A Compact T/R Switching Circuit Using Quadrature Couplers and Drain-Driven HPAs

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ABSTRACT

A novel T/R switching circuit is proposed for microwave T/R modules. It consists of balanced high-power amplifiers with quadrature couplers, and a low-noise amplifier which is connected to the isolation port of the coupler. In RX-mode, the HPAs are switched off by controlling drain voltage of FETs. A prototype C- to Ku-band T/R switching circuit has been fabricated, and the validity of our switching method has been confirmed experimentally.

INTRODUCTION

Microwave T/R module is one of basic components in a wide range of communication and radar applications [1]-[3]. Circulators have been used conventionally to switch TX and RX in the module, but they suffer high costs and large area in active phased-array antenna where thousands of T/R modules have to be mounted. Furthermore, their characteristics can be unsatisfactory in more than one-octave bandwidth operation required in some radar applications. More sophisticated T/R switching circuit without circulators has been proposed by Mehhary [1], where a low-noise amplifier for RX is connected to isolation port of a quadrature coupler which constitutes a balanced high-power amplifier (HPA) for TX. In [1], high-power switches are employed at the output to meet the requirement of high reflection coefficient at the output of the HPA in RX-mode. However, they degrade the output power and efficiency of HPA significantly.

To overcome these problems, we have proposed a novel T/R switching circuit where the switches at the output of the HPAs in [1] have been removed thoroughly. In the circuit, TX-mode and RX-mode are switched by controlling drain voltages of the HPAs. By controlling drain voltages rather than gate voltages, higher reflection coefficient at the output of the HPA can be obtained to reduce RX-loss. In addition, a prototype C- to Ku-band T/R switching circuit has been fabricated with high-power MMIC amplifiers, and the validity of our switching method has been confirmed experimentally.

CONFIGURATION OF THE T/R SWITCHING CIRCUITS

Figs. 1(a) and 1(b) show schematic diagrams of the conventional [1] and the novel T/R switching circuits, respectively. In the Figs, HPAs are configured in balanced shape with quadrature couplers, and a low-noise amplifier (LNA) for RX is connected to the isolation port of the output coupler. In RX-mode, the received signal at the

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antenna is divided with quadrature phase difference, and the divided signals come to the output ports of each HPA, then they are reflected back and combined in-phase at the isolation port of the coupler where LNA is connected. In TX-mode, the output signals from each HPAs have quadrature phase difference due to the coupler at the input of the balanced amplifier, and they are combined in-phase at the antenna port and out-of-phase at the isolation port of the coupler where the LNA is connected. Hence, T/R switching can be realized without circulator, and as a result, its loss and the size of T/R module can be reduced significantly.

In the above circuits, reflection coefficient Γ_{off} at the output of HPA in its off-state (RX-mode) must be high to reduce RX-loss because it is expressed by 20logΓ_{off} (dB). To obtain high Γ_{off}, FET switches have been employed conventionally as shown in Fig. 1(a). However, they make the size of the T/R module larger and degrade the output power and efficiency of the HPAs significantly due to their losses. On the contrary, in our novel circuit in Fig. 1(b), the switches are removed and the FETs in the HPAs are switched on and off by controlling their drain voltages. As a result, the loss in TX-mode is reduced, and the size of the T/R module can be reduced even further.

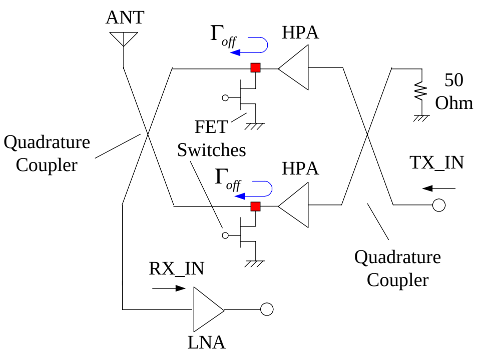

Fig. 1(a) Conventional T/R switching circuit.

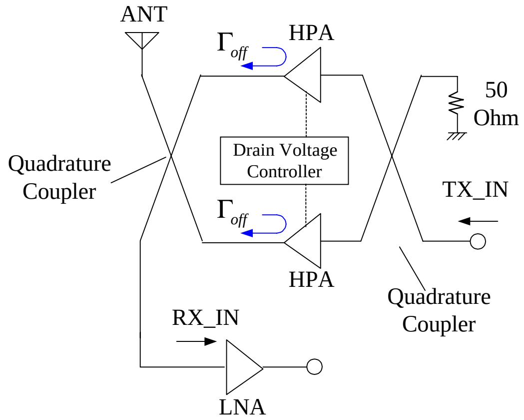

Fig. 1(b) Proposed T/R switching circuit.

