EM Analysis of Ka Band Multi-Throw PIN Diode MMIC Switches

Andrzej Rozbicki, James J. Brogle
M/A-COM Technology Solutions Holdings, Inc. (“MACOM”)
Lowell, Massachusetts, USA
andrzej.rozbicki@macom.com

***Abstract*— Advantages and results of using a 3D EM simulator such as HFSS to design a compact integrated circuit (IC) are presented. Any electromagnetic (EM) fields’ disturbances and interactions caused by the size and shapes of high frequency circuit elements have a significant effect on IC performance, die size and cost. Two SP4T four-throw PIN diode switches with different topologies are analyzed. The first switch uses a topology of two shunt diode with ¼ wavelength elements. The second switch uses series-series-shunt diode topology. Both switches have integrated bias circuits and DC blocking capacitors. These SP4T switches use the patented MACOM AlGaAs heterojunction PIN Diode process. The optimal performance was achieved due to intense use of the EM simulator.**

Keywords*— *AlGaAs; PIN diode; monolithic microwave integrated circuit; switch; Ka Band;

I. Introduction

A PIN diode is a P-N junction with an intrinsic layer (I-region), located between the P-layer and the N-layer. The pin diode’s special feature is the relatively wide intrinsic layer that provides unique properties. In OFF state the diode is represented as constant capacitance C_j and high brake down voltage. In ON state the diode acts like a resistor R_{RF} which varies approximately linearly with the forward bias current.

In the ON state (forward bias), a PIN diode for small signals at high frequencies (F>0.5*π*τ) [1], behaves like a resistor. The resistor value is determine entirely by the injected charge, proportional to the DC bias current (J_F) because the stored carriers in the intrinsic layer are not completely swept away by the RF signal or by recombination.

The dynamic RF resistance R_{RF} is simply given by [1]:

$$R_{RF} = \frac{W^2}{J_F\,\tau\,(\mu_n + \mu_p)\,A} \tag{1}$$

Where: A–anode area, W–intrinsic layer width, ρ–resistivity, μ_n–electron mobility, μ_p–hole mobility, τ–carrier lifetime, q–unit electron charge, Δn–concentration of free electrons.

The R_{RF} resistance plus diodes contacts make the diode’s series resistance R_s. In the OFF state (reverse bias) a PIN diode’s intrinsic layer is depleted of electrical charges and has high resistivity and the dielectric constant of a semiconductor material (GaAs in case of this design). The electrical field is constant and the diode forms a capacitor which capacitance is approximated by: $C_j = \varepsilon * A/\mathbf{W}$, where ε – semiconductor permittivity. At maximum electrical field, the breakdown voltage can be estimated by $V_{BD} = E_m * W$, where E_m-maximum electrical field.

In EM simulations the intrinsic I-region is represented by either a high-resistivity GaAs-layer in OFF state or with a conductive material in ON state. The conductivity is defined by a process of measuring group of diodes and curve fitting to equivalent HFSS model.

II. A Multi-Throw Switch

A multi-throw switch at a high frequency requires careful design of each circuit element. The main circuit elements of a switch, shown in Fig. 1 and Fig. 3, and their corresponding schematics in Fig. 2 and Fig. 4 in die form are: RF bond pads, DC capacitors, Common arm, Signal junction (four-throw for SP4T switch), Signal arms that consist of shunt

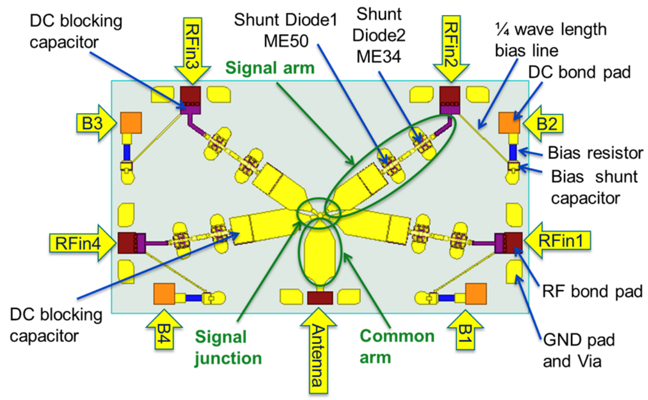

Fig. 1. SP4T shunt PIN diode switch.

and/or series PIN diodes connected with air bridges (in case of shunt-only configuration, as shown in Fig. 1.; the signal arm requires ¼ wavelength transmission lines which are presented in the schematic Fig. 2 by TL1, TL2, TL3, and TL4), and a Bias circuits that consist of ¼ wavelength transmission lines (RF chokes) and shunt capacitors, and DC bond pads.

