Fully Terminated Ka Band High Isolation, High Power MMIC SPDT Switch in GaAs PIN Technology

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Abstract — **In this paper we present the design and performance of a millimeter wave MMIC SPDT switch. The switch is produced in a GaAs PIN process. The switch is fully terminated in all 3 ports due to an integrated resistor layer in the PIN process, and has an OFF state. The isolation is better than 40 db, return loss better than 20 db in all states. The power handling capability exceeds 5 watt. To our best knowledge, this is the first reported millimeter wave switch to posses all of the above properties.**

I. INTRODUCTION

High power switches in Ka band are critical elements for many transmit/receive systems (communication, radar, EW, etc.). To achieve the high power handling capability it is necessary to use PIN diode MMIC technology. Several MMIC switches based on PIN technology have been reported in the literature starting from the late eighties ([1]-[6]), however, none of the above has <u>all</u> the necessary capabilities: power handling (several watts), high isolation (40 db), good matching (20 db), non-reflective (matched under all operation states, including OFF) and fast switching (several nanoseconds). In this paper we present the design and performance of an SPDT switch, which posses all of the above properties. The switch is manufactured in a GaAs PIN process featuring shunt diodes with high breakdown voltage and resistive layer to allow on-chip terminations. In section II a brief description of the PIN process is presented. The diode structure and model used in the design are outlined in section III. The switch specifications are depicted in section IV, and the design is described in section V. The measurements and performance are presented in section VI.

II. PIN TECHNOLOGY

A SEM photograph of a PIN diode in a coplanar structure used for measurement and characterization is depicted in Fig. 1. The PIN diode is processed on a GaAs substrate with an epitaxial layer containing the PIN layers. The diode structure is vertical with the cathode at the bottom and the anode on the top. Air bridge is used to connect the anode to the circuit. In Fig.1 the cathode is connected to the coplanar ground. In the microstrip version the cathode is connected to the backside of the substrate (ground) by two via holes. The PIN process includes also Silicon Nitride capacitors and Tantalum Nitride resistors (enable on-chip terminations). The total topography of the epitaxial layer and metal layers is around 6 microns. This constitutes a big lithography challenge. The diodes breakdown voltage is guaranteed to 60 volt, and is typically around 70 volt. The diodes can handle current densities as high as 60 kv/cm^2 at elevated temperatures. The high breakdown voltage coupled with the high current density capability allow high power handling (several watts at Ka Band).

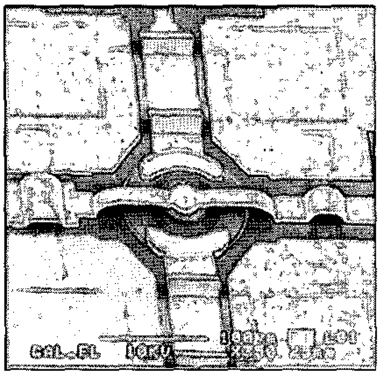

Fig. 1 SEM photograph of coplanar PIN diode

III. DIODE STRUCTURE AND MODEL

The microstrip shunt diode cell consist of the diode itself, two via holes, one of each side connecting the cathode to ground and two air-bridge lines, one on each side, connecting the Anode to the transmission lines. A photograph of the diode is depicted in Fig. 2.

Diode Off capacitance is determined by the diode diameter. Air-bridge parameters affect the associated parasitics as well as power handling capability of the switch. Therefore, a wide air-bridge (28 microns) was chosen to enable maximum power capability. The wide air-bridge results also in lower impedance and better switch performance including lower losses.

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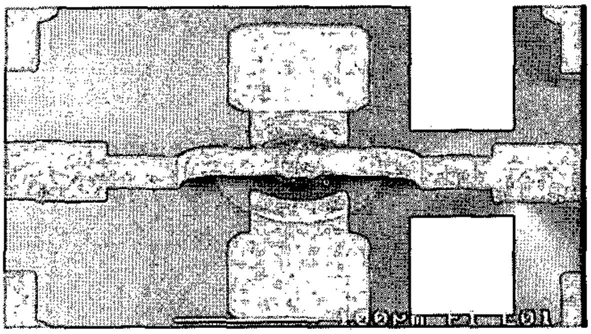

Fig. 2 The microstrip PIN diode

The diode cell model includes the diode itself, the via holes and the air-bridges. The model of the diode is presented in Fig. 3. The via holes are modeled as inductances. The air-bridges are modeled as transmission lines based on EM simulation that was performed by IE3D by Zealand Inc. The simulation of the air-bridge as transmission line included all physical dimensions : GaAs substrate parameters, air-bridge height above the GaAs substrate and metal thickness. The transmission line impedance and Effective dielectric constant are extracted and used as a model of the air-bridges in the diode cell model.