BIAS DEPENDENCE OF REFLECTION COEFFICIENT AT THE OUTPUT OF HPA

As mentioned above, the reflection coefficient Γ_{off} at the output of the HPA in its off-state (RX-mode) must be as high as possible. In this paper, bias dependence of Γ_{off} of a high-power MMIC amplifier shown in Fig. 2 has been measured. The MMIC employs an AlGaAs/InGaAs pHEMT [4] with gate width of 1.6 mm in the driver stage and the same pHEMTs with gate width of 2$\times$2.4 mm in the power stage, and its output power is P_{1dB} = 30 dBm in C- to Ku- band. The measured Γ_{off} 's are plotted in Fig. 3, where bias voltages are set to three conditions as shown in Table I. As can be seen from Fig. 3, Γ_{off} can be almost highest in the condition (c) in the measured frequencies.

Table I Bias conditions of FETs in its off-state

	V_d [V]	V_g [V]
(a)	6.0 (on)	-2.0 (off)
(b)	0.0 (off)	-2.0 (off)
(c)	0.0 (off)	0.0 (on)

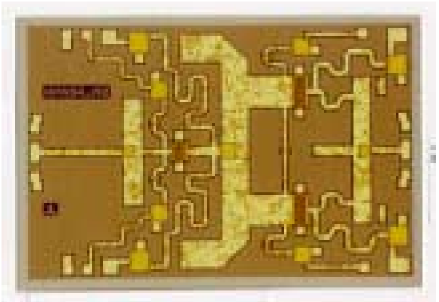

Fig. 2 Photograph of C- to Ku-band high-power MMIC amplifier.

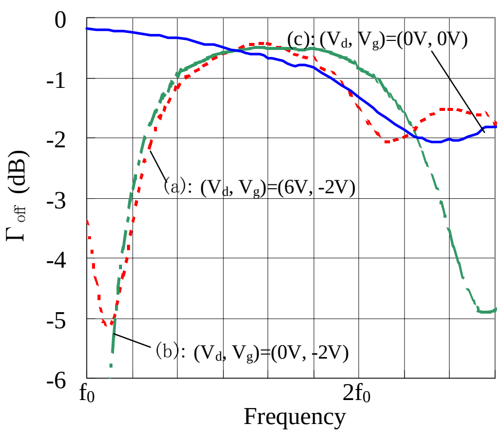

Fig. 3 Measured Γ_{off} 's of the MMIC amplifier.

This is explained by an equivalent circuit of the output stage in the MMIC shown in Fig. 4. In the equivalent circuit, drain-to-source resistance R_{ds} has bias dependence and it is calculated by

$$R_{ds} = \left(\partial I_{ds} / \partial V_{ds}\right)^{-1}$$

which is the inverse of the slope in I_d-V_d characteristics of the FET as shown in Fig. 5.

Hence, R_{ds} becomes smaller in the linear region than in the saturation region, and R_{ds} becomes smaller as V_g increases as shown in [5]. As a result, the bias condition (c) makes R_{ds} smallest among the three bias conditions (a) – (c), where the output of the FET is almost short-circuited and Γ_{off} becomes highest. On the contrary in the bias conditions (a) and (b), R_{ds} becomes larger and the matching circuit at the gate of the FET can be more visible through the gate-to-drain capacitance C_{gd}, which decreases Γ_{off} and makes Γ_{off} frequency-sensitive.

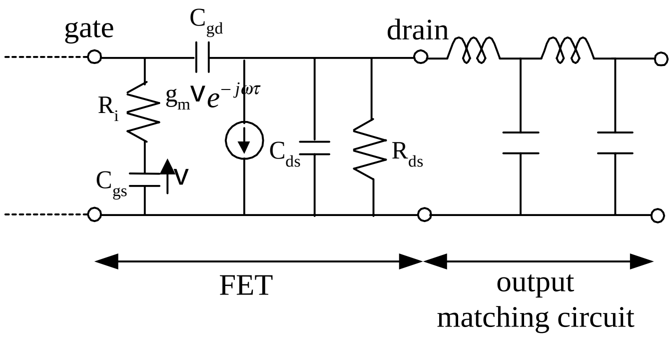

Fig. 4 Equivalent circuit of the output stage in the MMIC amplifier.

