A High Power, mmW, AlGaAs PIN Diode Switch

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Abstract:

The design and performance of high power, millimeter wave, MMIC switches based on the patented MACOM AlGaAsheterojunction PIN diode process is presented. It will be seen that the design process of a reflective SPDT shunt switch switch, extensively utilized HFSS and ADS software. This switch was designed to meet demanding requirements of low insertion, loss less than 0.8 dB, >40dBm CW power handling, and achieving a minimum isolation of 30dB.

Key Words: AlGaAs, PIN diode, monolithic microwave integrated circuit; switch, Ka Band

II INTRODUCTION

Monolithic microwaveintegrated circuits (MMICs) based on high power PIN diodesare increasingly used for many transmit/receive systems in advanced defense electronics and telecommunications applications. Examples of such systems include radar, half-duplex data links, Internet-protocol-based (IP-based) wireless LAN's, and millimeter-wave imagers. For such applications, switches are required to have high power handling, low insertion loss, good matching, fast switching,andfor non-reflective switches good return loss in off state.

While the use of bandgap engineering has been widely applied to bipolar transistors fabricated in elemental silicon and group IV materials, i.e. SiGe, SiC, SiGeC, etc.; and III-V compounds, i.e. GaAs, AlGaAs, InGaAs, InGaP, InP, etc., the application of this technology to high frequency, microwave, and mmW diode structures was largely ignored. MA-COM Technology Solutions' patented development of the heterojunctionAlGaAs/GaAs PIN diode [1]-[3] is one of those rare improvements, the first reported application of a wide bandgapheterojunction used in place of a conventional p-n junction, contained in a PIN diode structure that only enhances the diode RF and microwave performance with no trade-off in any other characteristic.

III DISCUSSION

During the development of this technology, it was found that the recombination rate for electrons at the P+ GaAs - I-region junction is sizable in comparison to the P+ AlGaAsheterojunction. The combination of lower recombination rates and higher carrier injection will yield a greater number of carriers thus lowering the effective resistivity of the I-region. This effect is demonstrated by the fact that the average measured insertion loss response for a SP3T switch manufactured in GaAs and AlGaAsexhibits a difference of 0.12 dB at 20GHz[5]-[7].

Analysis of the simplified impedances presented by a PIN diode at microwave frequencies, the resistance R_S under forward bias and the capacitance C_T under reverse bias, leads to basic equations for insertion loss (IL) and isolation (ISO) of the basic switch topologies[4], as given below, with the assumption that the R_S and the C_T of both series and shunt diodes are identical. These are first-order approximations that do not include diode and interconnect parasitics, nor the effect of adding multiple arms to the switch. In practical designs, these secondary effects must be accounted for, and one can take advantage of ¼ wave transformations in the case of shunt diode designs and impedance matching in all cases.

$$\underline{\text{Series}}\ IL = 20 \cdot \log_{10}\left[1 + \left(\frac{R_S}{2 \cdot Z_0}\right)\right] \tag{1}$$

$$\underline{\text{Series}}\ ISO = 10 \cdot \log_{10}\left[1 + \left(\frac{X_C}{2 \cdot Z_0}\right)^2\right] \tag{2}$$

$$\underline{\text{Shunt}}\ IL = 10 \cdot \log_{10}\left[1 + \left(\frac{Z_0}{2 \cdot X_C}\right)^2\right] \tag{3}$$

$$\underline{\text{Shunt}}\ ISO = 20 \cdot \log_{10}\left[1 + \left(\frac{Z_0}{2 \cdot R_S}\right)\right] \tag{4}$$

Single-pole-multi-throw switches may be designed in a number of topologies, all of which are based upon "series" configurations where series elements are the gating devices in each arm of the switch, or "shunt" structures where shunt diodes are the gating devices in each arm. In fact, a series of PIN based switch circuits, in SPST through SP8T configurations fabricated utilizing AlGaAs PIN diode structures have been produced, tested, and have demonstrated excellent broadband RF performance from 50 MHz through 50 GHz[8].

For series configured switches, the RF energy in the "on" arm is flowing through the series PIN diode. It can be seen from the above equations that the RF power handling is limited by the dissipation and the insertion loss in this series element. For shunt configured switches, the RF energy in the "on" arm is not flowing through the PIN diode, but instead is being transferred from input to output through low loss, high Q transmission lines. In this case the RF dissipation is primarily due to I^2R losses in the metallic conductors with the diode blocking element DC reverse biased in an off-state. The insertion loss in this shunt configuration is limited by the diode shunt capacitance and for multi-throw configurations the loss in the ¼ wave transformers need to provide isolation between switch arms.

