Research Report

A 76-77 GHz High Isolation GaAs PIN-Diode Switch MMIC

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76-77GHz帯高アイソレーションGaAs PINダイオードスイッチMMIC

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Abstract

This paper presents the design, fabrication, and performance of a 76-77 GHz high isolation single-pole triple-throw (SP3T) switch implemented by coplanar waveguide (CPW) GaAs PIN-diode MMIC technology. The switch MMIC was developed for an electronically scanning antenna module specialized for use in an automotive holographic radar system. A PIN-diode pair is shunt-connected in the gap between the signal line and the ground plane of the CPW to prevent parasitic capacitance and especially series inductance, which influence the bandwidth of isolation. This switch has double shunts on each output arm to obtain high isolation. Each output arm is designed, in the ON-state, to be equivalent to a series of two excellent transmission lines for broadband performance. In fact, although the center frequency shifts about 3.5 GHz lower than the designed one, the proposed switch still provides more than 32 dB isolation, less than 2.0 dB insertion loss, less than -16 dB (input) and -18 dB (output) reflection simultaneously from 76 to 77 GHz, regardless of the combinations of bias states.

Keywords Switch, MMIC, PIN-diode, CPW, Millimeter-wave, Automotive radar

要　旨

本報告では，コプレーナ線路を用いたGaAs PINダイオードMMIC技術により実現した76-77GHz高アイソレーション1入力3切替出力スイッチについて，その設計技術，製作技術および性能を紹介する。このスイッチは，自動車用ホログラフィックレーダシステム専用に設計された電子スキャンアンテナモジュール向けに開発された。アイソレーション特性のバンド幅に影響を及ぼす寄生容量と直列インダクタンスを抑制する目的で，ダイオードの接続位置としてコプレーナ線路の信号線路と両側のグランドとの間隙部分にペアでシャント接続している。オン状態の出力アームは広帯域特性を実現できるように2つの良好な伝送線路が直列接続されたものと等価になるように設計されている。実際，設計段階に比べて中心周波数はおよそ3.5GHz低めに出来上がったが，それでもなお我々が提案するスイッチは，76-77GHzの帯域内において32dB以上のアイソレーション，2.0dB以下の挿入損失，入力側で-16dB以下，出力側で-18dB以下の反射特性をバイアス状態の組み合わせによらず，同時に満足している。

キーワード　スイッチ，MMIC，PINダイオード，コプレーナ線路，ミリ波，自動車レーダ

特集

1. Introduction

Electrically scanning millimeter-wave automotive radars have been developed as forward-looking sensors for adaptive cruise control (ACC) [1, 2]. TOYOTA CRDL, INC. has proposed a millimeter-wave holographic radar system simplified by switching both the transmitting and receiving antennas[3]. That radar has accomplished a high azimuthal angular resolution of less than 2 degrees and a field of view (FoV) of more than 20 degrees simultaneously. A SP3T switch MMIC with high isolation performance is the keydevice in this radar system. In this paper, a 76-77 GHz CPW SP3T switch MMIC with double shunting PIN-diode pairs for high isolation performance is reported.

In **Chap. 2**, we describe the construction of our original antenna array system and the function of SP3T switch MMICs with their required specifications for simplified holographic radar. In **Chap. 3**, the structure of the GaAs PIN-diode used for the switching device in MMICs is described. In **Chap. 4**, the circuit architecture of the SP3T switch and the simplified equivalent circuit models for the PIN-diodes are introduced and the circuit design specialized for double-shunted switch MMICs with broadband performance is proposed. Following the introduction of wafer fabrication in **Chap. 5**, the RF performances of the completed switches are demonstrated in **Chap. 6**.

2. Switch requirements for an automotive holographic radar system

The holographic radar needs plural sets of receiving antennas, which are arrayed horizontally at a certain pitch. The angular resolution is determined by the number of receiving antennas. If the array pitch of the receiving antennas and the 3 dB beam width of a receiving antenna are 1.5 wavelengths and 26 degrees, respectively, it is necessary to use more than nine sets of receiving antennas to obtain an angular resolution of less than 2 degrees[3].

The configuration of fundamental holographic radar consists of a transmitting antenna, a transmitter, nine sets of receiving antennas, four sets of SP3T switches that are connected in a cascade mode, a receiver, and a signal processing unit. The antenna switching to operate in a time division manner is employed, and a receiver is then able to obtain every received signal corresponding to each receiving antenna. There are ten antennas and four SP3T switches in total. The large number of components is an obstacle to cost reduction, high reliability, and the downsizing.

