Distortion Properties of MESFET and PIN Diode Microwave Switches

Robert H. Caverly

Dept. of Electrical and Computer Engineering
University of Massachusetts Dartmouth
N. Dartmouth, MA 02747

Gerald Hiller

Burlington Semiconductor Operations
M/A-COM, Inc.
Burlington, MA 01803

ABSTRACT

This paper presents a comparison of the distortion properties of microwave switches that employ either PIN diodes or GaAs MESFET semiconductor devices. It analyzes the distortion properties of both devices in a typical switch application. This information will enable design engineers to predict distortion performance and will facilitate the choice of either element in a distortion sensitive application. The results of the analysis indicate that either device is capable of performing with third order intercept point at approximately 40 dBm or better at frequencies from 10 MHz through beyond X-Band. This level of distortion is generally satisfactory for many small signal applications. If better distortion performance is required, the PIN diode is superior.

INTRODUCTION

A solid-state microwave switch will probably employ either a gallium arsenide (GaAs) MESFET or a silicon (Si) PIN diode as the semiconductor element. Each offers specific performance features that allow the circuit designer to select the appropriate device to fit a particular application. The PIN diode based switch is capable of operating at lower loss at high microwave frequencies and can handle much higher power levels in comparison to the MESFET. However, the MESFET switch requires virtually zero driver energy through an isolated bias port and can switch faster than a PIN diode.

The distortion generated by the switch is an additional performance characteristic that must be addressed in many switch applications. This paper presents a comparison of the distortion properties of microwave switches that employ either PIN diodes or GaAs MESFET semiconductor devices. It analyzes the distortion properties of both devices in a typical switch application. This information will enable design engineers to predict distortion performance and will facilitate the choice of either element in a distortion sensitive application. The results of the analysis indicate that either device is capable of performing with third order intercept point at approximately 40 dBm or better at frequencies from 10 MHz through beyond X-Band. This level of distortion is generally satisfactory for many small signal applications. If better distortion performance is required, the PIN diode is superior.

ANALYSIS

MESFET Distortion Properties

Distortion in GaAs MESFET switches is governed in the on-state by the nonlinear channel resistance [1]. Here, the RF signal varies the drain-source channel cross section, causing the channel resistance to vary witl
frequency dependence of the MESFET dist
by not only its electronic and geometric
such as pinch off voltage, gate length and perimeter and channel doping, but also by the built-in gate bias circuit cut-off frequency. This cut-off frequency is approximately $1/2\pi Rg(Cgs + Cgd)$ where Rg is the gate bias resistance. The distortion intercept point has been shown to improve in the vicinity of the gate bias circuit cutoff frequency [1] and reaches a maximum at some higher frequency (see Figure 1). For a typical 1 micron device used in a SPDT switch, such as indicated in Figure 1, the maximum third order intercept point is approximately 50 dBm at 1 Ghz. The levels of distortion are relatively constant with frequency below this cut-off frequency. The absolute levels of distortion increase with the open channel current capacity for a given pinch-off voltage. In order to externally control

on-state FET switch distortion it is possible to adjust Rg to shift the cut-off frequency to one more acceptable for the application [2].

In the off-state, the distortion introduced by FET switches is governed by the signal controlled time varying nonlinearities in Cgs and Cgd [3]. The relationship for the post-pinch-off values of Cgs and Cgd are [4]

$$C_i(t) = \varepsilon W \tan^{-1}\left[V_p / V_{bi} - V_p - V_i\right]^{1/2} \quad \text{F} \qquad (1)$$

where V_{bi} is the built-in voltage, V_p is the pinch-off voltage, $V_i = V_{io} + V_i(t)$, V_{io} is the dc bias term, and "i" is "gs" or "gd". The distortion generated in the off-state MESFET is a function of the derivatives of C_i where the (n+1) order distortion is derived using the n^{th} derivative. The first and second derivatives of C_i (used in deriving the second and third order distortion components) can be written as:

$$\frac{dC_i}{dV_i} = \frac{\varepsilon W}{2} \frac{1}{V_{bi} - V_{io}} \sqrt{\frac{V_p}{V_{bi} - V_p - V_{io}}} \quad \frac{F}{V} \qquad (2)$$

$$\frac{d^2C_i}{dV_i^2} = \frac{\varepsilon W}{2} \frac{1}{V_{bi} - V_{io}} \sqrt{\frac{V_p}{V_{bi} - V_p - V_{io}}} \cdot \left[\frac{1}{2V_p} \frac{V_p}{V_{bi} - V_p - V_{io}} + \frac{1}{V_{bi} - V_{io}}\right] \frac{F}{V^2} \qquad (3)$$

The variation of Cgs with Vgs may be reduced by higher levels of reverse bias. The appropriate bias point for both distortion and power handling lies midway between the gate breakdown voltage and the pinch off voltage [3,5].

