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Low cost W-band SPST PIN diode switch by Q-MMIC technology

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Abstract: A high performance PIN diode single-pole-single-throw (SPST) switch for W-band application using a low cost approach was developed. By utilizing flip-chip PIN diodes mounted onto a separately fabricated passive circuit having a quartz substrate, a W-band quasi-monolithic millimeter-wave integrated circuit (Q-MMIC) switch was achieved. A 3-D PIN diode model and a compensation structure were adopted to acquire a low loss and high isolation switch. The measurement results show the minimum insertion loss is about 0.5 dB at 88 GHz and less than 2 dB over the frequency range of 80 to 101 GHz. The isolation is greater than 30 dB from 84 to 105 GHz. The total size of the switch is 1.5 mm × 3.0 mm.

Key words: quasi-monolithic millimeter-wave integrated circuit (Q-MMIC), switch, PIN diode, W-band

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基于 Q-MMIC 技术的 W 波段低成本 PIN 管开关

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摘要：采用低成本方法设计了一款 W 波段单刀单掷开关. 通过在单独加工的石英基片无源电路上安装倒装 PIN 管，获得了一款 W 波段准毫米波单片(Q-MMIC)开关. 为了获得低损耗、高隔离度性能，开关设计中采用了 3-D PIN 管模型和电路补偿结构. 测试结果表明开关在 88 GHz 时插入损耗最小，最小值为 0.5 dB；在 80 ~ 101 GHz 频率范围内，开关导通时的插入损耗小于 2 dB；在 84 ~ 104 GHz 频率范围内，开关隔离度大于 30 dB. 整个开关电路尺寸为 1.5 mm × 3.0 mm.

关 键 词：准毫米波单片；开关；PIN 管；W 波段

中图分类号：TN773.2　　**文献标识码**：A

Introduction

Switches are important components in many millimeter-wave systems such as radar, communication links and phase array systems. For such applications, switches should exhibit high isolation as well as low insertion loss. PIN switching diodes offer unique advantages over HEMTs such as low ON-state resistance and small OFF-state capacitance combined with high power-handling capability. Therefore, they are widely used in many millimeter-wave systems. In recent decades, monolithic PIN diode switches with excellent characteristics have been reported by the authors at W-band frequencies[1-5]. However, most of them are implemented in III-V compound semiconductor technology, such as GaAs or InP, and the high cost of these materials prohibit them for low cost applications.

Q-MMIC technology allows the passive circuitry, which occupied a large area of the die, to be fabricated on a low cost substrate separately while the discrete components, such as PIN diode, schottky diode, HEMT, etc., are mounted onto substrate for integration with the passive circuitry by flip-chip technology. As the discrete device and passive circuitry are fabricated separately, the Q-MMIC technology offers several advantages over the MMIC technology, such as low cost, short turnaround times, design flexibility and so on. W-band low noise amplifier[6], sub-harmonic mixer[7] employing Q-MMIC technology, has been reported. In spite of the merits of Q-MMICs for millimeter-wave applications, due to lack of sufficiently accurate modeling of the discrete compo-

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nents to enable circuit design, their use has been limited.

In this work, a broadband W-band PIN diode switch using Q-MMIC technology is demonstrated. An accurate PIN diode model based on full-wave EM simulator is presented. In order to implement a broadband switch, an effective compensation method is adopted. Accordingly, a W-band SPST switch is simulated and optimized using a full wave EM simulator by using 3-D PIN diode model. To validate the design concept, the PIN diode switch was fabricated and measured. Measurements show insertion loss is less than 2 dB from 80 GHz to 101 GHz and isolation is greater than 30 dB over 21 GHz bandwidth at 94.5 GHz center frequency.

