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Investigation on the Pulse Characteristics of RF/Microwave Limiter Based on Multistage PIN Diodes and Schottky Diodes

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***Abstract*—Limiters are a kind of important module to protect the front end from physical damage in the case of RF/microwave receivers are exposed to EMP radiation. However, typical PIN limiters employed in most RF receivers are faced with the conflict between power capability and limiting level. To solve the problem, we proposed in this paper a new design of limiter based on multistage PIN diodes and Shcottky diodes, and set up the time-domain PSpice simulation model of that limiter, and made simulation and experimental research. The research results showed that the response time of the limiter was less than 1 ns; its power capability of μs-duration microwave pulses was more than 50 dBm, and the limiting effect was more than 30 dB; when injected with square-wave pulses of 30-ns duration, its peak voltage threshold was more than 200 V, the limiting effect with reference to rising edge about 20 dB, and the limiting effect to flattop more than 30 dB.**

Keywords-Limiter; EMP; PIN diode; Schottky Diode; PSpice

I. INTRODUCTION

Limiters are a kind of important module to protect the front end from physical damage in the case of RF/microwave receivers are exposed to EMP radiation and therefore are very important in many situations. There are two kinds of limiters, the passive and the active. Input power threshold of generally employed limiters is about several watts, and the output power is about several milliwatts; their attenuation scale to large signal is usually tens of dB, while less than 2 dB if small signals pass through the limiter. Currently, there mainly consists of 4 limiter design schemes, namely, limiters based on passive TR tubes, on second electron multiplication tubes, on ferrite limiters and limiters based on semiconductor switches and sensitivity-time-control (STC).

As most RF systems require the front end modules are provided with the characteristics of small volume, convenient operation and high reliability, limiters based on passive TR tubes have obvious advantages and are commonly adopted. Passive TR tubes refer to many kinds of passive semiconductor limiting devices, such as TVS diodes, PIN diodes and Schottky diodes. The disadvantages of the above limiters are that there exists conflict between power capability and limiting level, which means that large power capability usually results in high limiting level and leads to poor protection to its following modules (mostly low noise amplifier, LNA), while low limiting level results in small power capability and is easy to be damaged [1]. Accordingly, to design limiters with excellent pulse characteristics, what we need is not only adequate circuit scheme, but appropriate diodes as well as simulation models with high accuracy.

II. TIME DOMAIN SIMULATION OF PULSE CHARACTERISTICS OF THE LIMITER

A. Design of the limiter's circuit and modeling of main devices

The design described in this paper employs the method of multistage limiting and takes use of PIN diodes and Schottky diodes to generate a circuit with high power capability, nanosecond start-up time and low leaking power level, as shown in the following figure. In this circuit, the first stage limiting device is a PIN diode with 10-μm intrinsic layer (usually referred to as "I layer"), the second stage consists of two anti-paralleling PIN diodes with 5-μm I layer, and the last stage consists of two 2.5-μm PIN diodes and two Schottky diodes. Each PIN diode has the same wire-bond inductance of 1.5 nH and package capacitance of 0.25 pF. The length of the transmission lines connecting each stage, namely TL1, TL2 and TL3, are respectively 0.03λ, 0.05λ, and 0.09λ, where λ equals to 30 cm.

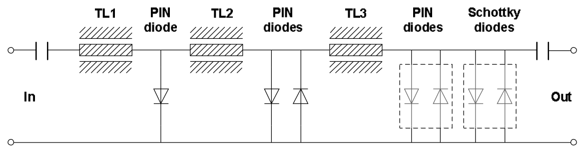

Fig. 1. Schematic of the multistage limiter circuit

Fig. 2 showed the equivalent PSpice circuit model of PIN diode, which can accurately models the conductance modulation mechanism in the I region. The circuit covered one main circuit and two subcircuits. In the main circuit, controlled current source Grmod represented the current flowing through the I region, and Gpin represented the total current in the diode. The subcircuit #1 included two diodes and two voltage sources, and subcircuit #2 included several controlled sources and a trapezoid RC network, which were used to describe the charge accumulation effects in the I region [2],[3],[4]. Table I listed the main model parameters of the PIN diode subcircuit.