IV Results

Based upon the technological advance achieved in the fundamental operation of heterojunction, anode GaAs PIN diodes and the modes of switch operation described above, a shunt configured SPDT AlGaAs/GaAs PIN diode switch was chosen as the best candidate to achieve high power handling, more definitelygreater than 10 watts of RF power, at mmW frequencies, explicitly covering Ka-Band. This switch approach has the advantage of essentially no RF energy being dissipated in the PIN diode, with the only disadvantage ofa limited operating frequency range of approximately one octave due to the bandwidth of the requisite ¼ wave transformers.

The designand the simulated performance of a reflective SPDT shunt switch coving the 24 GHz to 40 GHz frequency band, including on chip matchingcomponents, require accurate device models for the active AlGaAs PIN diodes and ADS and HFSS software for electromagnetic and structure modeling.

In order to correctly predict the performance of the circuit, first an ADS equivalent circuit model of the AlGaAs PIN diode that will be used in the shunt configured switch must be generated. DetailedAlGaAs PIN diode equivalent device modelswere derived from the measured S-parameters of existing AlGaAs PIN diodes that were employed in the broadband commercial PIN switch family and are shown in Figure 1 and Figure 2.

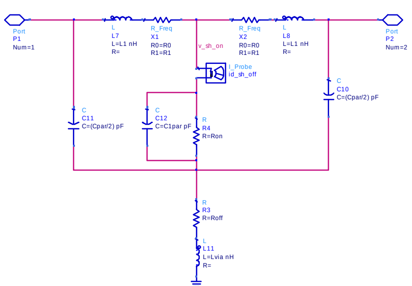

Fig. 1. On State Diode Model in ADS

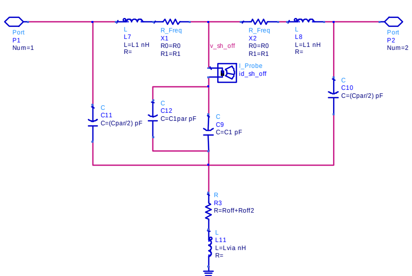

Fig. 2. Off State Diode Model in ADS

The S-parameters were then transformed to extract a resistance versus frequency curve for forward biased diode and shunt capacitance versus frequency for reverse biased diode. The size/capacitance of the shunt diode was optimized so that the diode is both capable of operating through 40 GHz and has the ability to handle the maximum peak power of 10 wattsthrough the switch.

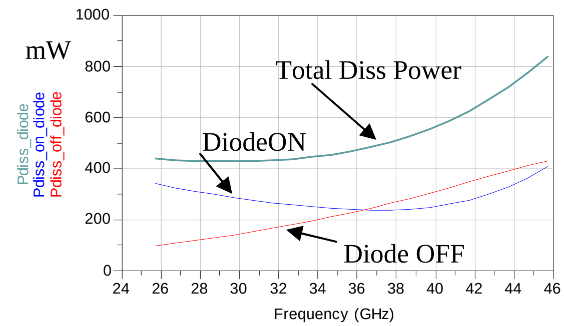

Fig.3 Dissipation Power for the Shunt Diode at 10 watts of Incident Power at 40 GHz

A simple thermal analysis was performed to insure that the diode selected would handle high power conditions.Simulated power dissipation, shown in Figure 3,predicts that for diodes in the off state should not exceed 300mWand for both diodes in the circuit at any given state should not exceed 550mW at 10 watts of incident RF energy at the high end of the desired operating band, 40 GHz[9].

Once the capacitive and thermal properties of the diode were optimized for power and frequency operation, an HFSS model of the shunt diode was extracted and used in impedance matching simulations to further optimize the switch insertion loss, isolation, and return loss.

Circuit insertion losses were optimized by properly selecting the elements for a low ripple Chebyshev response.Lower insertion loss of theshunt diode switch can be achievedby lowering theoverall system impedance. At 50 ohms for a given shunt diode having a C_T=0.12pf, the theoretical insertion loss is 1.5dB. If the system impedance is reduced to 40 ohms the insertion losscould be reduced to 1.0dB, and at 30 ohms0.63dB can be obtained. Using HFSS modeling, this approach was appliedto this high power Ka-Band design.

The quarter wavelength section of each arm was carefully simulated and the impedance was lowered so that at 35GHz the impedance is 38ohms. In order to maintain relatively high return loss and low VSWR the common arm was designed also asa quarter wavelength section with lower impedance in range of 36ohms. To compensate the lower impedance of the input,a section of transmition line connecting the quarter wavelength section with the input test pad that represents high impedance. Each section of these transmition lines were modeled using HFSS and simulation of the whole system were performed in ADS software.

The results of this combined ADS E&M and HFSS structure modeling for the SPDT all shunt switch over a 24 GHz to 42 GHz frequency range is presented in Figure 4 below. This simulation includes the reactive effects of a lossless bondwire interconnectionof 0.075 nH at each port of the switch. It can be seen that a reasonably flat response can be expected for all the switch parameters across this entire frequency band.