1 PIN diode model

Accurate diode model is essential for circuit design. As operating frequency increases, the parasitic effects of the flip-chip device become more and more significant and result in an inaccurate diode model if those effects are not properly account for[8]. As there is no suitable commercial flip-chip PIN diode for choice, the diode used here is a beam lead PIN diode (MA4AGBLP912). By cutting off the beam leads, the diode is used as a flip-chip diode. The nominal overall chip dimensions are 280 μm × 178 μm × 100 μm (length × width × thickness, excluding the dimension of the beam lead). In order to analyze the parasitic effects, the diode chip structure was modeled by Ansoft HFSS according to the method presented in Ref. [9]. Figure 1 demonstrates a shunt configuration diode model by HFSS. The normalized parallel impedance Z_p/Z_0 look forward to PIN diode from the microstrip line can be extracted from the HFSS simulation results[9]. Figure 2 shows the normalized parallel impedance Z_p/Z_0 of the PIN diode in the frequency range of 90 ~ 100 GHz. It can be seen that the PIN diode presents a high inductive reactance series with a small resistance under forward bias state and a high capacitive reactance under reverse bias state.

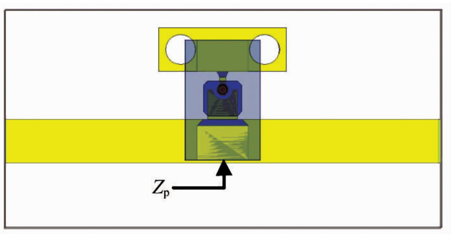

Fig. 1　Shunt configuration PIN diode model by HFSS
图 1　HFSS 中并联开关模型

In order to simplify analysis, the PIN diode can be equivalent to inductor (L_{FB}) series with a resistor (R_{FB}) under forward bias state and capacitor (C_{RB}) series with a resistor (R_{FB}) under reverse bias state, respectively, as shown in Fig. 3. The performance of the switch is limited by those parasitic parameters. Compensation of the PIN diode parasitic parameters therefore provides a mechanism for improving the switch performance.

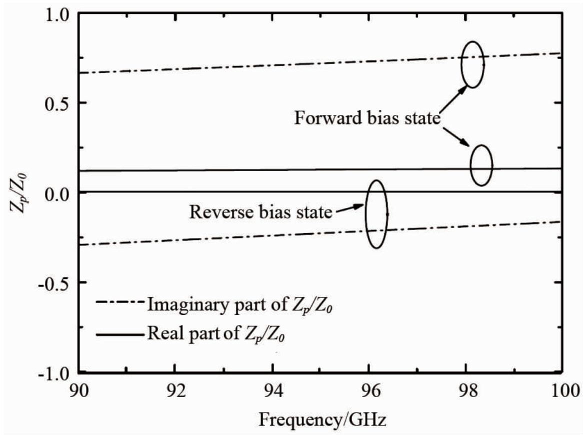

Fig. 2　Normalized parallel impedance Z_p/Z_0 under both forward bias state and reverse bias state
图 2　正向和反向偏置状态下归一化并联阻抗 Z_p/Z_0

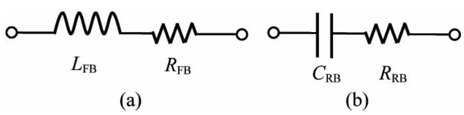

Fig. 3　PIN diode simplified equivalent circuit (a) forward bias state, (b) reverse bias state
图 3　PIN 管的简化等效电路(a) 正向偏置,(b)反向偏置

2 Circuit analysis and design

The conventional shunt switch configuration is adopted in this work. As the isolation obtained from single diode is limited by the resistance loss, three PIN diodes spaced by a transmission line from each other are employed. The circuit schematic is shown in Fig. 4. An open circuited radial stub is used to tune out parasitic inductance (L_{FB}) of the PIN diode under the forward state. As we known, beside the parasitic inductance, the isolation of the switch is also limited by series resistance of the PIN diode under the forward bias state R_{FB} and transmission line impedance that PIN diodes connected to[10]. Since R_{FB} is the property of the PIN diode and can't be tuned out, high impedance transmission line can be used to further improve the isolation performance. If only isolation performance is concerned, the impedance Z_1 and Z_2 of the high impedance line should be as large as better and the electrical length should be $\theta_1 = \theta_2 = 90$ degree. However, as return loss of the switch under the "on" state is taken into account, Z_1, Z_2, θ_1 and θ_2 should be selected properly.