The results of modeling FET distortion in both switch states may be seen in Figure 1, which shows that the on-state nonlinearity is the dominant distortion mechanism. The off-state distortion shown in Figure 1 is derived using Equations 2 and 3 for the same SPDT switch. The distortion generated by the MESFET in the on-state is more significant than in the off-state, and therefore predominates the net distortion generated.

PIN Diode Distortion Properties

In the forward biased PIN diode, distortion is generated because of the time varying forward resistance. The resistance varies because of the modulation of the PIN diode stored charge by the microwave signal. The forward bias distortion levels may be predicted using Equations 4 and 5 [6]:

$$IP2 = 34 + 20 \log (Q_{nc}\, f_{MHz}/R) \text{ dBm} \qquad (4)$$

$$IP3 = 24 + 15 \log (Q_{nc}\, f_{MHz}/R) \text{ dBm}. \qquad (5)$$

where Q_{nc} is the stored charge in nanocoulombs and f_{MHz} is the operating frequency in megahertz.

Distortion in a forward biased PIN diode may be reduced by selecting PIN diodes with a high ratio of stored charge to diode resistance (Q/R), and may be further minimized by increasing the forward bias current which further increases the Q/R ratio. The steps taken to reduce forward bias PIN diode distortion tend to increase the switching speed of the device because of the increase in stored charge.

In the off-state, the distortion in PIN diodes is governed by RF voltage controlled non-linearities on the instantaneous reverse bias capacitance that occur even beyond the dielectric relaxation frequency [7]. These capacitance variations with voltage are caused primarily by the so-called end region diffusion tail.
usually show smaller capacitance variati
diodes and therefore perform with
However, thicker PIN diodes have an adverse influence on forward bias distortion due to higher forward resistance. These capacitance variations may also be reduced by using processing techniques that provide more abrupt doping transitions (for example, MBE or MOCVD grown material).

Figure 2 shows calculations of third order intercept point for a series connected PIN diode switch in both the on and off-states for a typical PIN diode used in a microwave switch. The diode modeled is dc biased in the forward direction at 10 mA and in the reverse direction at -10 volts. The diode has an I-region thickness of 10 microns and its carrier lifetime is 100ns. Note that at low frequencies, the on-state is the primary contributor to distortion while at high frequencies, the off-state diode predominates the distortion.

COMPARATIVE ANALYSIS

Models were developed for both the on and off-state MESFET and PIN diode which were used in simulating the third order intermodulation distortion produced in a SPDT switch. The switches under consideration contain both on and off-state devices. The models used in the comparison have all been experimentally verified [1,2,6,7]. A composite result is shown in Figure 3 which compares a MESFET SPDT switch distortion with a PIN diode SPDT switch under typical bias conditions for typical devices used in microwave switches. Note that the PIN diode switch shows better distortion performance at frequencies above about 5 MHz. The off-state distortion begins to dominate above the VHF range; however, even here the PIN diode switch has better distortion performance. For both PIN diodes and MESFETs at frequencies above approximately 100 MHz, the third order intercept point is always greater than approximately 40 dBm, a level satisfactory for most applications.

Some significant distinctions between the distortion properties of PIN diodes and GaAs MESFETs should be noted. In a PIN diode switch, virtually unlimited minimal distortion may be achieved primarily by varying the biasing conditions. The consequences of improving the distortion properties are continually slower switching speed and increasingly more bias power. The forward biased PIN diode is the primary contributor to distortion at frequencies below approximately 1 GHz whereas at higher frequencies the reversed biased diode predominates. In a GaAs MESFET switch, the distortion generated in the on-state predominates at all frequencies. This distortion mechanism is the time varying channel resistance which is influenced by the design of the device and the gate bias circuit cut-off frequency. In addition, the distortion generation and the switching speed mechanisms are not strongly related.

