USE OF SWITCHING $\hat{Q}$ IN THE DESIGN OF FET MICROWAVE SWITCHES*

H. A. Atwater and R. W. Sudbury

Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02173

ABSTRACT

The application of FET's as microwave switches suitable for monolithic integration is analyzed by means of a procedure based on the switching $\hat{Q}$ of Kurokawa and Schlosser. Factors determining the $\hat{Q}$ of FET's for switching are discussed.

Introduction

In microwave and millimeter wave modulators for both amplitude and phase modulation, use is frequently made of semiconductor devices in two impedance states under different bias conditions. This paper describes a systematic criterion for the characterization of devices for such applications, based on the switching $\hat{Q}$ of Kurokawa and Schlosser. The procedure is particularly useful in the development of monolithic circuits where impedance-transforming elements may be integrated on the substrate together with the device structure. The use of a depletion-mode MESFET as a two-state bidirectional switch is described and the switching $\hat{Q}$ is determined from the equivalent circuit. The power theorem of Hines is applied to FET impedance switches to establish switching power limitations.

Switching Quality Factor

For switching modulators which utilize the reflection from switched two-state semiconductor terminating impedances, Kurokawa and Schlosser proposed the switching figure of merit[1]:

$$\hat{Q}^2 = \frac{|Z_1-Z_2|^2}{R_1R_2} \qquad \text{(1a)}$$

$$\hat{Q}^2 = \frac{4|\Gamma_1-\Gamma_2|^2}{(1-|\Gamma_1|^2)(1-|\Gamma_2|^2)} \qquad \text{(1b)} \qquad (1)$$

where Z_1 and Z_2 are the two impedance states of the reflection terminations, R_1 and R_2 are their resistive components, and Γ_1 and Γ_2 the reflection coefficients of Z_1 and Z_2. The numerical value of the $\hat{Q}$ parameter is preserved under impedance transformation by a lossless impedance transformer. The two impedance states Z_1 and Z_2 can be readily determined by microwave network analyzer measurement, and may include any tuning or resonating elements included with the device[2].

For the reflection switch, Γ_1 and Γ_2 in Equation 1b are the transfer functions of the switch in its two operating states. The performance characteristics of a reflection switch are presented in a plot of Γ_1 vs. Γ_2 with $\hat{Q}$ as a curve parameter in Figure 1. In this paper, the terms 'isolation' and 'forward loss' are used to designate the insertion loss for the switch in its 'off' and 'on' conditions, respectively. Each point on these curves represents the operating characteristics of a reflection switch that can be achieved with devices having the $\hat{Q}$ value indicated. These curves correspond to zero phase shift of Γ. The operating point of a switch may be moved along its curve of constant $\hat{Q}$ by lossless impedance transformation. The peaks of the curves in Figure 1 correspond to the condition in which one impedance state (Z_1 or Z_2) is transformed to present a matched termination, corresponding to infinite isolation. The curves in Figure 1 are symmetrical about a line at 45° with the axes. Hence, each axis represents isolation or forward loss, depending upon which arbitrary selection of Z_1 and Z_2 for the two states is made.

By the use of Eq. (1a), the transfer function diagrams may be constructed for any switching circuit for which the transfer function, or the forward scattering factor S_{12}, is known as a function of the two-state impedance (Z_1, Z_2) in the switching circuit. Figure 2 is the transfer function diagram for one output channel of an SPDT, or T/R switch, with zero phase shift. This figure applies to both the SPDT switch constructed with switching elements connected in series, or in shunt with $\lambda/4$ line sections for isolation. The curves for the SPDT switch indicate the existence of two available circuit solutions for each $\hat{Q}$ and forward loss. The curves exhibit a minimum available forward loss for each $\hat{Q}$ value.

The transfer curves of four idealized switching circuits using devices for a $\hat{Q}^2$=1000 are plotted for comparison in Figure 3. This figure shows that the maximum isolation at low forward loss is obtainable as indicated by curve D with the reflection switch. The single shunt or series element switch is shown in curve B. Another switch type, the combination shunt-series switch, in which shunt and series-connected semiconductors are connected electrically close to-

---

*This work was sponsored by the Department of the Army.