Reverse bias state capacitance C_{RB} of the PIN diode is the main factor that deteriorated the return loss of the switch and results in a poor insertion loss performance. In addition, the open circuited radial stub which is used to tune out L_{FB} also presents a capacitance C_{RS} in series with C_{RB}. In order to achieve a low loss switch, incorporating with high impedance lines, shunt capacitance C_T

$=(C_{RB}\times C_{RS})/(C_{RB}+C_{RS})$ can be absorbed in to a low pass filter. By choice Z_1, Z_2, θ_1 and θ_2 properly, the return loss over the frequency band of interest can be improved effectively.

DC bias is feed though by a bias choke at each anode of the PIN diode and an additional bias choke is also connected to the transmission line to offer a DC return path, as shown in Fig. 4.

As there is only two operating states ("on" and "off" states) in the switch, the 3-D model of PIN can be taken into switch design directly as a passive element by setting "I" region material properties under forward bias and reverse bias states respectively. Therefore, the entire switch including PIN diode can be simulated and optimized by HFSS.

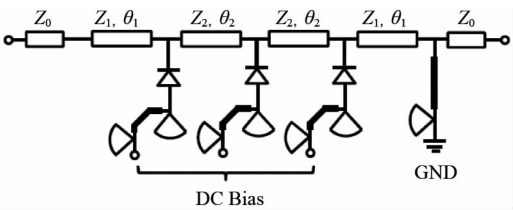

Fig. 4 Circuit schematic of the switch
图4 开关原理图

Quartz with a thickness of 100 μm is adopted as passive circuitry substrate in this work. Low dissipation factor (about 0.000 015, 1/6 of GaAs') and high surface finish offered a low loss microstip transmission lines. Furthermore, the lower permittivity of quartz allows larger distribute circuit element to be incorporated, which is very essential in W-band as too small circuitry size is inconvenient for the PIN diode assembling.

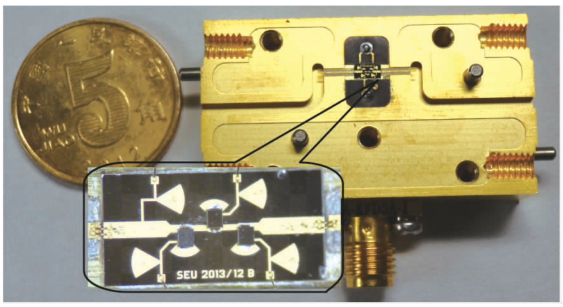

Fig. 5 Developed switch bottom block with chip, microstrip to WR-10 probe transition
图5 带有芯片,微带波导转换的开关模块(底部)

3 Simulation and measurement results

In order to valid the design method, the developed switch was fabricated with the size of 1.5 mm×3.0 mm. The pattern of passive circuits was fabricated on a quartz substrate with 100 μm thickness by employing thin film circuit technology. Compared with MMIC technology, thin film technology provides an enough accuracy for W-band application while keeping low cost. The PIN diodes are mounted using flip-chip technology and bonded to the circuit using EPO-TEK H20E silver epoxy. In order to compatible with the test system, a split switch block with WR-10 rectangular waveguide input/output port was designed based on the waveguide to microstrip transition probe, as shown in Fig. 5.

The performance was measured by Agilent E8363C PNA along with W-band Frequency Extension Modules by Farran Technology Ltd. Figures 6 and 7 show the performance of the switch under 'on' state and 'off' state from 80 GHz to 105 GHz, respectively. The insertion loss caused by the waveguide to microstrip transition is calibrated out by a 50 Ω microstrip line with two back-to-back waveguide to microstrip transitions. It can be seen from the measured results that the insertion loss is less than 2 dB from 80 GHz to 101 GHz and the minimum insertion loss is about 0.5 dB at 88 GHz under 'on' state. A return loss better than 10 dB from 80 GHz to 105 GHz is also observed from the measurement under the 'on' state. As illustrated in Fig. 7, isolation is greater than 30 dB over frequency range of 84 to 105 GHz.

