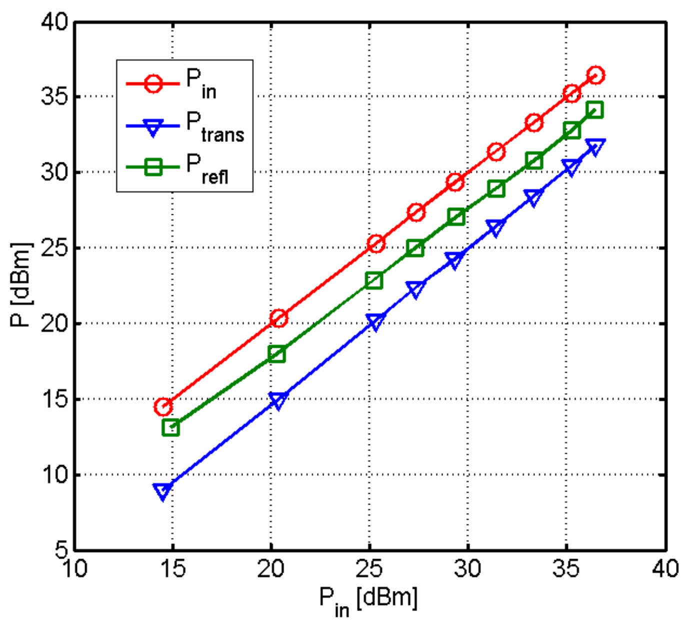


Figure 4.2 The inserted, transmitted and reflected power as function of the input power for the for the EV18N0402L Multi layer metal oxide varistor from Maida.

4.2.2 UWB measurement results

Figure 4.3 show the UWB pulse response (averaging of over 32 pulses) of the EV18N0402L MLV. Seen in the figure (to the left) is the incoming and transmitted pulse at low pulse power, already at this low level the transmitted pulse is limited, this means that the MLV introduces insertion loss at normal working levels. This loss is associated with the shunt capacitance of the MLV which limits the high frequency part of the pulse spectrum at all power levels. The right figure shows the pulse response at a higher peak pulse power level, in this case the MLV is limiting the input power but the pulse is too fast to be limited to the MLV max leakage specification (55 Volt) and higher subsequent measurements showed that higher pulse input power resulted in even higher MLV output power. A moderate leakage occurs throughout the measurements, the leakage energy at the maximum rated peak input power was 180 nJ (at 670 nJ input pulse energy) and this is believed to be above the damaging threshold of some front-end circuits. In this case, the transmitted energy will obviously depend on the pulse width. The time shift between reference pulse and limited pulse in figure 4.3 is due to difference in the measurements setup between limited pulse and reference pulse and only to a minor part due to time delay in the MLV.

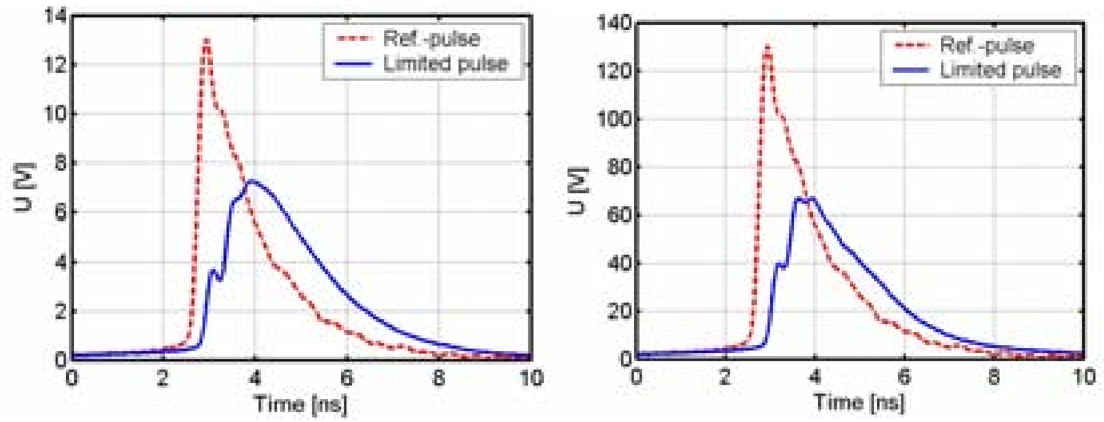


Figure 4.3 To the left the transmitted pulse is already limited at low levels, to the right the pulse peak is somewhat flattened but not according to the MLV maximum leakage specification, which shows that the EV18N0402L is not working as a proper limiter for UWB microwave pulses.

4.3 SRC CG75L

The CG75L, from SRC Devices (USA) is a gas discharge tube (GDT). It is designed to protect electrical equipment from damages caused by high voltage transients induced by lightning, inductive switching, or from other sources. The CG75L has an axial design with connection leads, these leads are cut as short as possible to minimize losses in the inductive leads. The maximum current rating for the CG75L was 5 strikes of 20 kA pulse with a 8/20µs (8 µs rise time and 20 µs pulse width) pulse shape. Figure 4.4 shows a schematic figure of the CG75L. In the measurement, the GDT was mounted in a fixture with SMA connections for both input and output and a separate connection to ground. The threshold voltage of the CG75L is 75 V and the arc voltage 10 V (I = 5A minimum). The arc voltage is the voltage required to maintain the arc.

Figure 4.4 Schematic figure of the GDT CG75L from SRC Devices.

4.3.1 HPM measurement results

The frequency in the measurements was 6.0 GHz, the PRF was 1 kHz and the pulse length was 100 ns. The input power was stepwise increased to the maximum output of 33 dBm (2 W). The measured parameters are shown in Figure 4.5 which contains transmitted and reflected power levels as a function of the input power, the input power is also shown for reference. It should be mentioned that the reflected power is under the noise floor in the beginning of the measurements, therefore the flat behavior. The GDT CG75L behaves much like the EV18N0402L Multi layer metal oxide varistor. The insertion loss of approximately 3 dB is constant throughout the measurements and there is no limitation of the transmitted power. As in the case with the MOV this result is expected and due to the fact that the threshold voltage of the GDT is much higher than the voltage of the inserted signal.

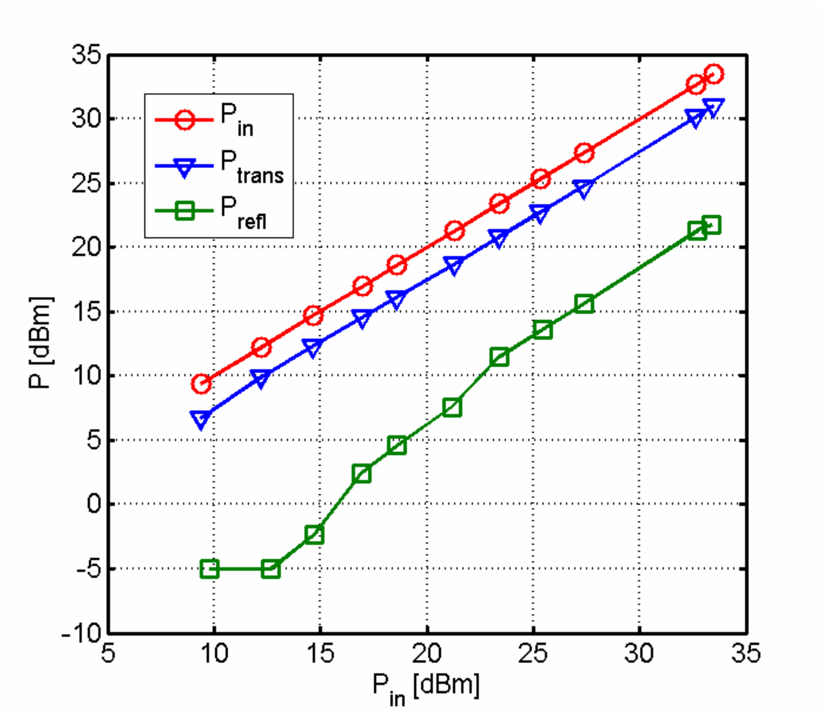


Figure 4.5 The inserted, transmitted and reflected power as function of the input power for the GDT CG75L from SRC Devices.

4.3.2 UWB measurement results

Figure 4.6 show two UWB pulse responses (averaging of over 32 pulses) of the CG75L GDT. To the left is the response of the GDT when the incoming pulse is below the threshold level of the GDT, at this low level no limiting action is observed in the GDT. To the right is the pulse response with a peak pulse level well above the threshold level is shown. Just as in the low level case, the limiter is not limiting the input pulse. The reason why the GDT is not triggered by the high level pulse is probably that the pulse is too short to trigger an arc in the GTD. Most of the energy is leaking through the GDT in the measurements. The maximum leakage energy was to 650 nJ (at 670 nJ input pulse energy) and this is believed to be over the damaging threshold of most representative front-end circuits. Again, a longer pulse would presumably give larger leakage energy. The relative difference between input and output power is equal at low and high pulse power and due to the small signal filter characteristic of the GDT. The reason why the CG75L had higher small signal loss in the HPM measurements is the higher frequency of the signal used in those measurements. The time shift between reference pulse and limited pulse in figure 4.6 is due to difference in the measurements setup between limited pulse and reference pulse and only to a minor part due to time delay in the GDT.

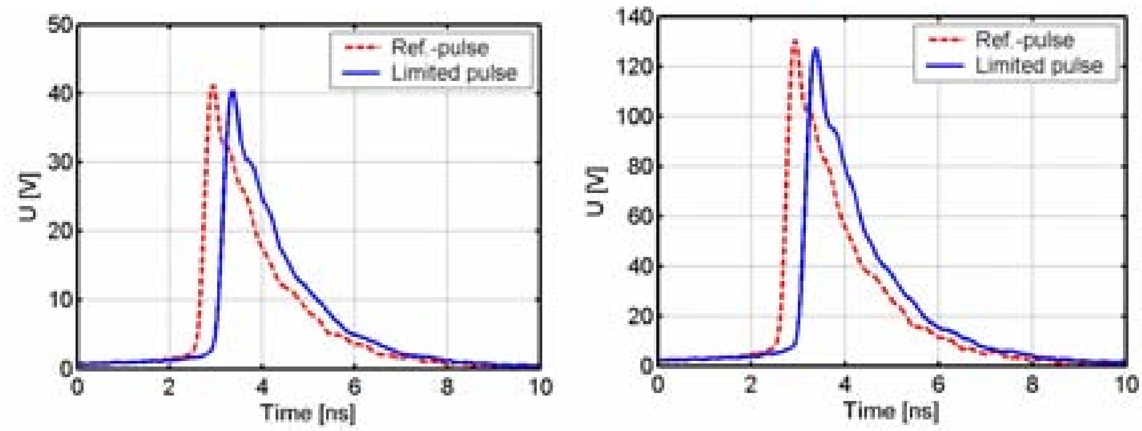


Figure 4.6 To the left the incoming and transmitted pulse at low signal level is shown, to the right the corresponding pulses at high signal level is shown. The GDT CG75L shows no limiting action in either case.

4.4 Triquint TGL2201-EPU

The TGL2201 from Triquint (USA) is a limiter based on VPIN-diodes. The limiter is designed in a GaAs MMIC process. Unfortunately most GaAs MMIC processes does not offer PIN diodes. Some of the key features of the limiter is the 3 to 25 GHz bandwidth, low flat leakage and a moderate power handling capability of 5 W i.e. 37 dBm CW. The TGL2201 is mainly intended to be used in military radars as protection in the front-end receiver chain. Figure 4.7 show a picture of the Triquint TGL2201-EPU limiter.