ACKNOWLEDGMENT

The work performed at the University of Massachusetts Dartmouth was supported by M/A-COM Burlington Semiconductor Operations.

REFERENCES

1. Caverly, R., "Distortion in Off-state Gallium Arsenide MESFET Switches", *IEEE Trans. Microwave Theory and Tech.*, in review.

2. Gutmann, R. and D. Fryklund, "Characterization of Linear and Nonlinear Properties of GaAs MESFET's for Broad-Band Control Applications", *IEEE Trans. Microwave Theory Tech.*, vol. 35(5), pp. 516-520, May 1987.

3. Caverly, R., "Distortion in Broad-Band GaAs MESFET Control and Switch Circuits", *IEEE Trans. Microwave Theory Tech.*, vol. 39(4), pp. 713-717, April 1991.

4. Takada, T. et. al., "A MESFET Variable Capacitance Model for Gallium Arsenide Integrated Circuit Simulation", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30(5), pp. 719-723, May, 1982.

5. Ayalsi, Y., "Microwave Switching with GaAs FETs", *Microwave J.*, vol. 25, pp. 61-72, Nov. 1982.

6. Caverly, R. and G. Hiller, "Distortion in p-i-n Diode Control Circuits", *IEEE Trans. Microwave Theory Tech.*, vol. 35(5), pp. 492-501, May 1987.

7. Caverly, R. and G. Hiller, "Distoı and RF Switches by Reverse Biased *MTT-S Digest*, vol. III, pp. 1073-1076, June, 1989.

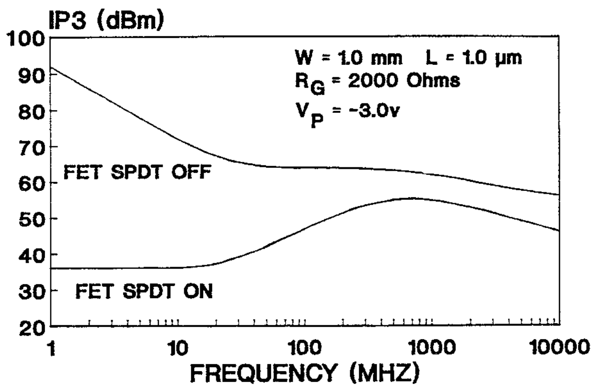

FIGURE 1. Third order on and off-state intermodulation distortion in a GaAs MESFET SPDT switch.

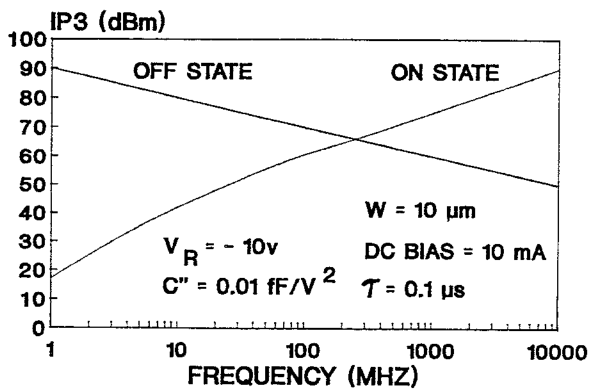

FIGURE 2. Third order on and off-state intermodulation distortion in a PIN diode reflective switch.

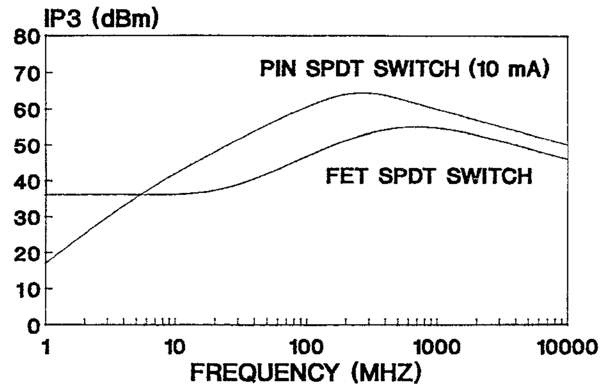

FIGURE 3. Comparison of third order intermodulation distortion in a GaAs MESFET and PIN diode SPDT switch.