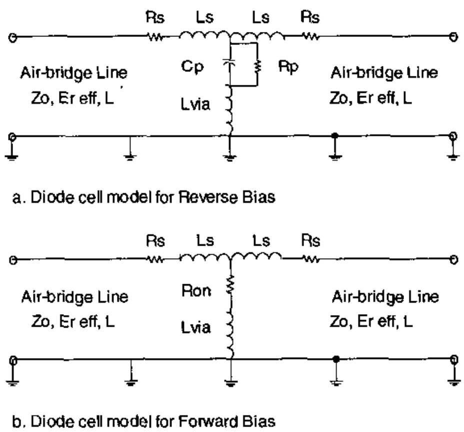

Fig. 3 The diode equivalent circuit model

The parameter extraction for the above diode model was performed by an accurate measurement of the diode over a wide frequency range followed by an extraction procedure. The model described above was used for the design of the switch.

The diode cell parameter extraction process is iterative since certain S-Parameters are determined by more than one diode parameter. The parameters are extracted as follows:

1. Diode Off capacitance, Cp is extracted from S21[dB] @ reverse bias. Best fit was achieved with the capacitance slightly frequency dependent following the equation :
$Cp = Cp0 + K * F(GHz)$; $K = 0.00036$
2. Air-bridge electrical length for reverse bias model is extracted from S21[Ang] @ reverse bias.
Step 1 and 2 are repeated iteratively until good fit of both S21[dB] and S21[Ang] is achieved.
3. Diode forward resistance, Ron is extracted from S21[dB] @ forward bias at low frequency (15GHz).
4. Via holes inductance, Ls is extracted from S21[dB] @ forward bias and high frequency (40GHz) since the inductance is affecting the diode performance mostly at higher frequencies.
5. Air-bridge electrical length for forward diode model is extracted from S11[Ang] @ forward bias. This parameter was extracted in step 2 above but it is somewhat smaller for forward bias since the returned power is considered here and not the through power as in step 2.
6. Parallel resistance at reverse bias, Rp is evaluated from S21[Ang] @ reverse bias and at high frequency (40GHz).
7. Series resistance, Rs is evaluated from S21[dB] @ reverse bias and at low frequency (5GHz).
8. Series inductance, Ls is negligible.

IV. SWITCH SPECIFICATIONS

The switch specifications are listed below:

Frequency range:	High Ka Band
Bandwidth:	2-3 GHz
Isolation:	>40 db
Return Loss (all states): (Non-Reflective)	>15 db
Insertion Loss:	<1.5 db
Power handling:	>5 watt

V. SWITCH DESIGN

A complete layout of the switch is depicted in Fig. 4. The layout shows clearly the input port at the top and two output ports (left and right) as well as the control ports for the diodes (bottom). Two diodes are used in each branch to obtain the required isolation. The switch is matched under all operating conditions. This is achieved by use of on chip terminations (50 ohm) on each port, which are switched ON/OFF depending on the state of each port. A port in OFF state is connected to its termination, thus achieving good matching in all states.

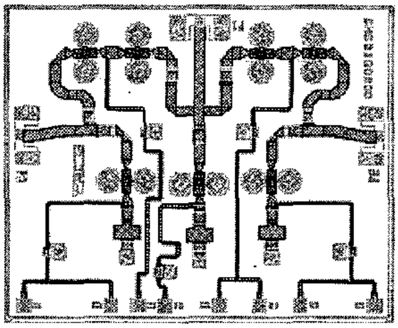

Fig. 4 Layout of the switch

This non-reflective property is very important for many applications, and can ensure unconditional stability of the transceiver under all operating conditions. Naturally, the addition of the extra diodes and resistors increases somewhat the chip size, however, the benefit of this property well exceeds the disadvantage of chip size increase. The size of the chip in Fig. 4 is 2.8x2.3 mm^2. The additional resistors and diodes increase the insertion loss of the switch. Our switch has an insertion loss of less than 1.5 db. A similar switch which is not non-reflective may have a loss of perhaps 1.2-1.3 db.

VI. MEASUREMENTS

The testing of the switch has been performed by measuring its 3-port S parameters in all three states by use of a standard network analyzer. The performance of the switch is depicted in Figs. 5-8. In Fig. 5 the insertion loss is shown. As can be seen, at the band of interest the insertion loss is less than 1.5 db. The isolation is depicted in Fig. 6. An isolation of better than 40 db is exhibited over a very wide bandwidth. The return loss of the input and output ports is shown in Fig. 7 for the ON state and in Fig. 8 for the OFF state. Good return loss is shown for both states, as expected for a non-reflective switch. For the small signal measurements each diode was driven into its ON state by a 20 mA DC current, and a 5 volt reverse voltage was applied for the OFF state.