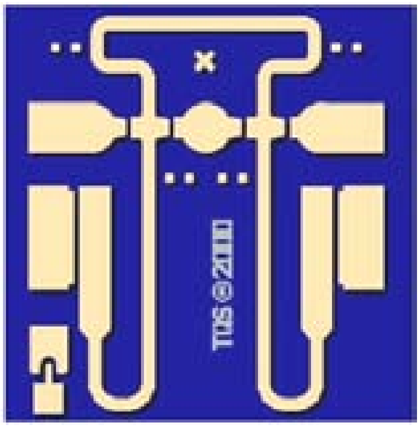


Figure 4.7 Picture of the Triquint TGL2201-EPU limiter MMIC chip.

4.4.1 HPM measurement results

The HPM measurements were done at 2.4 GHz, with a PRF of 1 kHz and a pulse width of 100ns. The input power level starts at 14 dBm and is stepwise increased to 36.5 dBm, which is the maximum input power available at that frequency. The measurements show good results and the maximum leakage power from the TGL2201 is below 17 dBm. This corresponds to about 5 nJ for a 100 ns long pulse, thus sufficient to protect an LNA. The small insertion loss was between 1 to 2 dB. The summary of the of the transmitted, reflected and input power measurements is shown in Figure 4.8. The measurements show that this limiter could be suitable as protection of front-end circuits. The high reflection level at low input power in figure 4.8 is related to noise in the detector rather than reflected power.

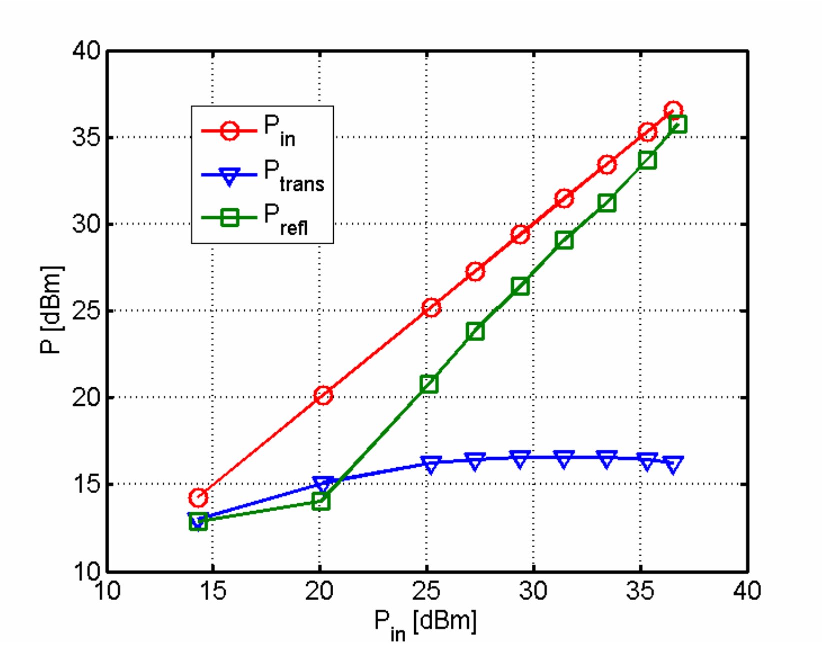


Figure 4.8 The inserted, transmitted and reflected power as function of the input power for the TGL2201from Triquint.

4.4.2 UWB measurement results

UWB-measurements were also done on the Triquint TGL2201. In these measurements a PRF of 1 kHz was used. The reason for choosing 1 kHz PRF was to stress the TGL2201 to the maximum. The input power starts at about 6 dBm (0.4 V) and is stepwise increased to 53 dBm (100 V). The transmitted pulse is limited to between 8 to 15 dBm (0.6 to 1.2 V), depending on the input power level. The apparent saturation of the limiter towards high input pulse power is related to a negative return voltage pulse and could probably be dealt with by including a DC return in the measurement setup. However, even including the return pulse this limiter is within 1 dB of the specified max leakage value for the range of rated input power. The transmitted energy is also limited to safe levels for the front-door circuits. Figure 4.9 show the UWB-pulse responses of the TGL2201. The maximum leakage energy was 26 pJ at an input pulse energy of 0.65 μJ, this is believed to be a safe level for LNAs. It seems reasonable to assume that the leakage energy will be acceptable also for pulses with much longer pulse width.

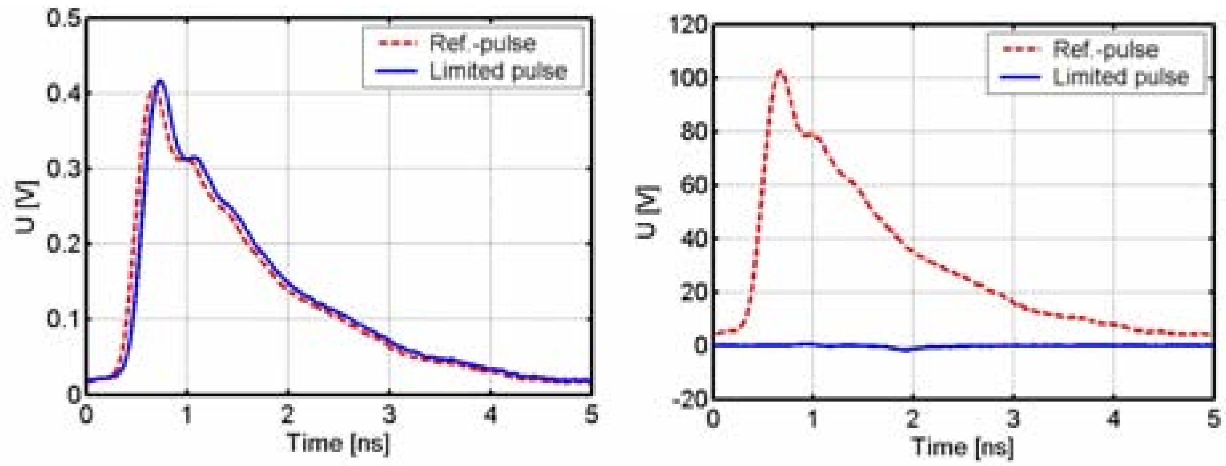


Figure 4.9 To the left the incoming and transmitted pulse at low signal level are shown, the TGL2201 is not limiting the UWB pulse. To the right the corresponding pulses at high signal level are shown. The TGL2201 is now limiting the UWB pulse very efficiently.

4.5 Previously Tested Objects

The following limiters or front-door protection devices have been selected among many previously tested devices. The intention is to give a survey of how well the different technologies work as protection against HPM and UWB pulses.

4.6 Omniyig OLP3226A

The Omniyig (USA) OPL3226A is coaxial limiter for the 2-8 GHz frequency band. The specified maximum leakage is +19 dBm with a maximum peak and CW input power of 100 W and 2 W respectively, with a PRF of 1 kHz and a pulse width of 1 µs. Figure 4.10 show a photograph of the limiter. It is designed with coaxial connections, with female / male SMA for output and input respectively. The limiter is based on PIN diode technology and has a frequency range of 2.0 to 8.0 GHz, with an insertion loss of less then 1.2 dB for the mentioned frequency band.

Figure 4.10 Picture of the Omniyig OLP3226A limiter.

4.6.1 HPM measurement results

The measurements on this component were done at 6 GHz, with a PRF of 1 kHz and a pulse width of 100 ns. The input power to the component starts at 12 dBm and is stepwise increased to 33 dBm. Figure 4.11 show the measured result, the transmitted and reflected power as a function of the input power is measured. The limiter starts to limit the transmitted power at about 12 dBm of input power. The maximum transmitted power is about 19 dBm, which is sufficiently low to protect an LNA, at least for a pulse width of 100 ns.

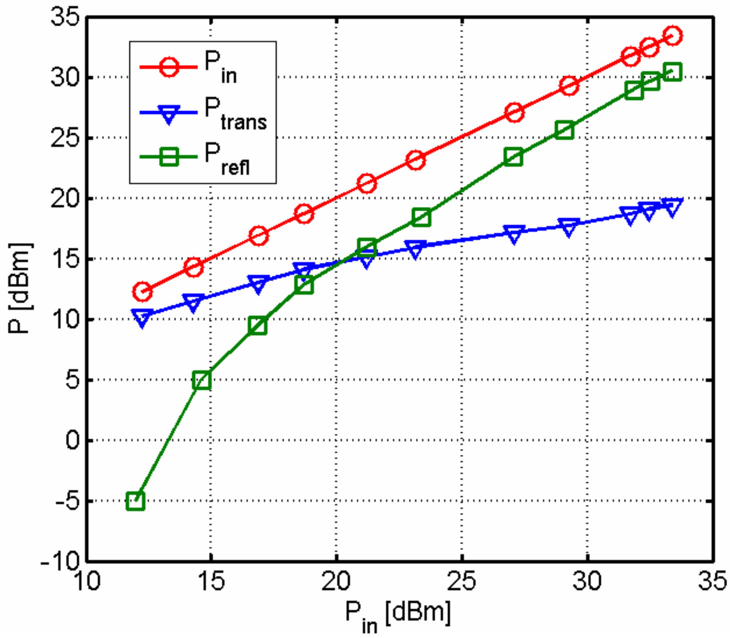


Figure 4.11 The transmitted and the reflected power as function of the input power for the Omniyig OLP3226A limiter.

4.6.2 UWB measurement results

The Omniyig OPL3226A was also tested with UWB-pulses (averaging of over 32 pulses). Figure 4.12 show (to the left) the incoming and transmitted pulse at low pulse power, the pulse distortion visible in the graph occurs because the main power of the pulse spectrum falls outside the pass-band of the limiter. Figure 4.12 show (to the right) a higher power input pulse and the corresponding transmitted pulse. As can be seen the pulse is effectively limited. Although some spike leakage occurs (peak leakage power 26 dBm corresponding to a voltage of 4.5 V) the leakage energy at the maximum rated peak input power was only 0.6 nJ (at 64 nJ input pulse energy) and this is believed to be well below the damaging threshold of representative front-end circuits. It seems reasonable to assume that the leakage energy will be tolerable also for longer pulse widths. As in former measurements the time shift between reference pulse and limited pulse (in the right figure) is due to difference in the measurements setup between limited pulse and reference pulse measurements and only to a minor part due to time delay in the TGL2201.

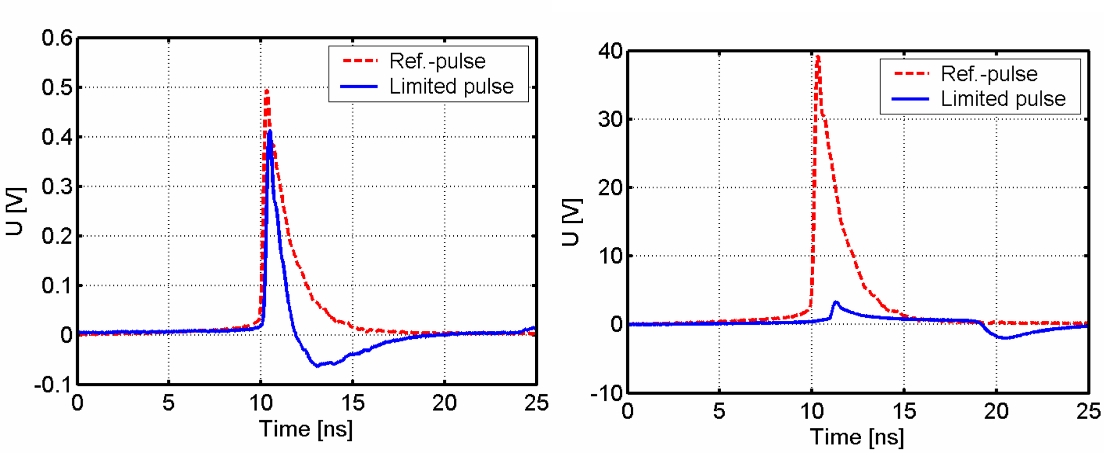


Figure 4.12 To the left the Incoming and the transmitted pulse below the limiting threshold is shown, to the right incoming and transmitted pulse at the limiters rated maximum peak power is shown.