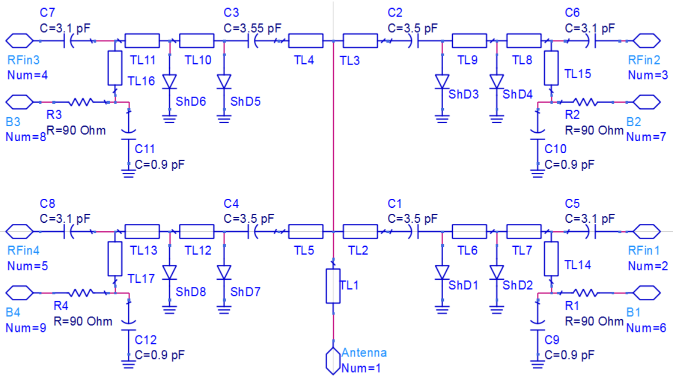

Fig. 2. Schematic of the SP4T shunt PIN diode switch.

The challenge of the design of a multi-throw switch is to achieve best and well matched RF performance between each RF input in the smallest die area that directly relates to the cost of the product.

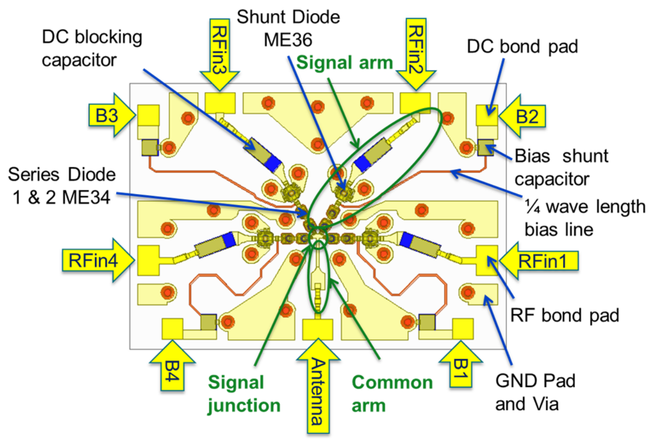

Fig. 3. SP4T series-shunt PIN diode switch.

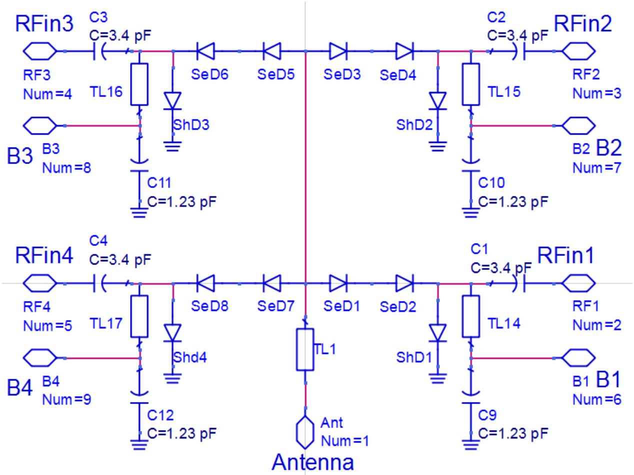

Fig. 4. Schematic of the SP4T series-shunt PIN diode switch.

Any detail of this type of circuit element has a significant influence on the performance of the switch. For example, the configuration and design of the signal junction can change the switch performance.

In case of the shunt diode switch configuration the multi-throw signal junctions needs low capacitance and requires ¼ wavelength in each signal arm connected to the junction. In addition, the junction, common arm, and each signal arm should provide electrical paths that have the lowest disturbance of an electromagnetic (EM) field. The series-shunt diode switch requires very short connections to each series diode and high impedance of the common arm to compensate for the capacitance of series diode in off state.