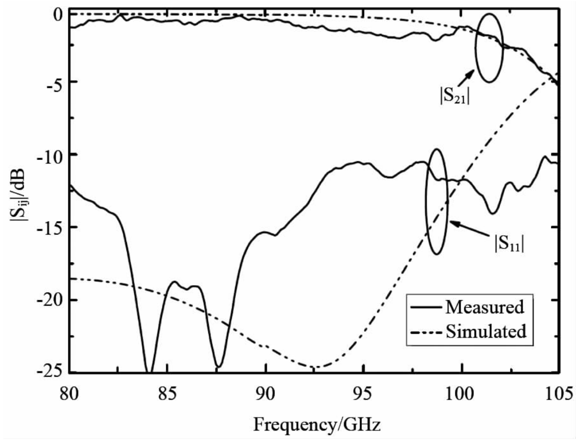

Fig. 6 On state performance of the SPST switch
图6 导通状态下开关性能

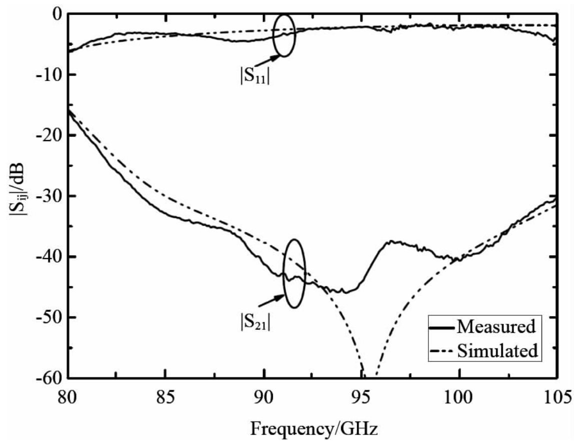

Fig. 7 Off state performance of the SPST switch
图7 断开状态下开关性能

Comparison between simulated and measured results is also shown in Figs. 6-7, and demonstrates a good agreement. The main reason that caused the differences between measurements and simulations in the 'on' state return loss and insertion loss may attribute to bond wires at input and output ports. Because the high impedance of the bond wires causes inductive discontinuities, it results in impedance mismatches and unwanted reflections. The mechanical and assemble tolerance may also the reason that caused measurements deviated from the simulations.

Comparisons of the developed switch with other published switches using MMIC technology are summarized in Table 1. The results demonstrate that the performance of the switch developed in this work is better or comparable to its MMIC counterparts.

Table 1 Comparison of switches performance
表 1 开关性能比较

Freqency band /GHz	Isolation /dB	Insertion loss/dB	Technology	Ref.
93.5	40	1.8	MMIC SPST	[1]
55 ~ 75	>20	<0.6	MMIC SPST	[2]
85 ~ 95	>30	<1.8	MMIC SPST	[3]
74 ~ 78	>35	<2.0	MMIC SPDT	[4]
25 ~ 90	>40	<3.2	MMIC SPDT	[5]
84 ~ 101	>30	<2.0	Q-MMIC SPST	This work

4 Conclusion

In this paper, a W-band switch employing Q-MMIC technology is developed. Based on 3-D PIN diode model, compensation method is adopted to improve RF performance. Measurements show the insertion loss is less than 2 dB over the frequency range of 80 to 101 GHz and the minimum insertion loss is 0.5 dB. Isolation is higher than 30 dB from 84 to 105 GHz. The total size of the switch is 1.5 mm × 3.0 mm. Compared with MMIC switches, the developed switch keeps a low cost property without compromised electrical performance. Furthermore, the switch can be readily integrated with other circuits, such as LNA, mixer, on the same substrate to from a low cost quasi system-on-chip (SOC) front-end.

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