4.7 Microsemi GG77311-05

The GG77311-05 limiter from Microsemi (USA) is designed to operate in the 2 to 18 GHz band. The maximum rated power is 2 W CW and 200 W peak and the leakage power transmitted through the component should not exceed 20 dBm, according to the specification. It is not clear which technology that is used in this limiter, but it is probably some kind of diode-technology, PIN or Schottky. It seems to employ a fast circuit that trigger the main diode to avoid spike leakage. A photograph of the GG77311-05 is seen in Figure 4.13.

Figure 4.13 Photograph of Microsemi GG-77311-05 limiter.

4.7.1 HPM measurement results

The HPM measurements were done at 6 GHz. The input power starts at –15 dBm and is stepwise increased to 33 dBm. The GG77311-05 starts to limit the input power at approximately 12 dBm of input power. The maximum leakage power is about 15 dBm, which is seen in Figure 4.14. The insertion loss is also relatively small before the limiter starts to clamp. This makes it suitable for protection for of front-end circuits. Figure 4.15 summarizes the HPM measurements.

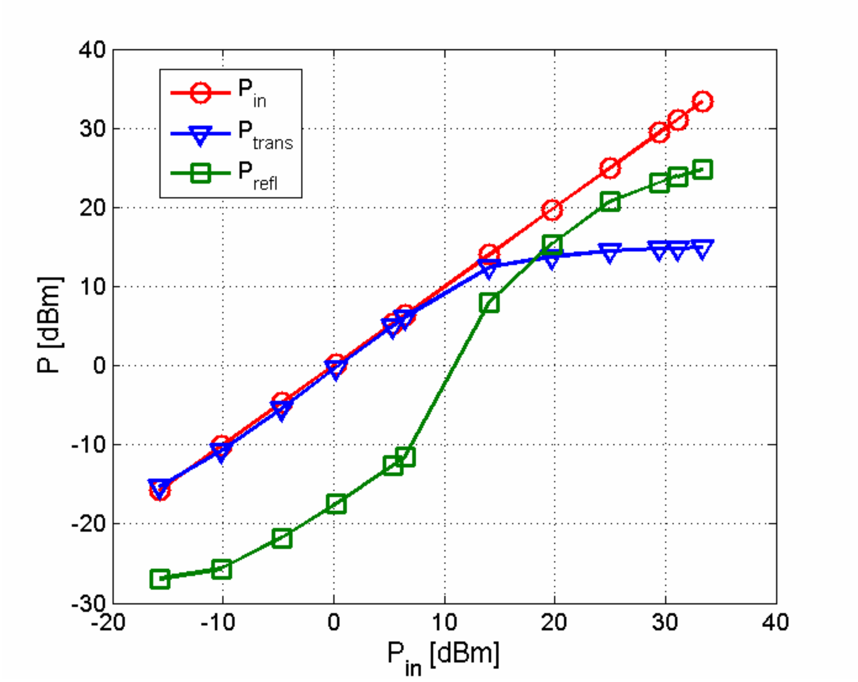


Figure 4.14 The Reflected and the transmitted power as a function of the input power.

4.7.2 UWB measurement results

Pulsed UWB (averaging of over 32 pulses) measurements has been done on the Microsemi GG77311-05. In Figure 4.15 are the input (reference) and output voltage waveform of two measurements, low input power (left) and high (right) are shown. As can be seen the higher power pulse is effectively limited but a negative voltage pulse is detected after the main input pulse. This is probably due to the uni-polar nature of the excitation in combination with the absence of a DC return for the limiter other than the measurement equipment (a dc return is recommended by the manufacturer). The pulse distortion in the low power measurement is again related to the pulse power being outside the limiters pass-band. The GG77311-05 shows good results in both the HPM and the UWB measurements and is believed to be suitable as front-door protection. The maximum measured leakage pulsae energy was 15 pJ at an input pulse energy of 7 nJ, this is believed to be a safe level for LNAs.

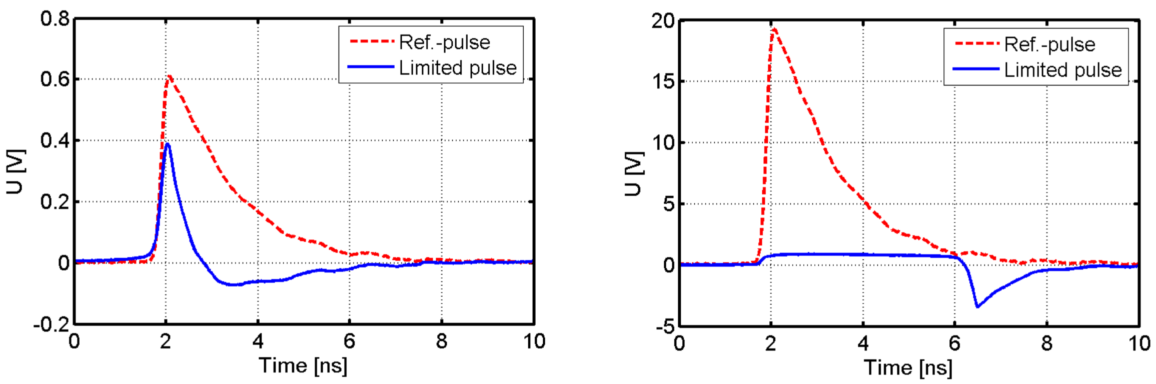
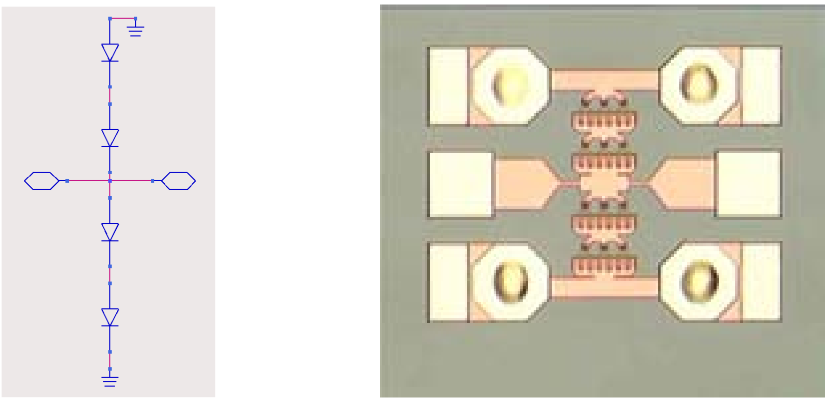


Figure 4.15 Input and output voltage waveform of the GG77311-05 for an input power below the limiting threshold (left) and above (right).

4.8 FOI GaAs MMIC Schottky-diode

The FOI designed Schottky-diode was fabricated in the OMMIC ED02AH process, small signal and CW measurements has been reported elsewhere [5]. The Schottky anode is processed in the gate metal step, enabling a line width of 0.2 µm. This enables a small diode capacitance and thereby broadband performance but limits the current carrying capacity of the diode. The realized limiter consists of two series connected diodes connected in shunt with the transmission lines and 2 series connected diodes connected with opposite polarity in shunt with the transmission line, see Figure 4.16 (a) and (b). The reason for using two series connected diodes of each polarity instead of a single diode of each polarity was to raise the limiting threshold of the circuit. In retrospect a single diode of each polarity might have been better as the use of two diodes raise the on-resistance of the shunt path during limiting and thereby increase the amount of power dissipated in the diodes compared to the power that is reflected back towards the source due to the impedance mismatch that appear on the transmission line when the diodes start to conduct.



(a) **(b)**

Figure 4.16 FOI Schottky-diode limiter schematic (a) and photography (b).

4.8.1 HPM measurement results

HPM measurement results for the limiter is shown in Figure 4.17, the measurements are pulsed narrow band measurements. The measurement was done at 6 GHz and the measurement consists of a burst of 32 pulses, with a rise time of approximately 5 to 10 ns and a pulse width of 100 ns. The agreement between simulated and measured limiting behavior was quite good [5] but the limiting characteristic was not flat enough for the device to be considered as a good limiter. It is encouraging though that the device model seems to be useful for this type of design. This limiter suffered irreversible breakdown at an input power of 30 dBm, with a 100 ns pulse length and a 10 % duty cycle, i.e. equivalent to a pulse energy of 0.1 µJ.

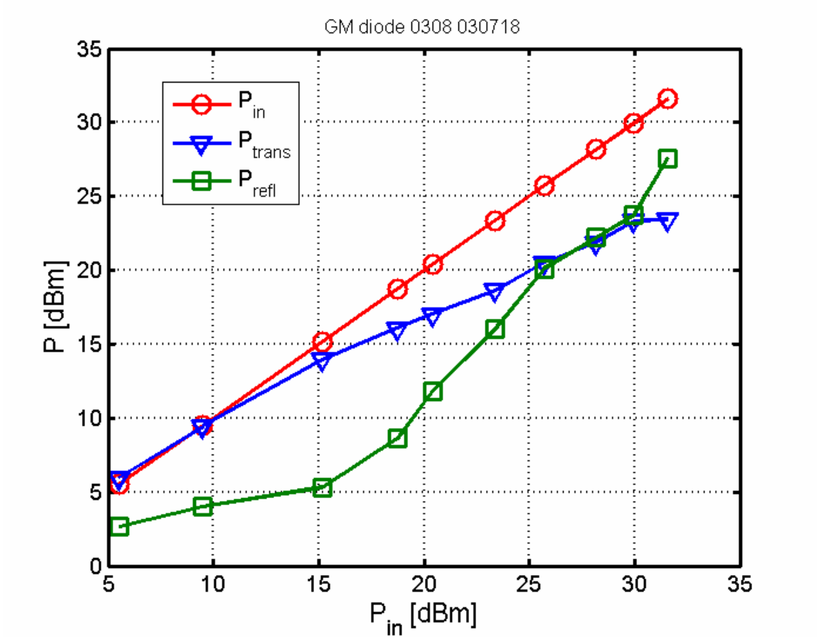


Figure 4.17 Input and transmitted peak power as a function of the input peak power from measurements on the MMIC Schottky diode.

4.8.2 UWB measurement results

UWB measurements were also done on the FOI Schottky-diode, using the same set-up as for previous measurements. The result is shown in Figure 4.18, the input pulse and the transmitted pulse. This small Schottky-diode limiter has no problem limiting the fast pulse, but when increasing the peak voltage, the limiter current saturates and the transmitted power from the limiter is too high. The Schottky-diode limiter was subjected to pulses of up to 28V (15 W) without failure.

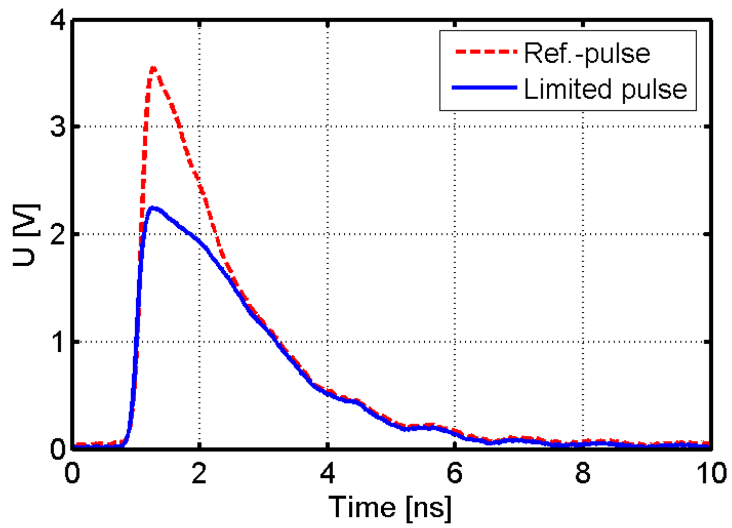


Figure 4.18 Input and output voltage waveform measured on the MMIC Schottky diode.

