DISTORTION IN MICROWAVE AND RF SWITCHES BY REVERSE BIASED PIN DIODES

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ABSTRACT

Distortion caused by PIN diode switches can significantly compromise microwave and RF communication system performance. This paper presents an original analytical and experimental study of distortion generated by reverse biased PIN diodes. Concise distortion relationships are presented and compared with the authors' previously published work on forward biased PIN diode distortion. The results indicate that reverse bias distortion can be worse than forward bias distortion, with further degradation as the frequency increases.

INTRODUCTION

Many microwave PIN diode switches have a requirement for maximum permissible distortion. Distortion in switches causes undesired harmonic signals or spurious in-band signals which may result in significant system limitations, particularly in sensitive receiver circuits. A PIN diode switch may contain both forward and reverse biased diodes, each contributing a measure of distortion.

The distortion introduced by a forward biased PIN diode has been analyzed and is now predictable [1-3]. Distortion generated by a reverse biased PIN diode is often not taken into account because it has been assumed to be much lower than that of the forward biased diode and no analysis to date has been reported to predict its distortion generating properties.

This paper reports the results of an original analytical and experimental investigation of the reverse biased PIN diode. Concise distortion prediction expressions have been developed and conclude that reverse biased PIN diodes may generate more distortion than forward biased PIN diodes.

The primary cause of reverse biased PIN diode distortion is the small but finite time varying capacitance induced by the microwave or RF signal. An ideal PIN diode operated at a reverse bias voltage beyond the punchthrough voltage and at frequencies higher than the dielectric relaxation frequency will exhibit no change in capacitance with increasing voltage, and therefore generate no distortion. The actual PIN diode, because of the diffusion tail phenomena, will exhibit a definite capacitance change and will generate real distortion.

As a result of an analysis of diffusion tail capacitance, expressions have been developed relating second and third order distortion to the first and second derivatives of the capacitance-voltage (C-V) characteristic. The predicted intercept points compare favorably to experimental data. It will also be demonstrated that distortion generated by reverse biased PIN diodes worsens with increasing frequency, contrary to the case of the forward biased PIN diode.

ANALYSIS

The analysis of the distortion introduced by the reverse biased PIN diode is based on the nonlinear time varying current passing through the diode [4,5]:

$$i(t) = dQ/dt = d[C\, v_i(t)] \;/\, dt \qquad (1)$$

where C is the PIN diode reverse bias capacitance and $v_i(t)$ is the microwave voltage across the diode. If C is a time-varying capacitance, then i(t) will contain harmonic and intermodulation products, in addition to the fundamental components, that will produce signal distortion in a microwave or RF switching circuit consisting of a series connected PIN diode between generator and load. The distortion analysis focuses on the variation of the PIN diode's reverse bias capacitance and its relationship to the time varying AC voltage.

The capacitance of the ideal PIN diode is generally assumed constant for all reverse bias voltages beyond the punchthrough voltage. In actual PIN diodes, however, the boundaries between the intrinsic layer and the end regions are not exactly abrupt, but rather exhibit a continuously increasing doping concentration that approaches the end region doping concentration. These so-called diffusion tails cause the reverse biased PIN diode's capacitance to continue to decrease for voltages beyond punchthrough, independent of frequency, since the depletion layer will advance into the end regions with increasing reverse bias voltage. The rate of capacitance change with reverse voltage is dependent on this diffusion profile shape, but may be directly determined from measured C-V data. Figures 1 and 2 show the C-V characteristic for 7 and 100 micron I-region width PIN diodes using measurement frequencies of 1 MHz and 1000 MHz that illustrates this. Thicker PIN diodes exhibit flatter C-V profiles than thinner diodes since the depth that the depletion boundary extends into the end region is a smaller portion of the overall device thickness. This results in a lower rate of capacitance change with reverse voltage for thick PIN diodes. Figures 3 and 4 show plots of dC/dV computed from 1 MHz and 1000 MHz C-V data for 7 and 100 micron PIN diodes (Figures 1 and 2) that demonstrate this point.

Equations for the two tone intermodulation distortion intercept points have been derived from Eqn. 1 for the series connected reverse biased PIN diode. They are related to the derivatives of the C-V data, measured at the input frequency, and are expressed as follows:

$$IP2 = 1/32\,(dC/dV)^2\, Z_0{}^3\, (\omega_1 + \omega_2)^2 \qquad (2a)$$

and

$$IP3 = 1/12\,(d^2C/dV^2)\, Z_0{}^2\, (2\omega_1 + \omega_2) \qquad (2b)$$

where ω_1 and ω_2 are the two tone input frequencies. These intercept point equations are referenced to the power available from the source. From these expressions it is evident that the intercept point decreases (distortion increases) as frequency increases. Also, thicker I-region PIN diodes exhibiting a flatter C-V characteristic are expected to perform with better distortion properties than thinner diodes.