0149-645X/81/0000-0370$00.75

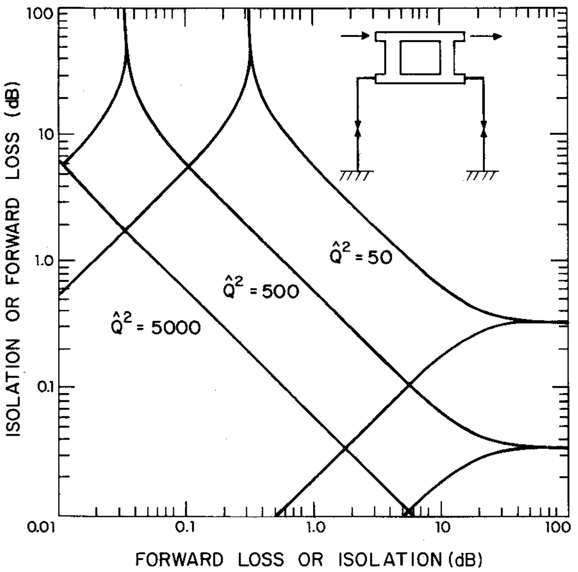

Fig. 1. Transfer characteristics of hybrid-coupled reflection switch

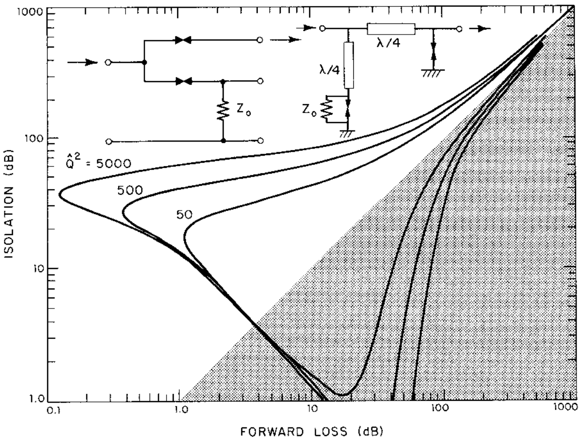

Fig. 2. Transfer characteristics of SPDT (T/R) switch of either of two circuit types

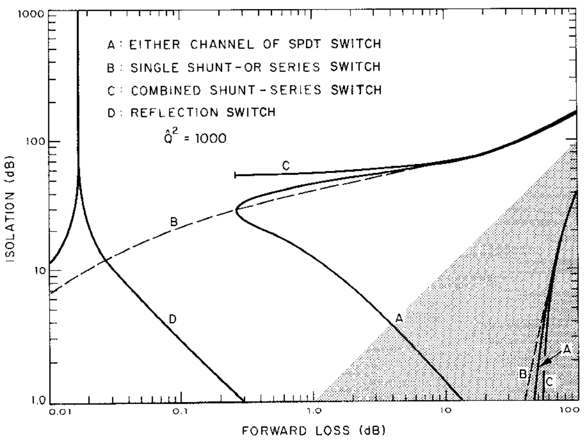

Fig. 3. Transfer characteristics for four switching circuits using semiconductor having $\hat{Q}^2$=1000

gether on the line is shown as curve C. This combination is terminated at a lower bound of insertion loss, when composed of real positive resistances. For comparison curve A shows the transfer curve for the SPDT switch previously described.

MESFET $\hat{Q}$ Parameter

The FET structure is shown in Figure 4 with a circuit model appropriate for switching analysis. The two impedance states may be represented as in Figure 5, and the $\hat{Q}$ expression (1a) becomes:

$$\hat{Q}^2 = \frac{R_C^2 + X_C^2}{R_S(R_S + R_C)} \qquad (2)$$

where X_C is the effective reactance from drain to source. Assuming for the low-resistance state: $R_C \ll X_C$, (2) becomes:

$$\hat{Q} = \frac{1}{\sqrt{R_S(R_S+R_C)}\ \omega C} \qquad (3)$$

which is equivalent to the Hines[3] form of device Q for diodes with differing forward and reverse bias resistances.

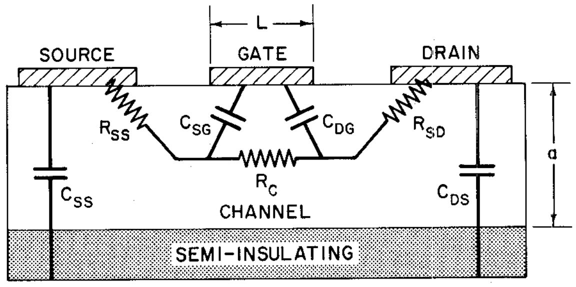

Fig. 4. MESFET structure showing equivalent circuit components

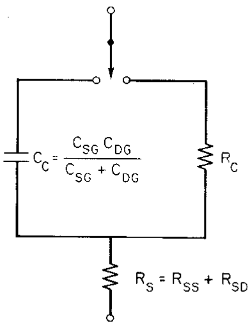

Fig. 5. Simplified switching circuit model for MESFET source-drain path

Power Theorem

Hines fundamental switching theorem[3] for diodes switches is general and can be derived from the $\hat{Q}$ expression and has also been derived from Tellegen's theorems.[4] In the latter form Hines theorem is:

$$|\Gamma^0 - \Gamma^S| \le \left| \frac{I_d^S V_d^0 - I_d^0 V_d^S}{4P_{incident}} \right| \qquad (4)$$

where the voltages and currents are half-amplitudes (one half the peak to peak value) and the superscripts S and 0 denotes the low impedance and high impedance states respectively. With $I_d^0 V_d^S << I_d^S V_d^0$ it takes the form given by Hines.

$$|\Gamma^0 - \Gamma^S| \le \left|\frac{I_d^S V_d^0}{4P_{\text{incident}}}\right| \qquad (5)$$

Increasing the magnitude of the gate bias shifts the breakdown voltage to a lower value and increases the magnitude of reverse drain bias voltage possible before significant current flows. The maximum peak to peak voltage is the breakdown voltage reduced by the pinchoff voltage $(V_B + V_P)$. The maximum half-amplitude current is limited to I_{DS}. Using the typical FET switch characteristic in Fig. 6 this can be expressed in terms of FET parameters as

$$|\Gamma^0 - \Gamma^S| \le \left|\frac{I_{DS}\,(V_B+V_P)}{8P_{\text{incident}}}\right| \qquad (6)$$

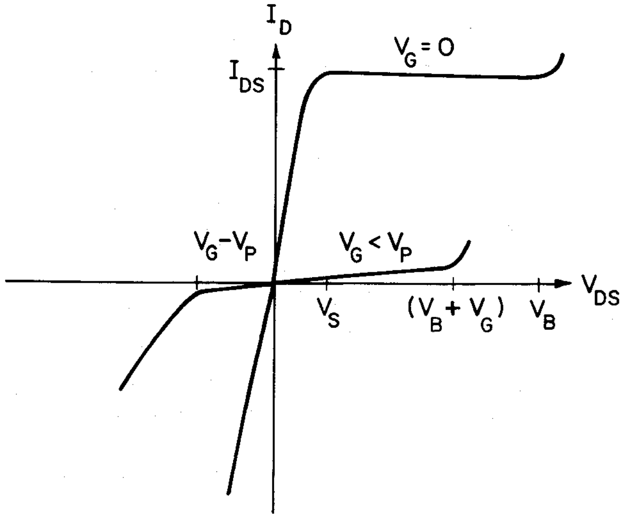

Fig. 6. FET drain characteristic curves

For a typical microwave power FET [5] which is not thermally limited, with I_{DS} = 350 mA/mm, V_B = +30 V, and V_{pinchoff} = - 5V, so that

$$|\Gamma^0 - \Gamma^S| \le \frac{|I_{DS}(V_B + V_P)|}{8P_{\text{incident}}} = \frac{1.1 \text{ Volt Amperes/mm}}{P_{\text{incident}}} \qquad (7)$$

Note that for a device in class A operation the maximum power (P_M) is limited by

$$P_M = \frac{I_{DS}}{8}(V_B + V_P - V_S) < \frac{I_{DS}}{8}(V_B + V_P) \qquad (8)$$

but for most GaAs FET's, the power limitation in the Hines expression can be approximated by the Class A power rating.

References

1. K. Kurokawa, W. O. Schlosser, "Quality Factor of Switching Diodes for Digital Modulation," Proc. IEEE, vol. 38, pp.180-181, January 1970.

2. W. V. McLevige, V. Sokolov, "Microwave Switching with Parallel-Resonated GaAs FET's," IEEE Electron Device Letters, vol. EDL-1, pp.156-158, August 1980.

3. M. E. Hines, "Fundamental Limitations in RF Switching and Phase Shifting Using Semiconductor Diodes," Proc. IEEE, vol. 52, pp.697-708, June 1964, Eq. (29).

4. R. Penfield, R. Spence, S. Duinker, "Tellegen's Theorem and Electrical Networks," Research Monograph No. 58, M.I.T. Press, Cambridge, Mass., 1970, p.93.

5. J. V. Dilorenso, W. R. Wisseman, "GaAs Power MESFET's, Design, Fabrication and Performance," IEEE Trans. Microwave Theory Tech., vol. MTT-27, pp.367-377, May 1979.