4.9 Summary

Many kinds of limiters have been tested and evaluated. Not all limiters are suitable as protection against HPM and UWB pulses. As seen from the tests, limiters based on diode technologies seem to have a good overall performance. Especially PIN-diode limiters are suitable as HPM and UWB front-door protection. These limiters are both fast in response time and clamps relatively high power levels. Due to the fast response times is the spike leakage minimized or almost non-existent. The diode limiters also have broad bandwidth in general.

The other less promising limiters, such as MOVs and GDTs and other types of limiters, might not be suitable as front-door protection for applications in the microwave range. The power levels used in theses measurements might also be to low to trigger some of the limiters. However these limiters should not be completely excluded, as some types could be used as a first stage protection, clamping the high power levels, while the diode limiter cleans up remaining power and clamps the fast transients.

The susceptibility levels of the limiters were not tested. It is of interest to know the breakdown levels for different pulse widths. This parameter might be investigated in the future.

5 Susceptibility Measurements of Low Noise Amplifiers

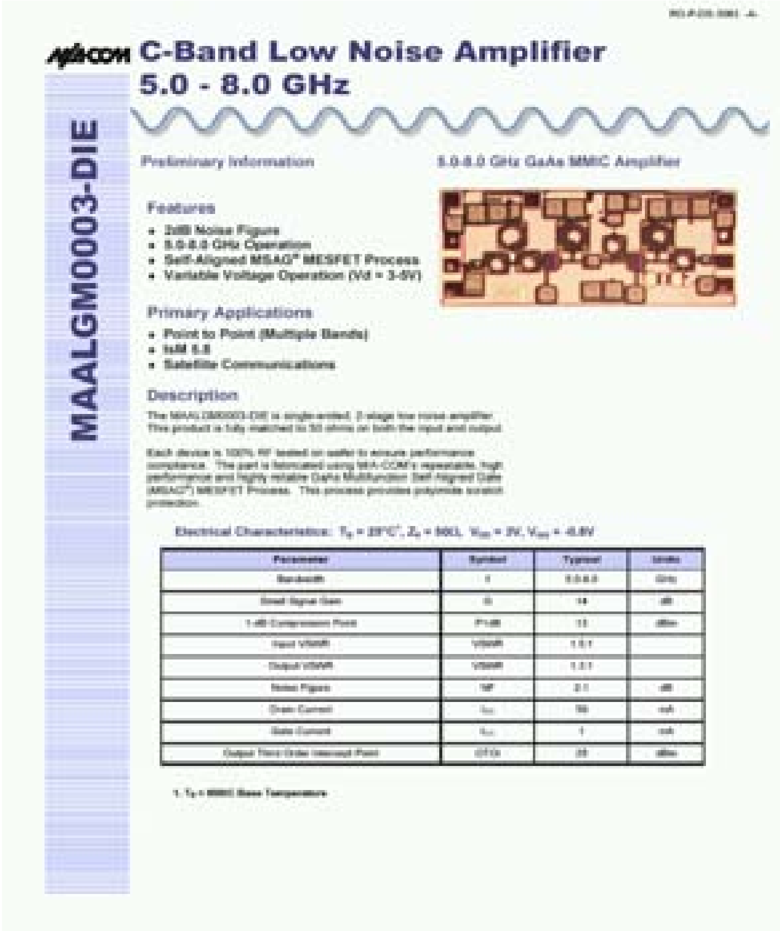
The LNA which test results is presented in this report is a part of the font-door component testing program at FOI. In total three different types LNAs will be tested. The two other types of LNAs will be purchased from other manufacturers fabricated in different processes. These tests are partly done to investigate the differences in power handling capability between the different processes. The main goal is to determine destruction levels for the LNAs by varying the input signal parameters, such as pulse width, CW, pulse burst, single pulse. The susceptibility levels of the LNA with and without correct biasing are also investigated. It is important to determine susceptibility levels for LNAs, because they are among the first components that will be hit by a high power EM-pulse. Also it makes it possible to specify the requirements of the protection devices.

5.1 Measurement Uncertainty

The output power from the amplifier is coupled to a cable. The output power from the cable has been measured with a HP 337A Power Meter using a HP ECP-E18A power sensor. Both the power meter and power sensor have been calibrated. In order to be able to do the calibration measurements a connection converter was connected to the power sensor. The connection converter have a loss of about 0.1 dB and due to variation of the tightening of the connections about 0.1 dB of losses can be added. The uncertainty of the power meter and power sensor are very small, only a few percent. In total the measurement uncertainty can be estimated to about 0.2 dB at a maximum. The small signal measurements have been done with a HP 8510C Network Analyzer, the Network analyzer was calibrated with an electronic calibration module, HP 85062-60006, controlled by an electronic calibration control unit, HP 85060C. The calibration was done for 5.0 to 8.0 GHz.

5.2 Test object

The LNA tested so far (MAALGM0003-DIE) is a two-stage low noise amplifier, from M/A-Com (USA). The LNA is designed for C-band operation, which corresponds to a frequency range of 5.0 to 8.0 GHz. The LNA is designed in a self-aligned MESFET GaAs MMIC process. Before the measurements, the LNA was mounted in a fixture, in order to ease and make the measurements more repeatable. The fixture was designed in a way that made replacement of LNA chips after finished tests simple. Ideally it would be good to have 2 or 3 fixtures, this would make the measurements more efficient. The datasheet for the LNA MAALGM0003-DIE can be seen in Figure 5.1.



M/A-COM C-Band Low Noise Amplifier
5.0 - 8.0 GHz

MAALGM0003-DIE

Preliminary Information

5.0-8.0 GHz GaAs MMIC Amplifier

Features
- 2dB Noise Figure
- 5.0-8.0 GHz Operation
- Self-Aligned MSAG® MESFET Process
- Variable Voltage Operation (Vd = 3-5V)

Primary Applications
- Point to Point (Multiple Bands)
- ISM 5.8
- Satellite Communications

Description

The MAALGM0003-DIE is single-ended, 2-stage low noise amplifier. This product is fully matched to 50 ohms on both the input and output.

Each device is 100% RF tested on wafer to ensure performance compliance. The part is fabricated using M/A-COM's repeatable, high performance and highly reliable GaAs Multifunction Self-Aligned Gate (MSAG®) MESFET Process. This process provides polyimide scratch protection.

Electrical Characteristics: $T_B = 25°C^1$, $Z_0 = 50\Omega$, $V_{DD} = 3V$, $V_{GG} = -0.8V$

Parameter	Symbol	Typical	Units
Bandwidth	f	5.0-8.0	GHz
Small Signal Gain	G	14	dB
1-dB Compression Point	P1dB	13	dBm
Input VSWR	VSWR	1.5:1	
Output VSWR	VSWR	1.3:1	
Noise Figure	NF	2.1	dB
Drain Current	I_{DD}	55	mA
Gate Current	I_{GG}	1	mA
Output Third Order Intercept Point	OTOI	25	dBm

1. T_B = MMIC Base Temperature

Figure 5.1 Datasheet for the LNA ,MAALGM0003-DIE, from M/A-Com.

5.3 Measurement Procedure

So far about 30 LNAs of this type have been tested. The measurements were done in order to maximize the information. First of all a visual inspection of the LNAs was done, if the LNA passed (which most of them did) it was mounted in to a fixture. Then small-signal and noise figure measurements were done on the LNAs, these measurements were saved as a reference data file. The small signal measurements were done with a HP8510C network analyzer in the band 5.0 to 8.0 GHz, with 201 points. Noise figure measurements were done using a set-up with a HP346B noise source and a HP8970A noise figure meter. The next step was large signal measurements i.e. HPM injection. The injections started at a low power level and were stepwise increased with increments of 1 dB, until breakdown of the LNA.

After breakdown small-signal and noise figure measurements were done again, in order to verify the damage. In some cases small signal and noise figure measurements were also done just before the breakdown of the LNA. The breakdown was preceded by an increase in drain current (see below). From these measurement results one can see how the small signal parameters and the noise figure are affected by degradation and destruction of the LNA.

The test set-up used for the HPM tests was almost the same set-up, which was used for limiter testing. The set-up is seen in Figure 5.2. It is a rather simple test set-up, which consists of a synthesized sweeper triggered by a pulse generator which makes it possible to vary the pulse parameters, i.e. pulse width, PRF etc. The pulsed (or CW) signal is than further propagated to the amplifier, before it is injected into the LNA (DUT).

The measured parameter is the input power in dBm to the LNA. The output power level of the power amplifier was measured with a power meter in order to calibrate for the losses in the cable and connections between power amplifier and the LNA.

The LNA under test is mounted in a fixture, with separate bias and RF connections. For the regular case, the LNA is biased to a correct working point according to the specifications. The bias voltages and currents are, gate-voltage Vgg = -0.7 Volt, drain voltage Vdd = 3.5 Volt and drain current Idd = 50 mA. The drain current was also used as an indication for degradation and damage of the LNA. In general it can be said that a small increase in drain current (1-5 mA), indicates degradation of the LNA, while a large increase (6-50 mA) indicates destruction of the LNA.

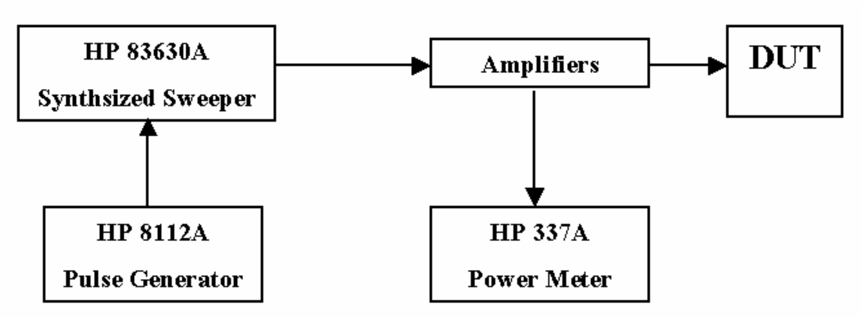


Figure 5.2 Block schematic over the LNA measurement set-up.

5.4 Measurement Results

The results from the LNA HPM measurements are shown in this chapter. To the left in Figure 5.3 a photograph of the MAALGM0003-DIE LNA can be seen. The photograph of the LNA was taken before the HPM measurements were done. Figure 5.3 also show small signal measurements (to the right) of the LNA prior to the HPM measurements. The comparison between the measured S-parameters and the S-parameters given in the specification shows good agreement. The S-parameters are normal for an LNA, the transmission loss (gain), s21, is between 11 to 15 dB for the 5 to 8 GHz band. Normal bias was applied, Vgg = -0.7 V, Vdd = + 3.2 V and Idd = 50 mA.