APPLICATIONS

Reverse bias distortion intercept points were derived using Eqn. 2 for a series connected PIN diode switch operating around frequencies of 10 and 1000 MHz. These results are shown in Table I. The results are based on C-V measurements and their derivatives taken at 10 MHz and 1000 MHz using the HP4192A LF Impedance Analyzer and the HP4191A RF Impedance Analyzer, respectively.

Table I also illustrates forward bias distortion on the same PIN diodes based on 10 mA resistance and stored charge data [1,2]. These results imply that for the 7 micron PIN diode the reverse bias (-10v) third order relative distortion (dBc) degrades by 32 dB as frequency increases from 10 to 1000 MHz. In the same frequency range the forward bias distortion improves by 60 dB. Also, at 10 MHz the forward bias distortion is the significant contributor whereas at 1000 MHz it is the reverse bias distortion that predominates. In all cases, the reverse bias distortion improves with increasing reverse bias voltage.

Second and third order distortion measurements have been performed at 1000 MHz using series connected reverse biased PIN diodes to verify the theoretical analysis. Figures 5 and 6 show the results of these measurements using previously described techniques for measuring PIN diode circuit distortion [1,2,6]. Good agreement between the measured and computed distortion intercept points is noted. The second order intercept point for the 50 micron PIN diode is approximately 10 dB higher than that of the 7 micron diode. The third order intercept point shows similar behavior. Note that the reverse bias distortion intercept point increases as the reverse bias voltage increases in all cases.

CONCLUSION

The objective of this paper was to provide a better understanding of the distortion mechanism in reverse biased PIN diode switches. The fundamental analytical conclusion is that the magnitude of the reverse bias distortion is inversely proportional to the slope of the C-V characteristic (for second order distortion) and frequency. This is in contrast to the forward bias PIN diode switch distortion case where the distortion improves with increasing frequency. The analysis shows that thick PIN diodes tend to exhibit less distortion than thin diodes. Experimental distortion data taken at 1000 MHz on diodes of different thicknesses confirm this phenomenon.

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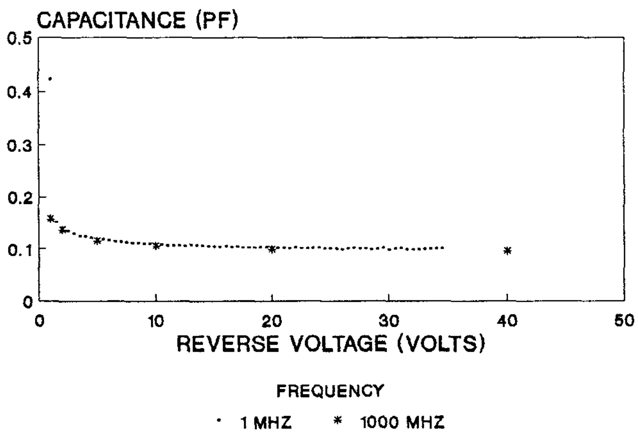

Figure 1. Reverse bias PIN diode capacitance for a 7 micron diode at 1 and 1000 MHz.

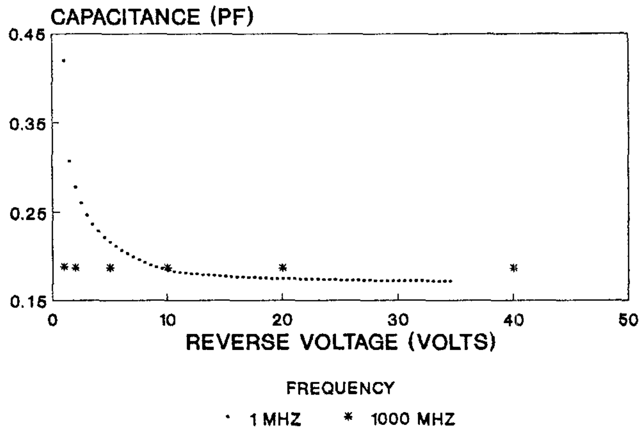

Figure 2. Reverse bias PIN diode capacitance for a 100 micron device at 1 and 1000 MHz.