III. Electromagnetic (EM) Field Analysis Discussion

Detailed analysis of EM fields help to identify weaknesses and disturbances which are diminishing optimal EM flow in passive structures. An example of such analysis is the four-throw junction structure of the shunt diode switch with quarter wavelength transmission lines.

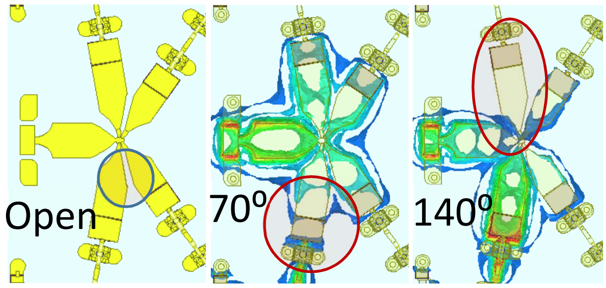

Fig. 5. "Open" junction and corresponding E-Field envelope at 70deg phase and 140deg phase.

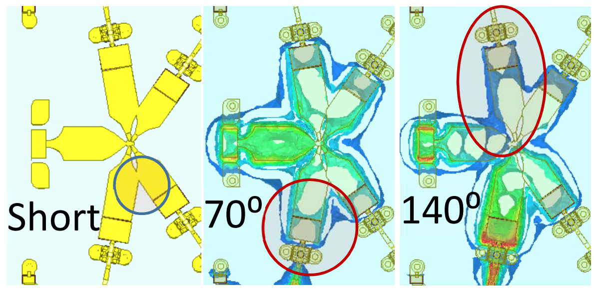

Fig. 6. "Shorted" junction and corresponding E-Field envelope at 70deg phase and 140deg phase.

Fig. 5 and Fig. 6 shows two very similar four-throw signal junctions. Each junction connects 5 signal arms over a narrow transmission line that results in a low capacitive structure. Each of these arms spreads out of the center and has no more connection to the adjacent arm. This junction we will call an "open junction", see Fig. 5.

The second junction (Fig. 6) has the same structure at the center, but 180um into each signal arm there is a metal connection between two adjacent signal arms; we will call this junction a "shorted junction".

At the frequency of interest of 30GHz and below, the "shorted" junction has much lower reflection coefficient (Fig. 7) at the antenna and output ports compared to the "open" junction reflection coefficient (Fig. 7). Markers m1, m2, m3, and m4 are set at 30 GHz.

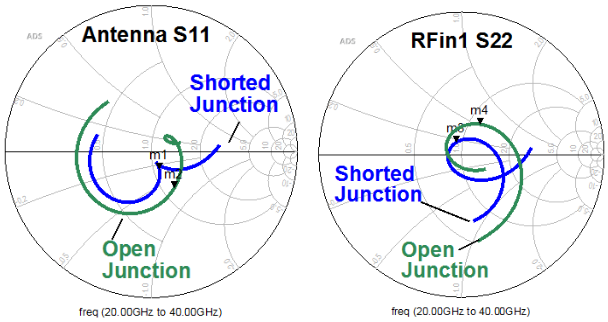

Fig. 7. Antenna and RFin1 Return Loss of "shorted" and "open" junction.

EM field's distribution (Fig. 5 and Fig. 6) shows a difference between these two junctions. In the case of the "open" junction, the EM field strength is collapsing before the first shunt diode of the signal arm in ON state. The signal arm is in ON state when the shunt diode is in the OFF state.

In the case of the "shorted" junction we observe that the EM field is evenly spread at each first shunt diode, independent of the state of the diode; see the blue envelope line Fig.5 and Fig. 6 which represents EM field strength of 1000V/m.