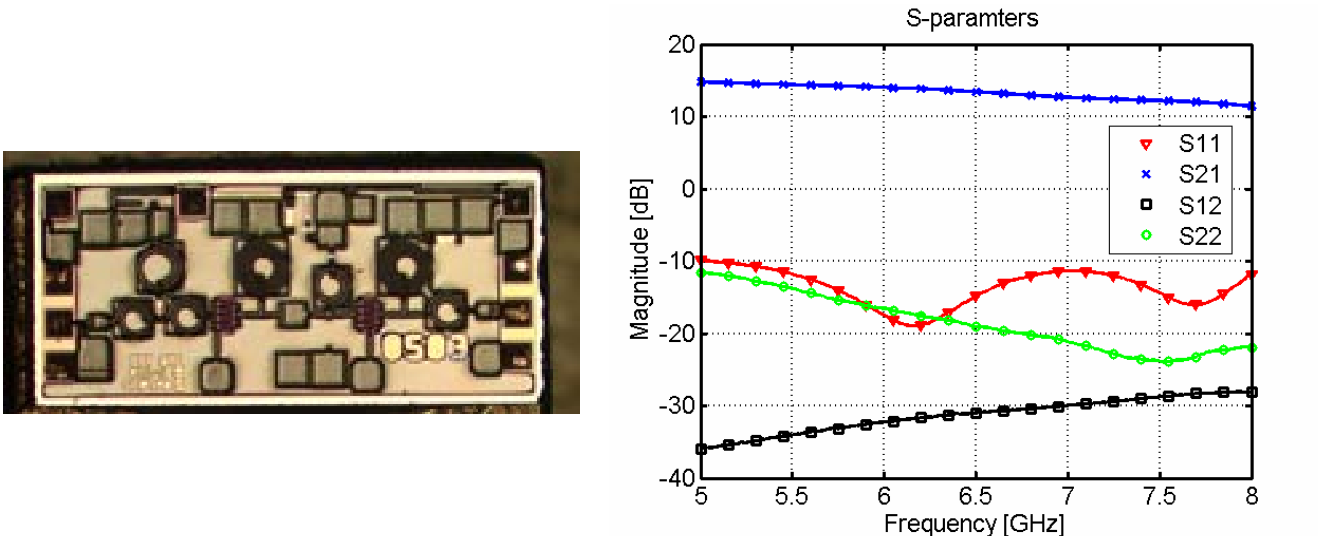


Figure 5.3 Photo and measured s-parameters of the LNA before injection of HPM pulses.

Just before breakdown of the LNA a degradation was seen. The degradation was indicated by an increase (1-5 mA) in the drain-current (Idd). The increase was permanent and the bias settings was otherwise as regular bias Vgg = - 0.7 V, Vdd = 3.2 V. The measurements of noise figure and S-parameters showed some degradation of the LNA performance. Figure 5.4 show a comparison between regular (square) and degraded (delta) noise figure. Figure 5.5 show the degraded s-parameters. It can be seen that the S-parameters suffers only a small degradation, but the noise figure suffers a degradation between 1 to 2.5 dB, which makes the LNA more or less useless in a front-end receiver. No visual damage was observed.

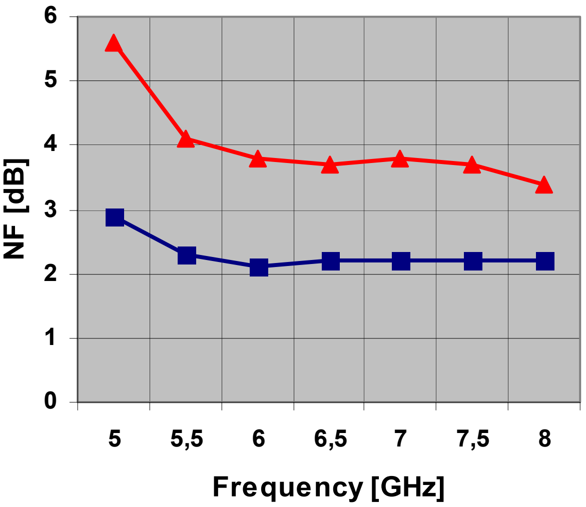


Figure 5.4 Noise Figure (NF) measurements before and after degradation, ■ indicates NF before, ▲ indicates after HPM pulses.

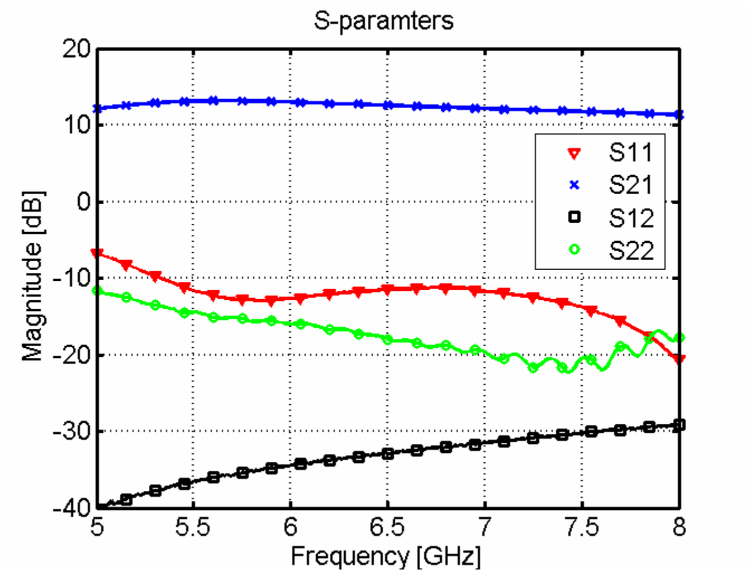


Figure 5.5 S-parameters of degraded LNA, after HPM pulses.

Below are the results from when the LNA has suffered breakdown i.e. permanent physical damage. The first sign of breakdown is a high increase in drain-current (Idd) from the normal 50 mA to 80-90 mA. A visual inspection reveals burnt out areas in the input stage of the LNA, mostly the gate area or the matching network area was burnt out. The biasing of the LNA was otherwise normal (Vgg= - 0.7 V, Vdd=3.2 V) except for the drain-current Figure 5.6 shows a photograph of the damaged LNA, where the burnt out area is encircled in red. The measured S-parameters after breakdown are shown in Figure 5.7. Figure 5.8 show the measured noise figure after breakdown. As can be seen from the result in the measurements, the LNA is completely useless after the breakdown.

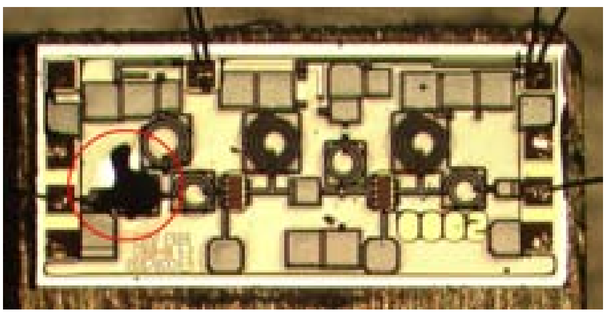


Figure 5.6 Photography of the burnt out LNA.

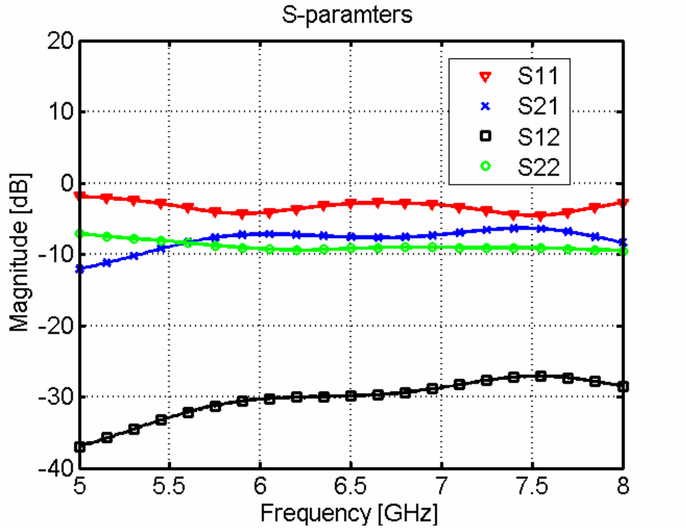


Figure 5.7 Measured s-parameters from the burnt out LNA

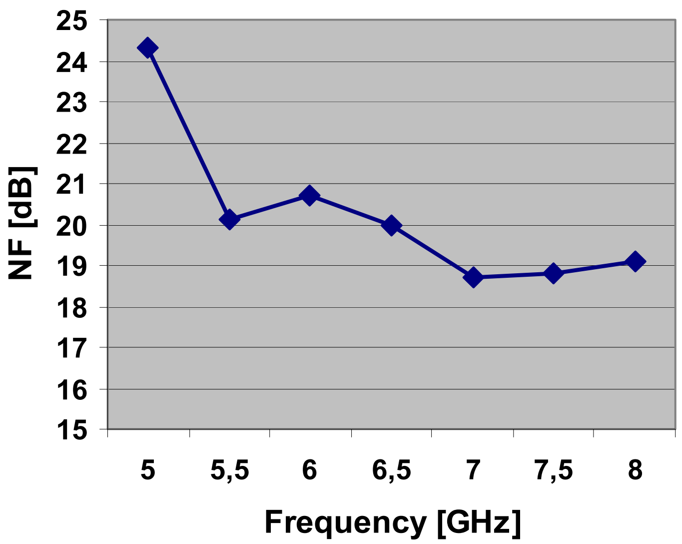


Figure 5.8 Measured noise figure (NF) from the burnt out LNA

In total about 50 MAALGM0003-DIE LNAs will be tested, so far have about 30 LNAs have been tested. This report summarizes the tests done so far. Various parameters, such as different pulse widths, CW, biased/unbiased, in-band/out-of-band have been investigated. Three LNAs were tested for each parameter in most of the cases, in order to get a somewhat more solid statistical base. A more detailed analysis will be made when all the measurements have been finished. Figure 5.9 show HPM power levels for destruction at different pulse widths. Figure 5.10 show HPM energy levels needed for destruction at different pulse widths. Figure 5.11 show the CW power levels needed for destruction when the LNA is biased/in-band, unbiased/in-band and biased/out-of-band. In-band = 6.0 GHz, out-of-band = 3.0 GHz.

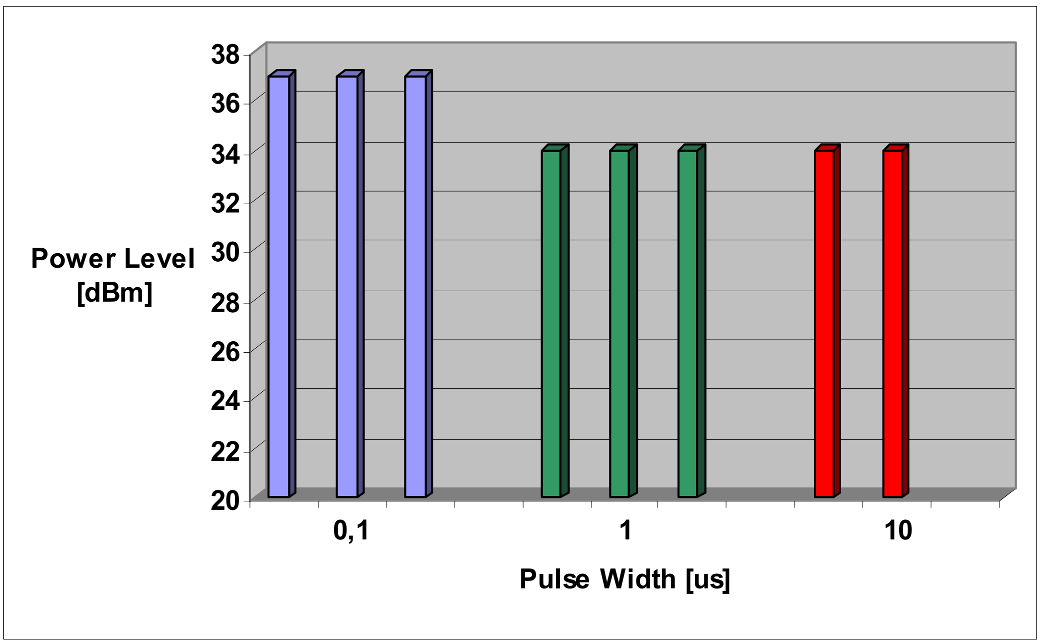


Figure 5.9 Power levels for destruction of the LNA for different pulse width.