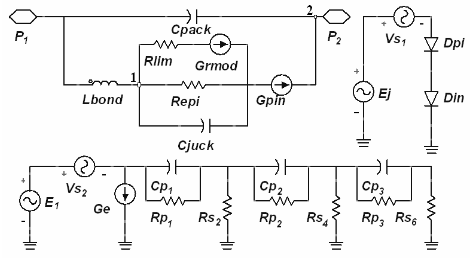

Fig. 2. Schematic of PIN diode PSpice subcircuit

TABLE I. MODEL PARAMETERS OF THE PIN DIODE SUBCIRCUIT

Region	Parameter	Unit	Description	Value
PN junction	is	nA	Saturation current	1.98
	n		Emission coefficient	1
	b		Ideal division factor	3
I layer	iknee	mA	High-injection knee current	10
	w	µm	base width	10
	τ	ns	carrier lifetime	50
	Cj	pF	zero-bias junction capacitance	0.3
	Rlim	Ω	Carrier scattering resistance	1.8×10^{-3}
	Repi	Ω	Base region resistance	8×10^{3}
Package	Lbond	nH	Bond-wire inductance	1.5
	Cpack	pF	package capacitance	0.25

The equivalent circuit model of the RF Schottky diodes and its SPICE parameters were shown in Fig. 3 and Table II. The diode used in the limiter circuit had 2-nH wire-bond inductance, 0.08-pF package capacitance. In the list of SPICE parameters, BV denoted the reverse breakdown voltage, CJO the zero-bias junction capacitance, EG the potential barrier height, IBV reverse breakdown current, IS the reverse saturation current, N the injection coefficient, and RS the parasitic resistance.

The experimental and simulation insertion loss curves of the designed multistage described above were shown in Fig. 4. The red one represented the experimental insertion loss while the black one was the simulation result. It can be observed that the error between the two curves was smaller than 3 dB until the frequency was above 7 GHz, which resulted from the less accurate high-frequency model of the PIN diode and the PSpice transmission lines.

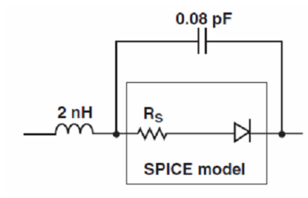

Fig. 3. Schematic of Schottky-diode equivalent circuit.

TABLE II. PSPICE MODEL PARAMETERS OF THE SCHOTTKY DIODE

Parameter	Unit	Value
BV	V	25
CJO	PF	0.2
EG	eV	0.55
IBV	A	10×10^{-4}
IS	A	1.4×10^{-7}
N		1.04
RS	Ω	0.65
PB	V	0.6
PT		2
M		0.5

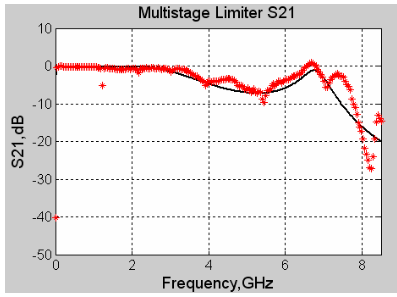

Fig. 4. The insertion loss curves of the designed multistage limiter (Red, experimental result, black, simulation result)

B. *Time-domain response simulation of the limiter injected with modulated microwave Pulses*

Firstly, we simulated the condition that modulated microwave pulses of 1-GHz center frequency and 30-ns duration were injected into the limiter, and the simulation results were as follows. The power of the input pulses was respectively 30 dBm, 42 dBm and 50 dBm.

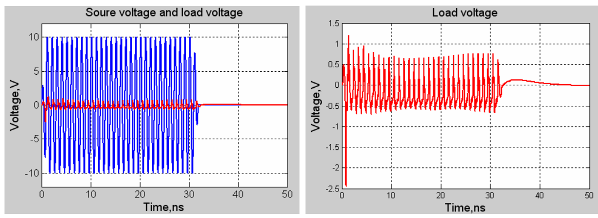

Fig. 5. Source and load voltage waveforms in the condition of 30-dBm injected microwave pulse (Vertical, voltage, V; horizontal, time, ns).