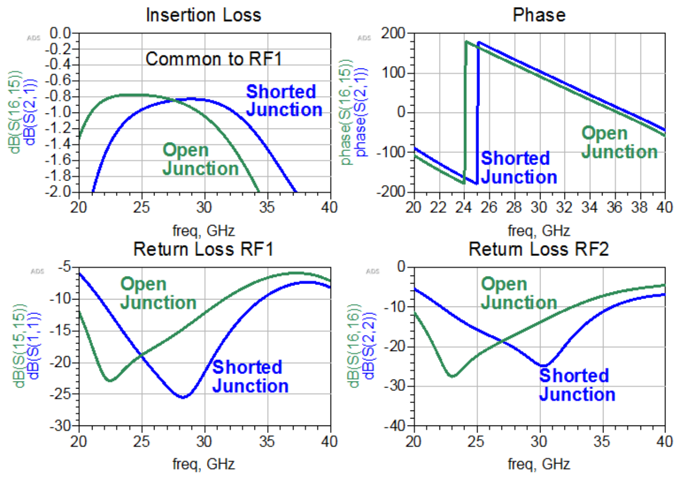

Fig. 8. "Open junction" vs "shorted junction"-HFSS simulation results.

The "shorted" junction stays in balance from 70 deg to 140 deg compare to the "open" junction which is in balance from about 80 deg to 130 deg. The longer balance period of EM fields results in better performance of the switch.

The described EM field disturbance is directly reflected in the performance of the switch. We observe a significant shift to loer frequency in the performance of the "open" junction.

The center of optimum performance of the "open" junction is shifted by 7 GHz, as shown in Fig. 8, to lower frequency and that automatically sets the insertion loss performance to lower frequency too. In addition, at frequencies below 30 GHz the "shorted" junction provides more equal RF performance between all signal paths.

The measured results of a switch with the "shorted" junction overlap with the HFSS simulations as shown in Fig. 9.

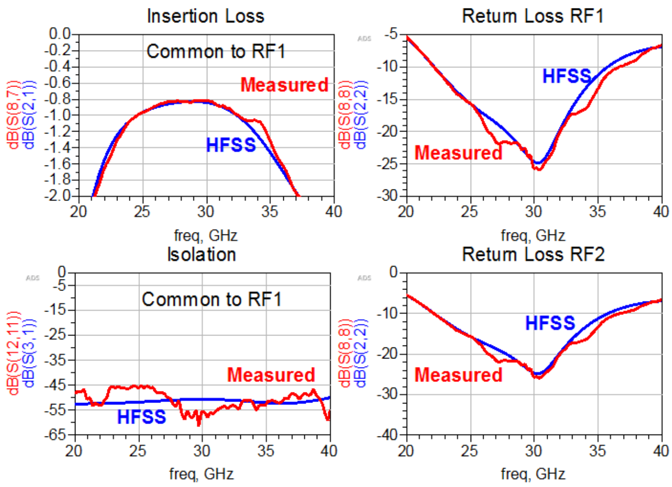

Fig. 9. On Wafer measured vs. HFSS simulated results; shorted junction SP4T shunt diode switch in each signal arm.

IV. SP4T Series-Shunt Diode Switch

The Ka Band SP4T PIN Diode Switch with two series diodes and one shunt diode in each arm is shown in Fig. 3 and its corresponding schematic in Fig. 4. In this case the flow of RF signal is controlled by a set of series diodes combined with shunt diode. There is no need for ¼ wavelength elements which limit significantly the frequency band of such switch. The series shunt switch has frequency band from 13 GHz to 37 GHz compare to the shunt only switch which bend is from 22 GHz to 35 GHz.

The series-shunt configuration is much easier to balance with as short as possible connections and symmetrical spread of circuit elements see Fig. 3 and Fig. 10. To achieve the best performance we need to maintain balance between the common arm and the capacitance Cd of series diodes in OFF state.

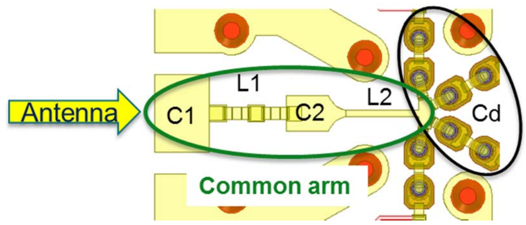

Fig. 10. Antenna to center junction connection of the series-shunt switch.

The balance was achieved duo to creating C1-L1-C2-L2-Cd tuning structure. Where the C1 is the antenna pad capacitance; L1 is an air bridge; C2 is the pad between L1 and L2; L2 is the connection to center junction connecting series diodes, see Fig. 10.