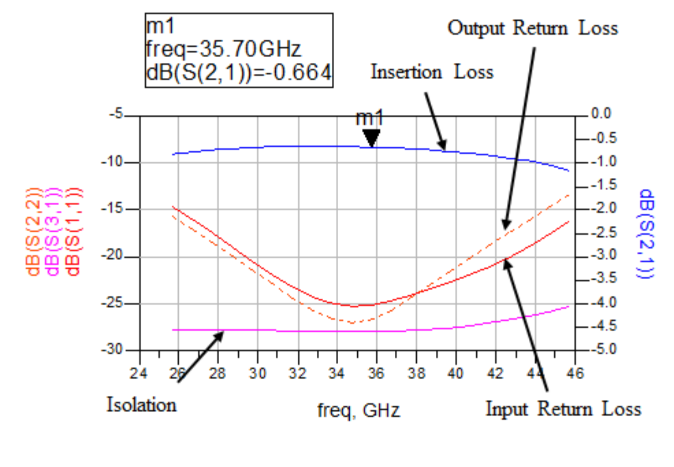

Fig. 4. Simulated Insertion Loss, Isolation, Input Return Loss, and Output Return Loss for the High Power mmW SPDT Shunt Switch

A photomicrograph of the final result of this process optimization process is shown in Figure 5.As can be seen, the trace connecting the bias pad and its capacitor to the armpresents a high pass filter and functions well in the desired frequency range of 30GHz to 40 GHz. Each arm was designed as a low impedance quarter-wave transmition line which ends in a high impedance air-bridgeconnected to the shunt diode anode. The width of the bridge was chosen so that it can handle high RF current density and provides the proper transformation with the Rs and Cj of the diode. To lower the diode's inductance to ground as well as to balance diode's symmetry the cathode is connected to the ground over two vias symmetrically placed on each side. The RF outputs are connected with the shunt diode over a high impedance transmition line that includes a blocking capacitorand was analyzed/optimized in HFSS for bestperformance.

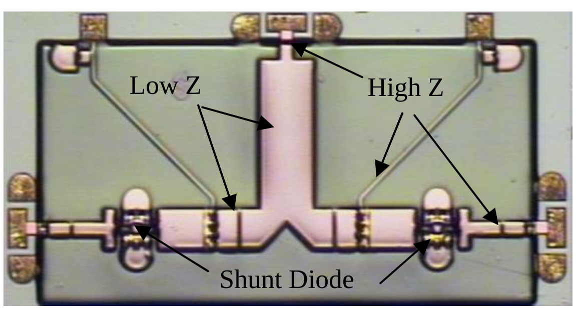

Fig. 5. Photomicrograph of the reflective KA-Band SPDT switch

A typical insertion loss of 0.55dB was achieved at 35 GHz and a maximum0.67dB was observed over the 30 GHz to 40 GHz band. Typical isolation ranged from28dB to 30dB over the same frequency range. This performance is presented in Figure 6.

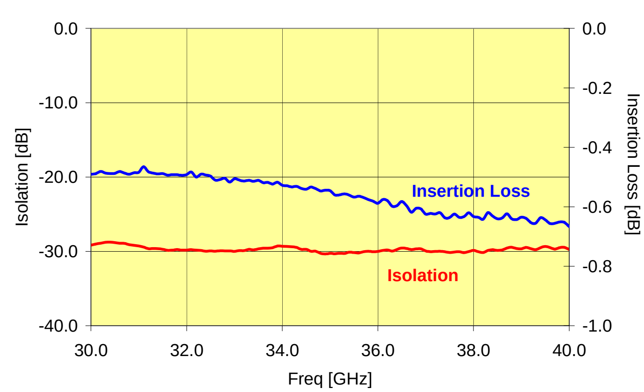

Fig. 6. Measured Insertion Loss and Isolation of Ka-Band SPDT high power shunt switch

Finally, the SPDT switch underwent high power testing in a brass fixture, at a frequency of 29 GHz, an 85°C baseplate temperature, with a 25 volt back bias applied to the shunt diode in the "on" arm, and included a thermal scan to measure the junction temperature AlGaAs PIN diode. The input power to the switch under these bias conditions was 41.2dBm, 13.2 watts, results are shown in Figure 7. It can be seen that under these drive conditions the maximum junction temperature occurred, as expected, directly over the shunt PIN diode in the "on" arm. The measured peak junction temperature was found to be 148.9°C, which is just below the specified reliability limit of 150°C for GaAs devices. Combined with the 85°C baseplate temperature a peak thermal resistance of 28.8°C/W is easily computed. These measurements clearly demonstrate the ability of this Ka-Band SPDT shunt diode AlGaAs PIN diode switch to reliably handle greater than 10 watts of incident power.