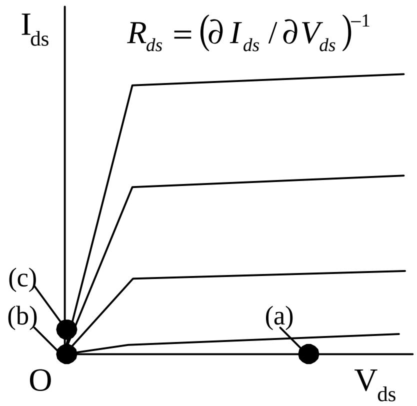

Fig. 5 I_d-V_d characteristics of FET.

PROTOTYPE T/R SWITCHING CIRCUIT

Fig. 6 shows a photograph of a prototype C- to Ku- band T/R switching circuit. The MMICs shown in Fig. 2 and Lange couplers as quadrature couplers are employed. Fig. 7 shows the measured RX-loss (transmission from RX-port to ANT-port with TX-IN port terminated by 50-Ohm resistor in Fig. 6). The measured RX-loss is less than 2 dB in more than octave-bandwidth, which includes the losses of extrinsic connectors and 50-Ohm lines for the measurement. In addition, isolation of about 10 dB is obtained between TX-port and RX-port in the measurement. It is almost the same value of a commercially available octave-bandwidth circulator .

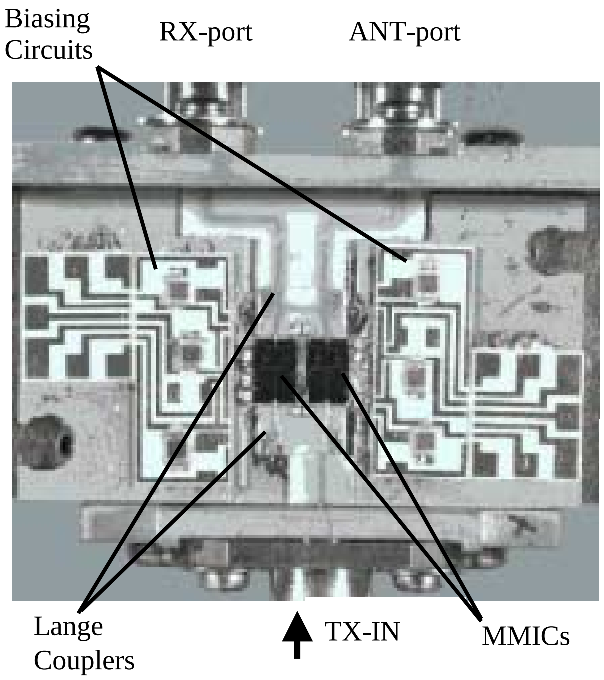

Fig. 6 Photograph of the prototype T/R switching circuit.

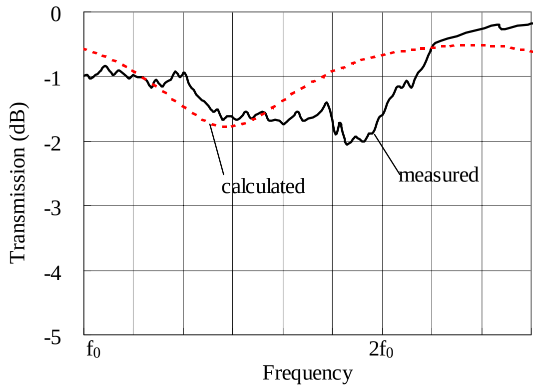

Fig. 7 Measured RX-loss of the T/R switching circuit.

CONCLUSION

A compact T/R switching circuit has been proposed for microwave T/R modules. It consists of balanced high-power amplifiers with quadrature couplers, and it can eliminate circulators and/or T/R switches in conventional T/R switching methods. In our circuit, low-noise amplifier for RX is connected to the isolation port of the coupler in the balanced HPA circuit, and the HPAs are switched on and off by controlling drain voltage to obtain high reflection coefficient at the output of HPA for reducing RX-loss. Furthermore, a prototype C- to Ku-band T/R switching circuit employing high-power MMIC amplifiers have been fabricated and the validity of our switching method has been confirmed experimentally.

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