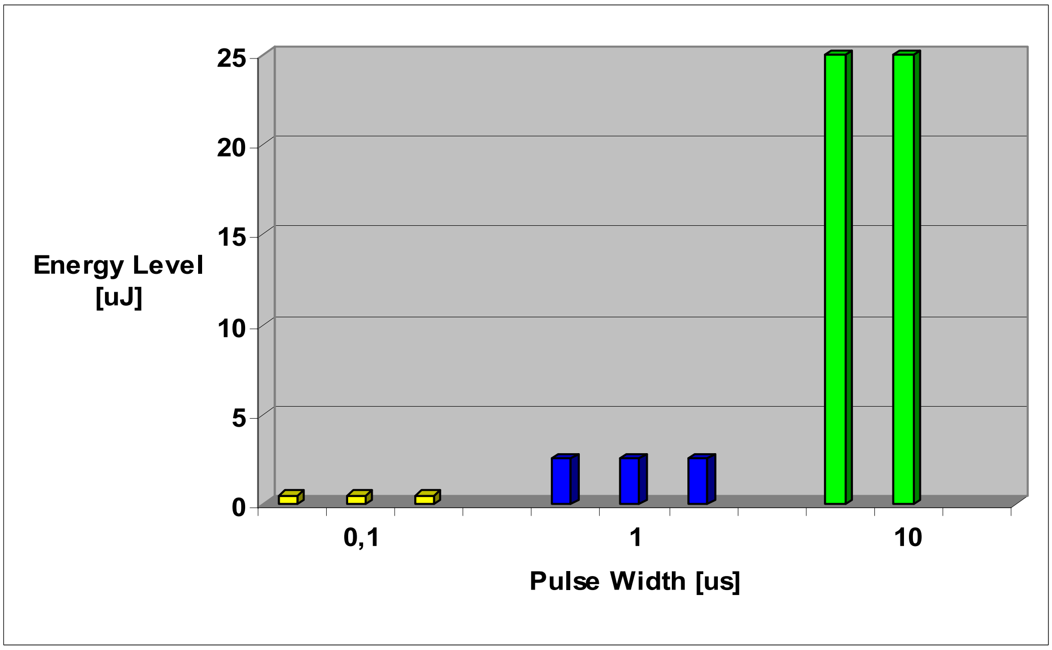


Figure 5.10 Energy levels for destruction of the LNA for different pulse width.

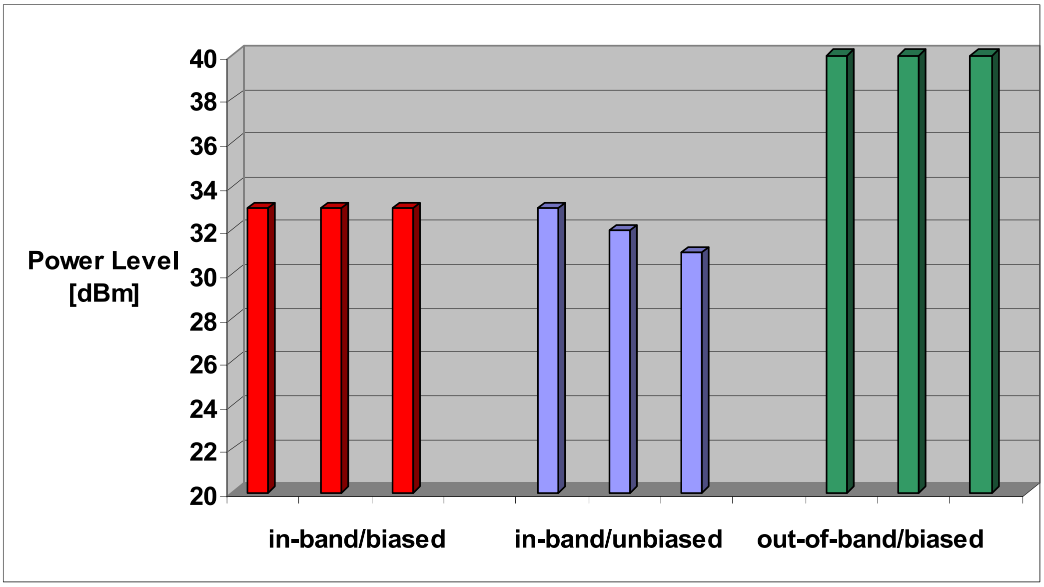


Figure 5.11 Power levels for destruction of the LNA for biased / unbiased and for out-of-band frequencies, these are CW measurements, the LNAs were exposed for 60 second.

5.5 Summary

The initial HPM susceptibility measurements on the LNAs show interesting results. The levels for destruction vary, when different input parameters of the LNA (such as pulse width, CW / single pulse, biasing etc.) is changed. By varying the width of the HPM pulse, it was discovered that the failure levels in terms of power decreased with an increasing pulse width, while the failure levels in terms of energy increased. The trend showed that when the LNA was unbiased, the failure level was practically unchanged, a slight decrease could be discerned. When the input HPM pulse to the LNA was out-of-band, the failure level increased, because more of the input power was reflected. Measurements of LNAs also show that LNAs suffers from degradation prior to total breakdown. The maximum difference between destruction power levels is 9 dB, with the maximum and minimum levels being 40 and 31 dBm respectively. These levels might vary between different processes and types of LNAs. So far have about 30 LNAs of one type been tested. The continuing investigation on LNAs will be more extensive, where two more types of LNAs will be investigated, a total of 150 LNAs is planned to be investigated.

6 Design of MMIC Schottky diode limiters

6.1 Task

The task was to evaluate the possibility to use the OMMIC ED02AH MMIC process for designing MMIC Schottky diode limiters. It is a continuing development of the FOI made MMIC Schottky-diode limiter described in chapter 4.8.

6.2 Ideal design

6.2.1 Power dissipation and required diode area

We started by selecting an approximate maximum power that the limiter should survive as this, together with the diode maximum rating, will determine the total diode area required. We selected a maximum input power survivability of 2W. A simple limiter circuit is depicted in Figure 6.1.

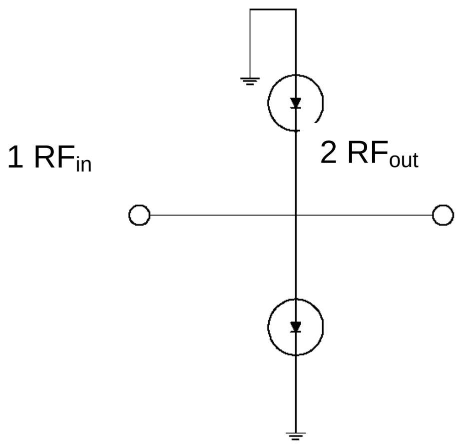


Figure 6.1 Schematic of diode limiter circuit.

The purpose of the limiter is to protect the front-end electronics from being destroyed by high power signals received in port 1. In Table 6.1 the desired limiter performance and key diode properties are listed.

Table 6.1 Required limiter and diode properties.

Property	Desired value
Input power survivability (limiter)	2 W (33 dBm)
Maximum output power (limiter)	100 mW (20 dBm)
Unbiased diode junction capacitance	0.2 pF *
Diode on-resistance (R_S)	~1 Ω

* The maximum allowed capacitance depends on the operating frequency and the limiter circuit. The listed value results in a small signal loss < 1 dB at 10 GHz for a limiter circuit like the one shown in Figure 6.1.

Figure 6.2 shows a simplified equivalent circuit of the limiter. The unbiased diode junction capacitance that gives rise to small signal loss is denoted Cj0 in the picture. The variable resistance, Rvar, is the diode resistance which cause the limiting behaviour by providing a low impedance path to ground when high power signals (or DC bias) are applied to the limier.

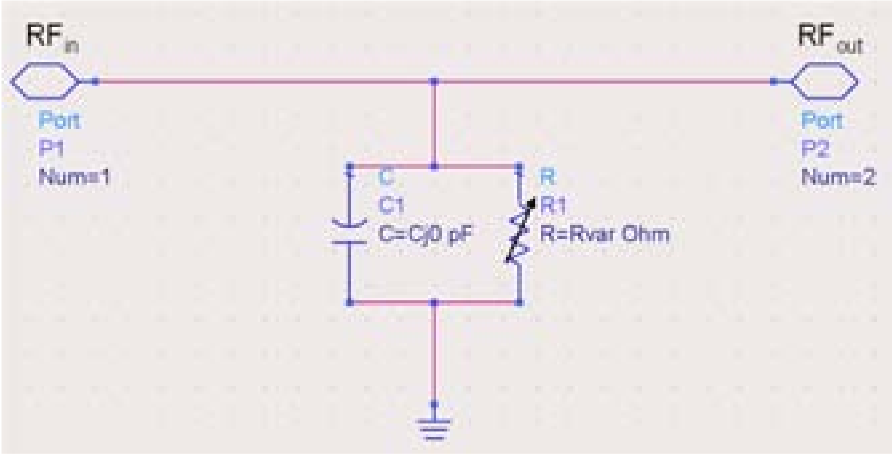


Figure 6.2 Simplified limiter equivalent circuit.

When the power received in port 1 increases the diodes start conducting providing a low impedance path to ground that results in most of the power being reflected back towards port 1 (while some is dissipated in the diodes and some delivered to port 2). The CW power delivered to port 2 should be limited to < ~20dBm, higher spike leakage can be tolerated but the diode should have the fastest response possible while still meeting the requirements of capacitance and power handling capability. A good limiter should provide sufficiently low impedance that most of the incoming power is reflected back towards the load when the diode current is saturated. This will increase the power survivability of the limiter. The reflection coefficient at the limiter input can be calculated with Eq. 1.

$$\Gamma = \frac{V_{reflected}}{V_{forward}} = \frac{Z_{load} - Z_0}{Z_{load} + Z_0} \qquad (1)$$

Where Z_{load} is the input impedance of the circuit when the limiter diodes are turned on and Z_0 is the system impedance (usually 50 Ω). The power reflected at port 1 might of course be reflected again due to mismatch at the source causing more power to be dissipated in the diode. A diode with $R_S = 1$ Ω in a 50 Ω system results in $P_D = P1 \times 7\%$, see Eq. (2).

The power dissipated in the diode P_D is described by

$$P_D = \frac{4R_S Z_0}{(Z_0 + 2R_S)^2} \cdot P_1 \text{ [6]} \qquad (2)$$

Where R_S is the diode on-resistance (at maximum input power where this expression is interesting the diode is fully turned on), Z_0 is the system impedance and P_1 is the input power at port 1. This expression is valid for a one diode limiter where one of the diodes in fig. 6.1 has been exchanged by a RF –isolated DC-return path. In a limiter like that in fig. 1 half that power would be dissipated in each diode.

The Schottky diodes available in this process have relatively high junction capacitance compared to the PIN-diodes usually used for microwave limiters. To achieve enough limiting and survivability while keeping the small signal loss minimal, as discussed in chapter 6.2.2, a multiple stage limiter will be attempted.

If we assume that 3 stages of diodes will give an on-state input impedance for the circuit of ~1 ohm we can calculate the current, using eq. (2) and Ohms law, to = 374 mA with $P_1 = 2$ W. This gives I = 125 mA/ stage (rms) and as each stage has both polarity diodes I ≅ 62 mA / diode (or diodes as series diodes will be used in some stages). The specified saturation current is ~2 mA /µm diode finger width (the diodes are processed with interdigitated fingers like a transistor). The diode finger length is

3 µm. With the maximum number of fingers (N = 6), to minimise the parasitic resistance, this gives a finger width of ~6 µm. By simulation the equivalent capacitance of one such diode was calculated to ~0.4 pF. From this comparison it was also noticed that the diode has substantial parasitic resistance in the off-state. This will unfortunately increase the small signal loss of the limiter.