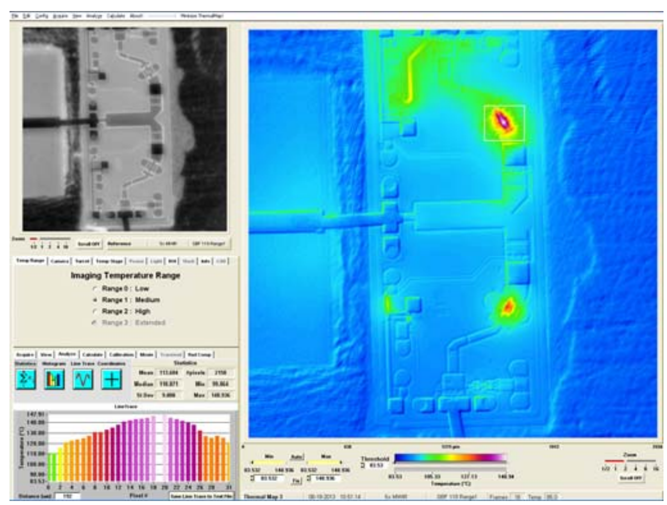

Fig. 7. Thermal Scan of AlGaAs/GaAs PIN Diode Switch under Power Testing at 29 GHz

V CONCLUSION

The Ka band PIN diode shunt configured switch described above has demonstrated both excellent RF characteristics and high power handling capabilities. This reflective switch has an insertion loss of 0.65dB at 35GHz and good flatness between 30 GHz and 40 GHz. Isolation is better than 27dB from 30 GHz to 40 GHz. The switch demonstrated power handling of 41.2 dBm, 13.2 watts,under CW operating conditions at a baseplate temperature of 85°C and a frequency of 29 GHz.

The high level of performance of this shunt configured switch was achieved as a resultof two main factors: MACOM's unique AlGaAsheterojunction PIN diode structure and intensive involvement of high quality simulation tools, HFSS and ADS.

REFERENCES

[1] D. Hoag, J. Brogle, T. Boles, D. Curcio, and D. Russell, "Heterojunction PIN diode switch," in *2003 IEEE MTT-S International Microwave Symposium Digest*, 2003, vol. 1, pp. 255-258.

[2] D. Hoag, T. Boles, and J. Brogle, "Heterojunction P-I-N diode and method of making the same," U.S. Patent 6794734, Sept. 21, 2004.

[3] D. Hoag, T. Boles, and J. Brogle, "Method of making heterojunction P-I-N diode," U.S. Patent 7049181, May23, 2006.

[4] "AG312 application note," MA-COM, Lowell, MA, USA.

[5] K. Kobayashi, L. Tran, A. Oki, and D. Streit, "A 50 MHz-30 GHz broadband co-planar waveguide SPDT PIN diode switch with 45-dB isolation," *IEEE Microwave And Guided Wave Letters*, vol. 5, no. 2, pp. 56-58, Feb. 1995.

[6] J-L. Lee, D. Zych, E. Reese, and D. Drury, "Monolithic 2-18 GHz low loss, on-chip biased PIN diode switches," *IEEE Transactions On Microwave Theory And Techniques*, vol. 43, no. 2, pp. 250-256, Feb. 1995.

[7] D. Heston, D. Seymour, and D. Zych, "100 MHz to 20 GHz monolithic single-pole, two-, three-, and four-throw GaAs PIN diode switches," in *1991 IEEE MTT-S International Microwave Symposium Digest*, 1991, vol. 2, pp. 429-432.

[8] T. Boles, J. Brogle, D. Hoag, D. Curcio, "AlGaAs PIN Diode Multi-Octave, mmW Switches", COMCAS 2011, November, 2011

[9] S. M. Sze and K. N. Kwok, *Physics of Semiconductor Devices,* 3rd ed.,Hoboken, NJ: Wiley, 2006.

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Timothy Boles - Mr. Boles holds the BA and MA degrees in physics from Washington University. He is the holder of 14 US patents and has authored/co-authored over 100 publications.Mr. Boles joined MACOM in 1991 and is one of six current Technology Fellows at MACOM Technology Solutions

Mr. Boles has been actively involved in the design, and development, of microwave devices and circuits for over three decades. This has included power and low noise bipolar and MOSFET transistors; silicon and SiGe MMIC structures; HMIC based integrated mixers, switches, and passive glass microwave and mmW circuits; GaAs and AlGaAsmmW IC's; and most recently GaN HEMT's.

James J, Brogle–Mr. Brogle earned EE & Physics BS from Polytechnic and St. John's Universities in NYC (1988), and M.Eng.Sc. from University College Cork, Ireland (1999). He has developed Si power diodes at General Instrument 1988-1999, and Si &GaAs microwave diode discrete, hybrid and RFIC/MMIC components at MACOM since 2000.

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