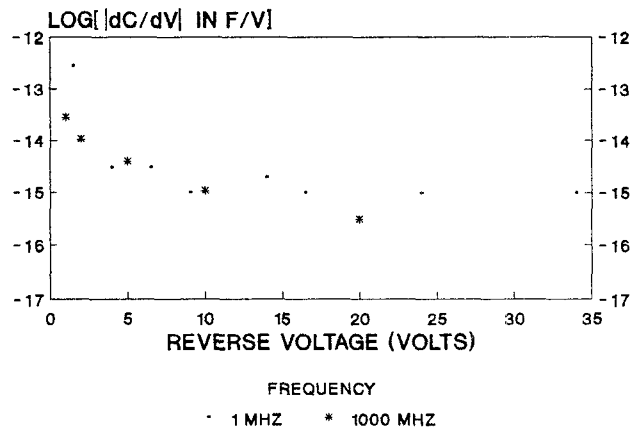

Figure 3. Reverse bias dC/dV at 1 and 1000 MHz for a 7 micron PIN diode.

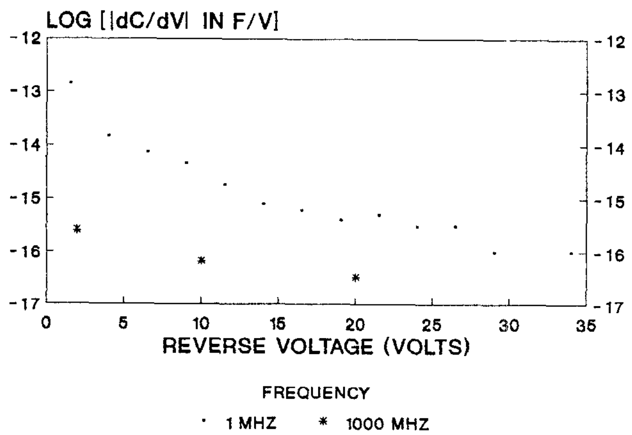

Figure 4. Reverse bias dC/dV at 1 and 1000 MHz for a 100 micron PIN diode.

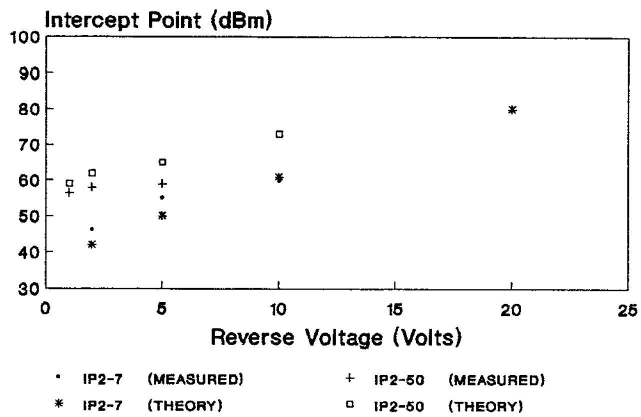

Figure 5. 1000 MHz second order intercept point measurements on a 7 and 50 micron PIN diode.

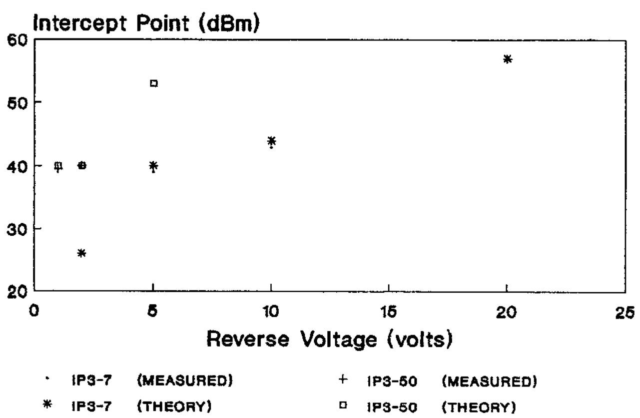

Figure 6. 1000 MHz Third Order Intercept Point Measurements on a 7 and 50 micron PIN diode

TABLE I

Predicted PIN Diode Intercept Points

		REVERSE BIAS				FORWARD BIAS	
Width	Frequency	IP2	IP3	IP2	IP3	IP2	IP3
microns		-10v	-10v	-20v	-20v	+10mA	+10mA
7	10MHz	94dBm	58dBm	102dBm	62dBm	39dBm	28dBm
	1000MHz	61dBm	42dBm	72dBm	47dBm	79dBm	58dBm
100	10MHz	92dBm	60dBm	112dBm	70dBm	77dBm	56dBm
	1000MHz	85dBm	57dBm	91dBm	60dBm	117dBm	86dBm