6.2.2 Minimizing small signal loss

In the small signal case when the limiter diodes are turned off, the shunt capacitance of the diodes cause an unwanted small signal loss. The small signal loss is inevitable but has to be minimised as the limiter is put before the low noise amplifier (LNA) and any loss in the limiter increase the noise figure of the system. If the limiter is processed on the same chip as the LNA the diode capacitance can be absorbed in the matching network of the LNA. As this is this is not the case here, we will try to use a synthetic transmission line or a low pass filter structure to minimise small signal loss. In these structures the capacitance will be the off-state diode junction capacitance and the inductors will be realised with line inductance or spiral inductors.

According to the transmission line equation:

$$Z = \sqrt{\frac{L}{C}} \qquad (3)$$

where Z is the line impedance, C shunt capacitance and L series inductance. For C = 0.4×2 = 0.8 pF (one diode of each polarity) and Z = 50 Ω (3) gives: L = 2 nH

And the transmission line cut-off frequency: $\omega_c = 2\pi \cdot f_c = \frac{1}{\sqrt{LC}}$

This gives: fc = 4 GHz.

If we try a 5th order low-pass Butterworth filter (2 capacitors and 3 inductors) with the capacitors = 0.8 pF this gives f_c = 6.5 GHz with the values:

L1 = 0.70259 nH
C2 = 0.73577 pF
L3 = 2.2736 nH
C4 = 0.73577 pF
L5 = 0.70259 nH

A 7th order Butterworth filter with the largest capacitor = 0.8 pF gives f_c = 7 GHz with the values:

L1 = 0.44269 nH
C2 = 0.49616 pF
L3 = 1.7924 nH
C4 = 0.79577 pF
L5 = 1.7924 nH
C6 = 0.49616 pF
L7 = 0.44269 nH

The low-pass filter structure seems as the better option and will be further studied by simulations in chapter 6.6.3.

6.3 Small and large signal evaluation by simulation

The simulation tool used for this work is Agilent ADS 2003A. The linear simulations have been done using the small signal S-parameter simulation and the nonlinear characterization uses the harmonic balance (HB) simulation technique. The transient simulations use the convolution step or pulse – response simulation.

Small signal simulations of different limiter structures showed that the parasitic resistance of the diode increase the small signal loss of the limiter circuit dramatically, especially at higher frequencies. A large number of circuit and diode configurations were simulated and are presented in Table 6. First the diode size was selected and 1-3 stages of diodes and the corresponding number of inductors (for a filter) was put in a circuit that was optimized for minimum small signal loss. The theoretical values of inductance from filter theory were used as a starting guess for the simulation. After small signal optimisation the limiting performance of the circuit was studied in a harmonic balance (HB) simulation. In Table 6. the different limiter circuits is described by the number of diode stages (N), the number of series diodes in each stage S_x (where x is the stage number) , the number of parallel diodes of the same polarity in each stage P_x and the diode finger width (W in μm) and number of fingers per diode (F). The same unit diode was used in different configurations in different stages. For example a circuit with N = 2, P_1 = 2, S_1 = 2, P_2 = 1, S_1 = 1, W = 15 μm and F = 4 is shown in Figure 6.3.

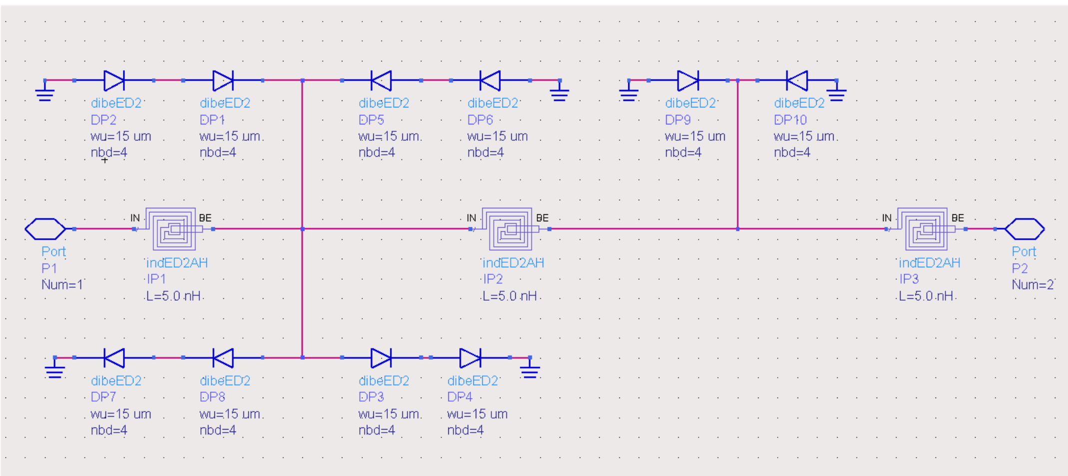


Figure 6.3 Schematic of limiter circuit.

For each limiter the following parameters are given: the small signal loss, the frequency related to the small signal loss (f_L), the isolation I (the loss between input and output), the input power P_{in} to which the isolation is associated and the frequency associated with the isolation simulation (f_I).

Table 6.2 Simulated performance of different limiter circuits.

Name	N	S_1	S_2	S_3	P_1	P_2	P_3	W [μm]	F	Loss [dB]	f_L [GHz]	Isolation [dB]	P_{in} [dBm]	f_I [GHz]
H	2	2	1	-	2	1	-	5	2	1	6	2.3	30	4
H2	3	3	2	1	2	2	1	5	2	1.4	6	4	30	4
I	2	2	1	-	2	1	-	15	4	1.5	2	15	30	2
J	2	2	1	-	2	1	-	10	4	1.6	2	11	30	2
Ilay_1	2	2	1	-	2	1	-	10	4	1.64	3	10.25	30	2
K	2	2	1	-	2	1	-	6	6	1.6	3	9.5	30	2
L	2	3	2	-	2	1	-	6	6	1.4	4	7	30	2
O	2	2	1	-	2	1	-	8	6	1.9	3	10	33	2
P	1	2	-	-	2	-	-	8	6	1.5	4	4.7	33	2
Q	1	2	-	-	2	-	-	15	6	2.5	3	9.3	30	2

As can be seen in Table 6.2 the isolation is too low i.e. less then 10 dB (ideally we would like ~20 dB) when the diodes are sufficiently small for the small signal loss at 6 or 4 GHz to be acceptable (i.e. ~1-1.5 dB). From the table either limiter I, K or Q seems to be the best choice and limiter K is selected for further study because it has acceptable isolation and better bandwidth than the others.

6.4 Evaluation of the selected limiter

Figure 6.4 show the small signal performance of the limiter. As can be seen the loss is acceptable up to ~3 GHz. The matching is good up to ~6 GHz which indicates that the losses between 3 and 6 GHz is mainly due to the parasitic resistance of the diodes although some line loss can also be expected in the spiral inductance used for the largest inductor.

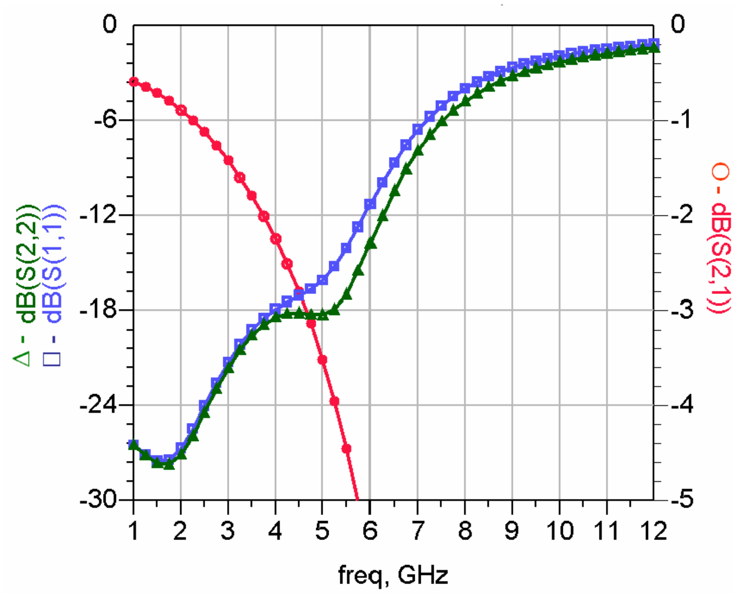


Figure 6.4 Small signal simulation of the limiter.

In Figure 6.5 the HB simulated limiting performance is shown. The onset of limiting occurs at ~10 dBm of input power and the limiter diodes are saturated at about 30 dBm of input power.

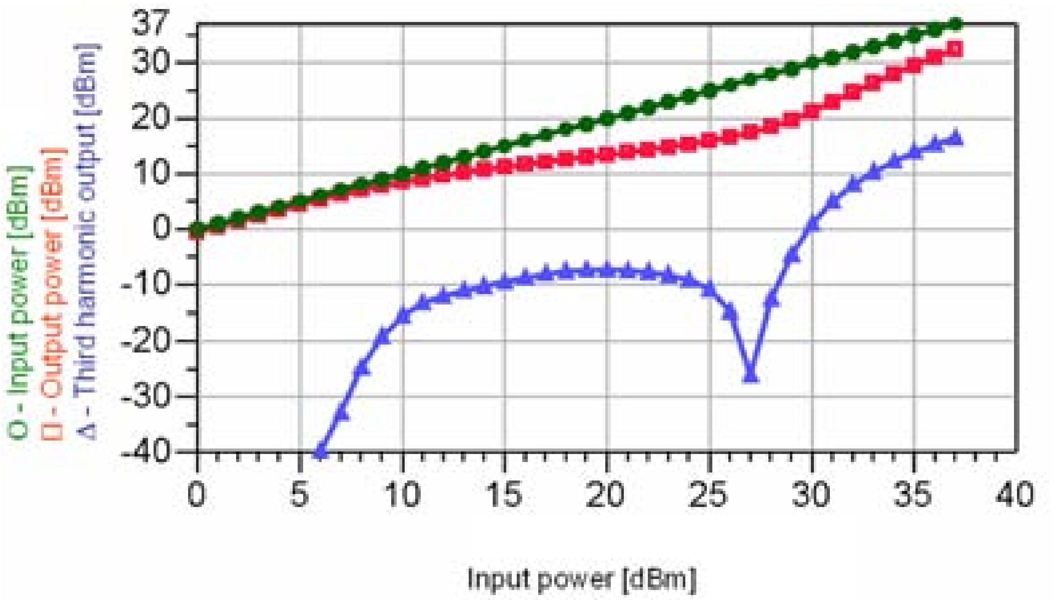


Figure 6.5 Simulated limiting performance at 2 GHz.

In Figure 6.6 the simulated diode current is shown as a function of input power. The maximum current at 30 dBm of input power translates to ~0.5 mA/µm diode width in stage 1 and ~0.6 A/µm diode width in stage 2 which is within the acceptable current and not too much of a difference. The early turn on of the limiter and the relatively small total current in stage 2 suggests that it might be possible to remove stage 2 to enhance the small signal performance. However, simulations showed that removal of the second stage decrease the isolation at 30 dBm input power by more than 2 dB which is unacceptable.