As presented in Fig. 11 the measured parameters are comparable with HFSS simulation results.

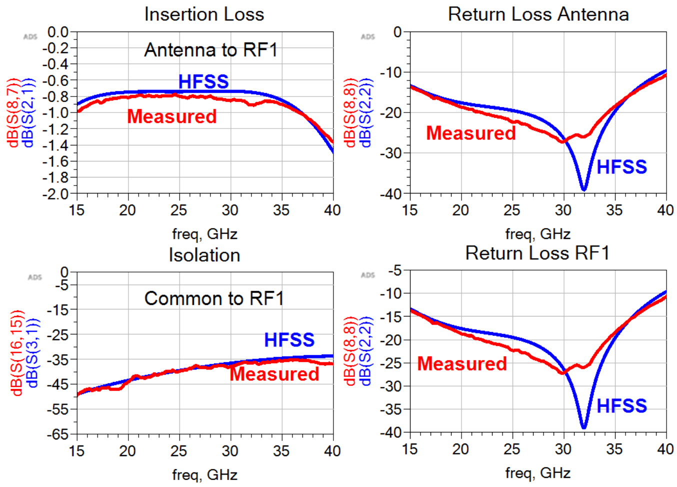

Fig. 11. SP4T series-shunt diode switch; Insertion Loss and Isolation measured on wafer vs. HFSS simulated results

V. Results

Both switches were designed with the goal to provide the best possible parameters in the frequency range from 26 GHz to 33 GHz.

The series-shunt switch has typical insertion loss below 1dB from 15 GHz to 37 GHz. The input/output return loss more than 20 dB from 22GHz to 32 GHz and better than 10dB from 13 GHz to 40 GHz. The isolation is 35dB to 40 GHz.

The shunt switch has typical insertion loss below 1dB from 25 GHz to 32 GHz. The input/output return loss more than 20 dB from 28GHz to 32 GHz and better than 10dB from 22 GHz to 35 GHz. The isolation is 45dB to 40 GHz and 55dB at 30Ghz.

The series-shunt Switch can handle 30dBm of CW RF input power. Measured P0.1dB was better than 31dBm. Measured IP3 from 26 to 32 GHz is more than 43 dBm.

VI. Conclusion

These two switches described herein demonstrate excellent RF characteristics at lower Ka Band frequencies from 26 GHz to 33GHz. The measured results show that despite the different configuration, the shunt diode switch has the same insertion loss as the series-shunt diode switch at the frequency of interest. Both switches have better than 1dB insertion loss from 25 GHz to 33GHz and good flatness. The insertion loss is the lowest reported for these types of switches in the literature.

The series-shunt diode switch has a wider frequency band of 13 GHz to 37GHz compared to the shunt diode switch with 22 GHz to 35 GHz, due to the ¼ wavelength design.

As expected the shunt diode switch has achieved a high isolation of 55dB due to the use of two shunt diodes connected with a transmission line representing about 30° of electrical length. The series-shunt diode switch isolation is 20dB lower at 30GHz.

From the cost point of view, the series-shunt diode switch, which occupies 2.95mm^2 of area, is much more cost effective compared to the shunt diode switch, which size is 6.06mm^2

The performance was achieved as a result of two main factors: MACOM's unique manufacturing process and the extensive involvement of high quality simulation tools such as HFSS and ADS. The presented design is a good example of how important 3D EM simulations are in assisting in the development of a product. It has been proven that HFSS is a very precise RF simulator that offers many useful tools for the design engineer to make it possible to create and achieve complicated high frequency MMIC circuit and be successful in the first run.

Finally, the performance of the designs presented exceeds that of any other reported MMIC switch operating in the lower Ka Band frequency range.

References

[1] S.M. Sze and Kwok K. Ng, Physics of semiconductor devices, Hoboken, New Jersey: John Wiley & Sons, Inc, 2007.

[2] M. F. Iskander, Electromagnetic Fields and Waves. Prospect Heights, IL: Waveland Press, Inc., 2000.

[3] D. Hoag, D. Curcio, T. Boles, "Development of High Voltage mmW GaAs PIN Diode Switch", GaAs MANTECH, 2001