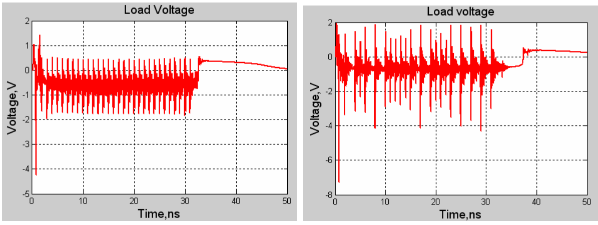

Fig. 6. Load voltage waveforms in the conditions of 42-dBm and 50-dBm injected microwave pulses (Vertical, voltage, V; horizontal, time, ns).

According to the simulation results, relatively high-amplitude spike appeared in the first cycle of the pulses, and in the static conditions the limiting levels were between 1~2 V. As the injection power increased, the amplitude of the spike grew, but the static limiting level kept the same. As the power reached 50 dBm, the limiting effect was about 34 dB.

C. Time-domain response simulation of the limiter injected with square pulses

During experimental processes, the duration of square pulse voltage source was 30 ns, and the rising and falling edges are both 1 ns. The voltage amplitudes of the input pulses were respectively10 V, 40 V and 100 V. The time-domain response simulation results of the limiter are shown below.

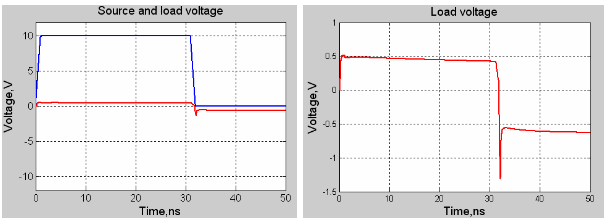

Fig. 7. Source and load voltage waveforms in the condition of 10-V injected square pulse. (Vertical, voltage, V; horizontal, time, ns).

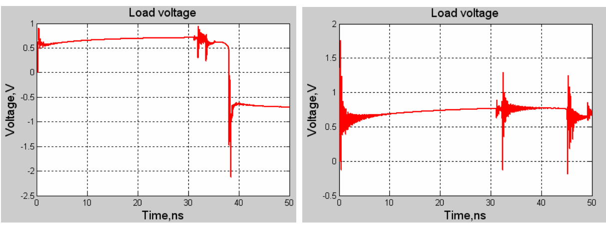

Fig. 8. Load voltage waveforms in the conditions of 40-V and 100-V injected square pulses. (Vertical, voltage, V; horizontal, time, ns).

According to the simulation results, in the condition of square pulses injection, the amplitude of the first spike was lower compared with the condition of modulated microwave pulses, which can be explained as the rising edge of square pulses was 1 ns while that of the microwave pulses was 0.25 ns (one quarter of its period), and therefore the PIN diodes in the limiter had relatively more time to reach low resistance state if 1-ns square pulses were injected into it.

III. Time-Domain Response Experiments of the Limiter Injected with Pulses

The configuration of the limiter injection experiments is shown below. In this figure, the two directional couplers are utilized to moniter the input and output voltage waveforms and transit the signals to the digital storage oscillator.

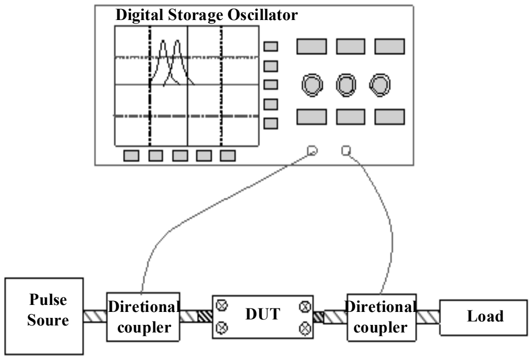

Fig. 9. Configuration of the limiter injection experiments.