Power measurements were performed by applying a power of 5 watt and measuring the insertion loss. The measurement was made initially with the small signal bias conditions, however, a substantial increase of the insertion loss was found due to RF switching. To solve the problem, in the OFF state a voltage of almost 20 volt was applied to the diodes. This completely solved the problem, and the measured insertion loss was the same as for small signal. The switching speed of the diodes depends strongly on the driver, and can be as low as a few nanoseconds.

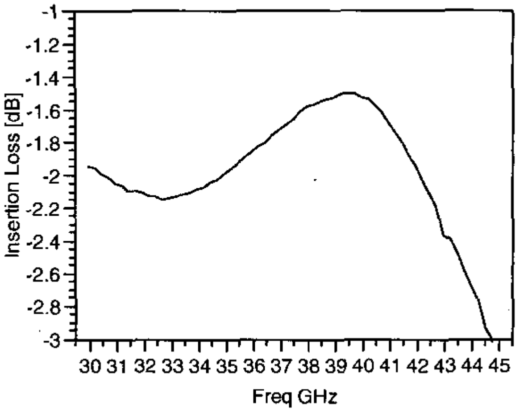

Fig 5 Insertion Loss of the switch (ON state)

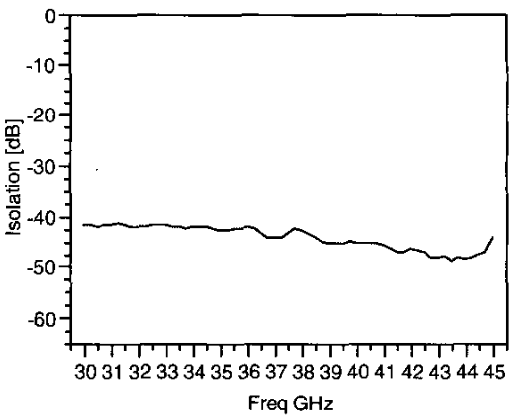

Fig. 6 Isolation of the switch (OFF state)

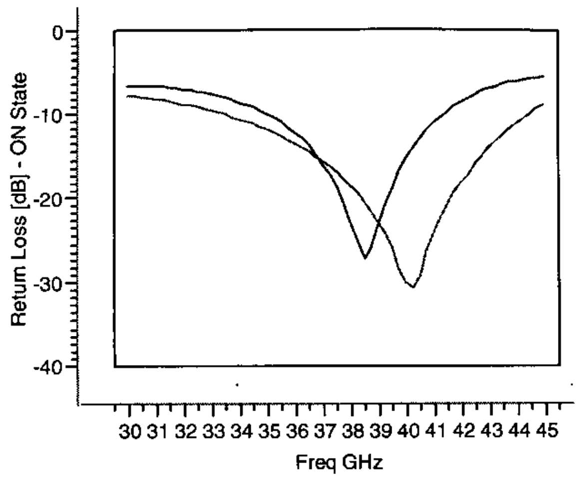

Fig. 7 Input & Output Return Loss (ON state)

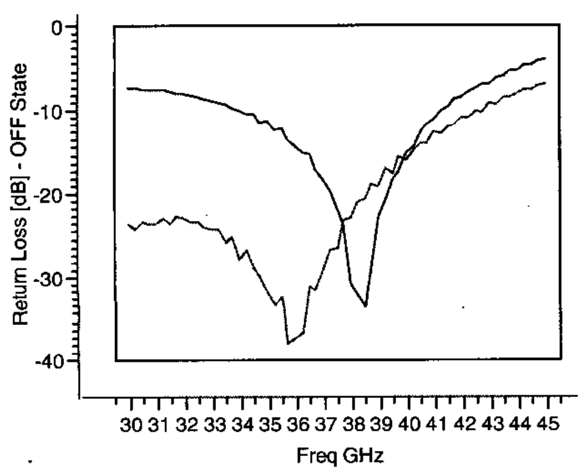

Fig. 8 Input & Output Return Loss (OFF state)

VII. CONCLUSIONS

In this paper the design and performance of a high power high isolation MMIC PIN switch is presented. The switch posses all the necessary properties of a T/R switch for transceivers in Ka Band. To our best knowledge, this is the first published T/R switch around 40 GHz which has 5 watt power handling capability, 40 db isolation, good return loss and fully terminated (non-reflective).

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