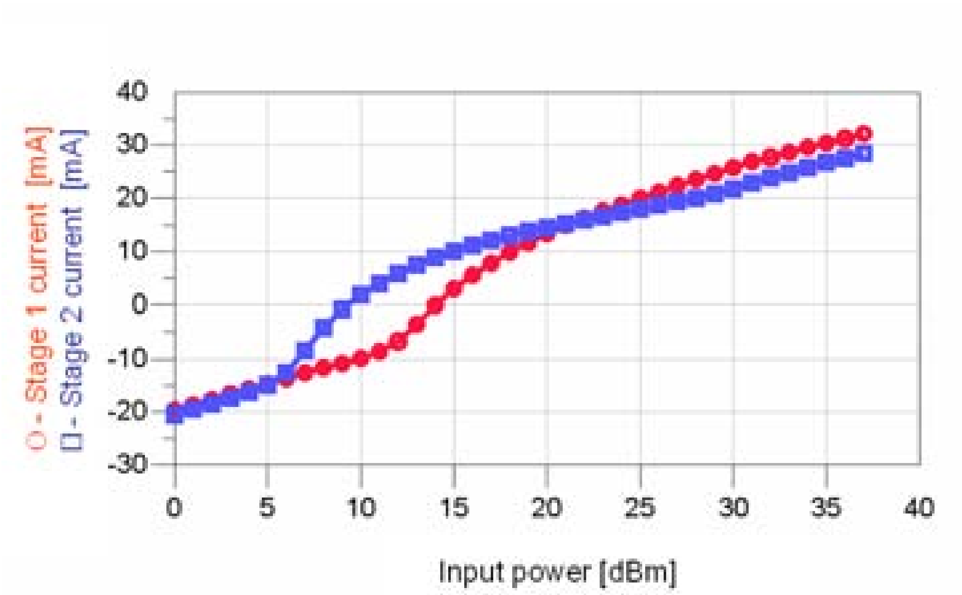


Figure 6.6 Simulated diode current.

Figure 6.7 show the simulated pulse response of the limiter. A 7 V step with 20 ps rise-time and 150 ps pulse length was applied to the input of the circuit and the response measured. As expected, since the diodes are quite small and fast Schottky diodes the pulse response contains no spike leakage. Due to input mismatch the high frequency content of the input pulse is reflected back towards the input. This indicates that the limiter should survive higher input power for out of band signals than for in band signals. Note that the accuracy of this simulation is somewhat dubious since the input signal contains higher frequencies that the diode model is specified for.

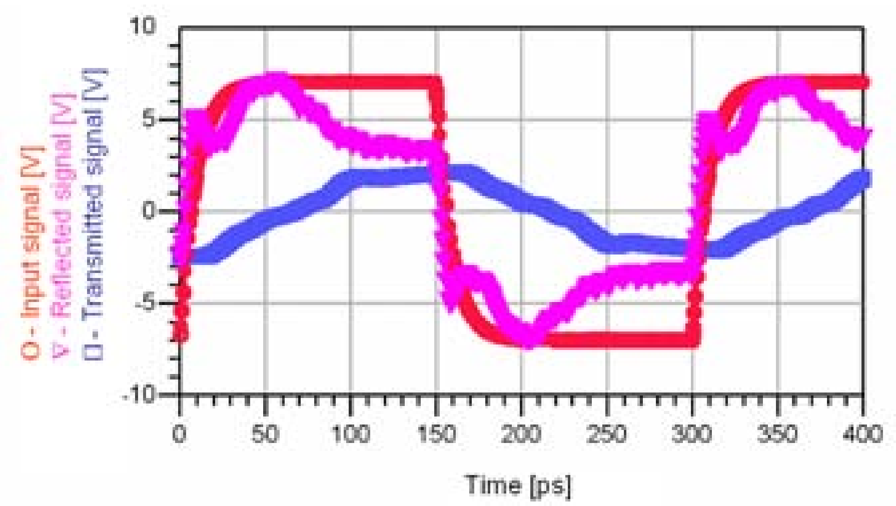


Figure 6.7 Simulated limiter pulse response.

6.5 Layout

In the simulations in chapter 6.3 and 6.4 only the diodes, via-holes and large inductors used the distributed foundry models. To perform a layout it is necessary to connect the different circuit elements with transmission lines in a way that may be physically laid out on the chip. This should be done while preserving as much as possible of the circuit performance. Figure 6.8 show the finished layout of the limiter. Simulation of this layout showed that the small signal loss at 3 GHz had increased by 0.1 dB to 1.5 dB and the isolation at P_{in} = 30 dBm had decreased 0.5 dB to 9 dB. In the layout shown in Figure 6.8 one could consider to share the pad via-holes with the diodes next to them to conserve ship-area. This should have only marginal effect on the limiter performance.

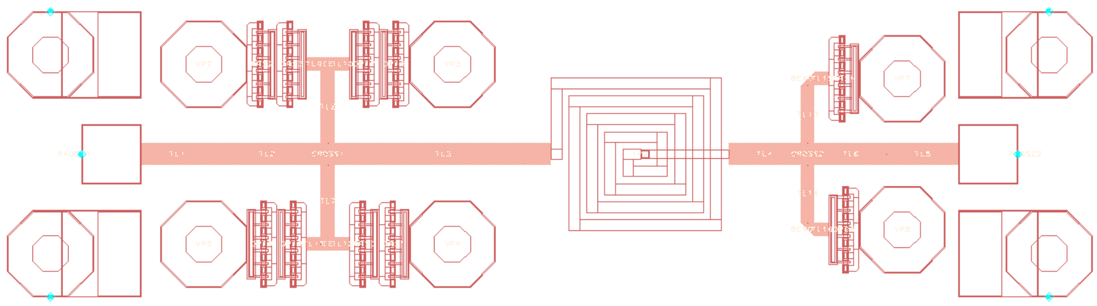


Figure 6.8 Limiter layout.

6.6 Summary

The simulated performance of the limiter is not very impressive and fails to meet the requirement of maximum 20 dBm output at 2 W of input power. It could be used from DC to 3 GHz to raise the allowed input signal strength of a sensitive circuit from 20 to 30 dBm however at the cost of ~1.5 dB small signal loss. The main problem is the parasitic resistance of the diodes that increase the small signal loss of the circuit, limiting both bandwidth and the use of larger diodes that would allow larger isolation. It might be possible to modify the diode layout to achieve a diode that is more appropriate for this application but this would require at least one extra process run to establish models for the modified diodes. There is also a possibility that a radically different design than the one attempted here might be more successful. One such possibility would be to use a smaller diode, for detection of incoming high power signals, to trigger an active limiter using diodes or transistors and external bias. But usually passive limiter circuits are preferred as they are more reliable and offer protection also when the system is not power on.

7 Summary And Conclusion

This report contains results from an extensive study of front-door protection devices, i.e. limiters. HPM and UWB measurements on various limiters and HPM susceptibility measurements on one type of LNA. The results show the characteristics of several different limiter technologies. The main objective was to investigate the limiters response to both UWB and HPM pulses. The HPM pulses has a rise time of ~5 ns and a pulse width of 100 ns, UWB pulses are very fast, with 300 ps rise time and around 1 ns pulse width. The results show that some but not all of the limiters have both very fast response time and a power handling capability to handle moderate power levels. Some of the limiters also have broadband frequency characteristics and they are also possible to integrate with small integrated circuits, which is very desirable.

The measurements show that some of the tested devices are not suitable for front-door protection against HPM and UWB pulses, these devices are GDTs and MOVs. Schottky and PIN diode limiters are suitable to be used as protection against permanent damage from both UWB and HPM pulses. These limiter can be integrated with the electronic equipment and increase the hardening level against HPM and UWB. Examples of civil and military equipment that can be protected with the tested limiters are WLAN and RADAR equipment or other common front-end receivers. Schottky and PIN diode limiters have shown to provide quite good protection against both HPM and UWB pulses. However the power handling capability of these devices is not very good, but might be adequate depending on the threat specification.

The diode-based limiters in general show a good capability to protect from HPM and UWB pulses. They are fast limiting devices with short response and recovery time. They are also able to withstand moderate CW and peak pulse power levels. Furthermore they also introduce a relatively small insertion loss and they work well for broad frequency bands, up to tens of GHz. The diode limiters are also small in size, which makes them an attractive alternative for use in array antennas and other applications where size is critical. Especially PIN-diodes have an exemplary behavior.

However if the power levels are higher (100 kV/m, HPM specification), the diode limiters might suffer burnout, due to their lack of high power handling capabilities. This requires other types of protection devices, which can handle higher power levels. The Gas discharge tubes (GDTs) and the metal oxide varistors (MOVs) are protection devices that have better power handling capabilities. The measurements of these devices have however showed rather poor results. The GDT and the MOV didn’t limit the transmitted power, but they might have been triggered if the input power was higher. This will be further investigated.

A combination of different technologies integrated into one limiter would be ideal. The combination of two different technologies, where the first stage takes care of high power pulses and a second stage that cleans up the remaining power and the fast transients of the pulses. For high frequency limiters it is important to have a low capacitance in order to minimize the insertion loss (which deteriorates the noise figure of the receiver). Otherwise the overall system performance will be seriously degraded.

The initial HPM susceptibility measurements on the LNAs show interesting results. The results show that LNAs suffers from degradation before they have a total breakdown. The levels for destruction vary, when different input parameters of the LNA (such as pulse width, CW / single pulse, biasing etc.) is changed. The maximum difference in destruction power levels is 9 dB, with the top and bottom levels of 40 and 31 dBm respectively. These levels might also vary between different processes and types of LNAs. So far have about 30 LNAs of one type been tested. By varying the width of the HPM pulse, it was discovered that the failure levels in terms of power decreased with an increasing pulse width, while the failure levels in terms of energy increased. The trend showed that when the LNA was unbiased, the failure level was practically unchanged, a slight decrease could be discerned. When the input HPM pulse to the LNA was out-of-band, the failure level increased, because more of the input power was reflected. The continuing investigation on LNAs will be more extensive, where two more types of LNAs will be investigated, a total of 150 LNAs is planned to be investigated.

Regarding the designed MMIC-limiters, the simulated performance of the limiter is not very impressive and fails to meet the requirement of maximum 20 dBm output at 2 W of input power. It could be used from DC to 3 GHz to raise the allowed input signal strength of a sensitive circuit from 20 to 30 dBm however at the cost of ~1.5 dB small signal loss. The main problem is the parasitic resistance of the diodes that increase the small signal loss of the circuit, limiting both bandwidth and the use of larger diodes that would allow larger isolation. It might be possible to modify the diode layout to achieve a diode that is more appropriate for this application but this would require at least one extra process run to establish models for the modified diodes. There is also a possibility that a radically different design than the one attempted here might be more successful. One such possibility would be to use a smaller diode, for detection of incoming high power signals, to trigger an active limiter using diodes or transistors and external bias. But usually passive limiter circuits are preferred as they are more reliable and offer protection also when the system is not power on.

8 Future Work

The evaluation of limiters and limiter technologies is more or less considered to be completed, many different limiters and limiter technologies have been tested and evaluated at FOI. The next step is to integrate front-door protection in different applications. The first application that will be investigated is a GaAs MMIC front-end LNA. The LNA and a GaAs MMIC limiter will be mounted in the same fixture. This way the integration of limiter/LNA can be evaluated. Another application that will be investigated is a WLAN system, where a limiter can be mounted between the antenna and the LNA. This set-up will be investigated and evaluated. Also the MULLE system [7] from LTU is of interest to investigate. The system susceptibility will be investigated and also the possibility to integrate a limiter in the system.

A second iteration of the GaAs MMIC limiter has been designed and is currently being processed. This circuit will be evaluated and the result of this evaluation will decide if the effort to design MMIC limiters will be continued.

A more extensive study of front-end circuits such as LNAs will be done. It is planned to finish the on-going measurements on the MAALGM0003-DIE LNA. Two more GaAs MMIC LNAs will be tested, to see how the susceptibility levels differ between different types of LNA. A total of about 150 LNAs from three different manufacturers and processes will be tested. The LNA susceptibility for UWB-pulses will also be investigated.

Acknowledgements

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