In the experiment process, firstly modulated microwave pulses with 200-ns duration, 1-GHz center frequency, 100-Hz repetition rates were generated and amplified by signal source. The power of the pulses increased from 4 dBm (corresponding to its peak voltage Vinpeak=0.5 V) by the step of 3 dB until it reached 50 dBm (Vinpeak=100V). The limiter kept undamaged through this process. After that, the input power continued to be 50 dBm while the pulse duration increased from 200ns by the step of 200 ns until it reached 2 μs. The test time was set as 1 minute in each condition, and the limiter's insertion loss was measured to check its state at each time when the duration was to be adjusted. The limiter still kept undamaged in the above test process. Fig. 10 showed the input and output voltage waveforms when the power was 50 dBm and the duration was 200 ns and 2 μs respectively. It can be observed that peak output voltage Voutpeak=2V, corresponding to the limiting effect about 34 dB.

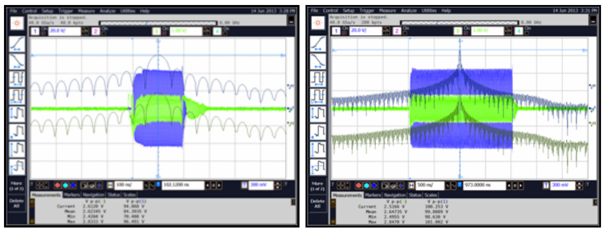

Fig. 10. Input and output voltage waveforms when input microwave pulse power was 50 dBm and the duration was 200 ns (left) and 2 μs (right) respectively. (Vertical, 40 V/div (blue), 2 V/div(green); horizontal, 200 ns/div)

In the next procedure, square pulses with 30-ns duration, 1-ns rising and falling edges, 100-Hz repetition rates were injected into the limiter. The amplitude of the pulse was increased from 40 V by the step of 20 V. The test time was set as 1 minute in each condition, and the limiter's insertion loss was measured to check its state during two different tests. The limiter kept undamaged until the voltage reached 280 V. Fig. 11 shows the input and output voltage waveforms when the input voltage amplitude was 270 V. If we take the amplitudes of the spikes of the input and output pulses as the assess index, the limiting effect is $20*\log_{10}(270/24)$, about 21dB; if the amplitudes of the flattop of the input and output pulses as the assess index, then the limiting effect is $20*\log_{10}(250/6)$, about 32dB.

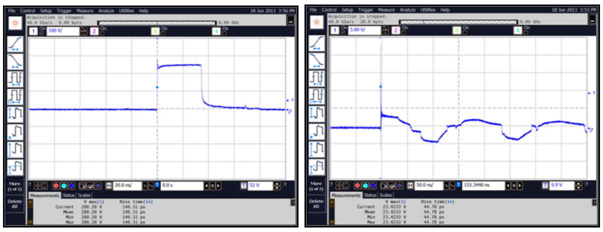

Fig. 11. Input (left) and output (right) voltage waveforms when the input voltage amplitude is 270 V. (Left: vertical, 100 V/div, horizontal, 20 ns/div; right: vertical, 5 V/div, horizontal, 50 ns/div)

IV. CONCLUSION

In this paper we proposed a new limiter design based on multistage PIN diodes and Schottky diodes, which owned the characteristics of high power capability, nanosecond start-up time and low leaking power level. In this limiter, the first stage limiting device was a PIN diode with the relatively thick I layer, the second stage consists of two anti-paralleling PIN diodes of thinner I layer, and the last stage consists of two PIN diodes of the thinnest I layer and two Schottky diodes. Simulation and experimental results showed that the response time of the limiter is less than 1 ns, its power capability about RF/microwave pulses with several microseconds duration is more than 50 dBm, and the limiting effect was more than 30 dB; its voltage capability when faced with square pulses with 30-ns duration, 1-ns rising edge was more than 200V, its limiting effect with reference to rising edge was about 20 dB, and the limiting effect with reference to flattop was more than 30 dB. In the future the work will focus on reduction of the small signal insertion loss so as to expand the limiter's operation frequency range.

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