TOYOTA CRDL, INC. has proposed a new holographic radar system simplified by switching both the transmitting and receiving antennas[3]. The structure is shown in **Fig. 1.** In this radar, instead of increasing the transmitting antennas from one to three, the numbers of receiving antennas are decreased from nine to three. There are three sets of both transmitting and receiving antennas. It is most important that there are only two SP3T switches used in the radar system.

On the other side, a SP3T switch should be fitted not only for receiving but also for transmitting. The required handling power is larger than the previous one used for transmitter power (10 dBm). The target magnitude of reflection is less than -15 dB, which is required for both input (pole-side) and output (throw-side).

Isolation level is very important for the accuracy of the detected azimuthal angular. The required isolation is determined to avoid degradation of the

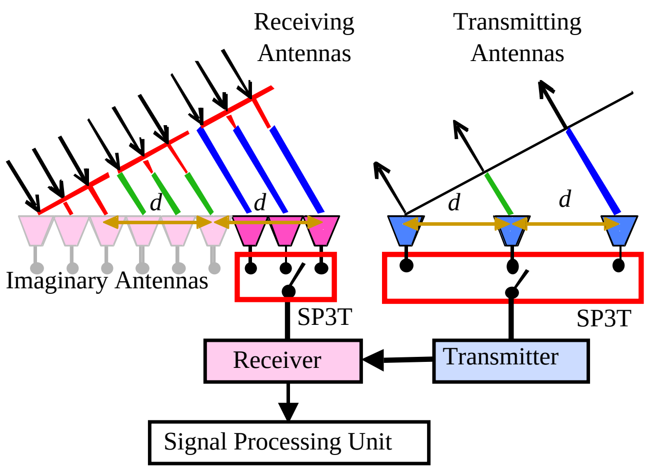

Fig. 1 Configuration of simplified holographic radar with switching both the transmitting and receiving antennas.

isolation between the transmitting elements and the receiving elements of the array antenna (25 dB). Usually, unintentional degradation of the switch isolation tends to occur after mounting and connecting. We estimated the degradation rate at 5 dB from our experience, and then the goal of bare chip isolation was fixed at more than 30 dB. This is very high performance for millimeter-wave switch MMICs.

It goes without saying that the insertion loss has to be sufficiently low (our goal is less than 2 dB) for a greater detecting range, and the switching time has to be sufficiently short (our goal is less than 10 ns) to secure of simultaneity.

3. GaAs PIN-diode for the CPW switch MMIC

The PIN-diode switch is suitable for high handling power use, compared with an FET switch or a Schottky-barrier-diode (SBD) switch, because of the high breakdown voltage. PIN-diode switches are often chosen as excellent millimeter-wave switches for their high power handling capability and high IP3 as well as their extremely high cutoff frequencies (over 1.6 THz) [4-8]. It is well-known that the cutoff frequencies for FETs or SBDs are less than approximately a fifth of the cutoff frequencies for PIN-diodes. These are the reasons why the PIN-diodes were chosen for the proposed millimeter-wave switch MMICs. The product of Ron and Coff, which is in inverse proportion to the cutoff frequencies, is usually about 100 Ω·fF for planar GaAs PIN-diodes developed for millimeter-wave use. Our planar GaAs PIN-diodes have a Ron·Coff comparable to or better than that of other devices reported in the literature[4, 5, 8].

Several microstrip line (MSL)-based switch MMICs with excellent performance have been demonstrated [2, 4-7]. However, the backside processes, such as wafer lapping, polishing, and via-hole etching, required for MSL-based MMICs are not promising for high yield and low cost. We then employed the CPW-based MMICs not only for eliminating the requirements for backside processes but also for making the MMICs compatible with flip-chip mounting or chip scale packaging.

We have approached a way of more effective shunting configuration which realizes the reduction of both series parasitic access inductance (Ls) and parallel parasitic fringing capacitance (Cp). The PIN-diode pair is shunt-connected in the gap (42 μm @Zo=50 Ω) between the signal line and the ground plane of the CPW just symmetrically on the centerline of the CPW's signal line. We have acquired broadband switch performance with robustness for deviations of process conditions and/or bias conditions, and then we obtained a high yield.

The SEM images of the PIN-diode that have been taken in four stages of the process are shown in **Fig. 2**. The images are operated with artificial coloring by using photo retouch software to assist in recognition of boundaries between several materials.

The brief expositions are described as follows, in conjunction with the images in Fig. 2. (a) At first, a double mesa structure is formed by wet etching. (b) Two alloy ohmic contacts are formed onto the n-layer on both sides of the first mesa. A non-alloy ohmic contact is formed onto the top of the p-layer (5 μm × 5 μm). (c) A lower interconnection metal layer is patterned to extend the n-contact toward the area for the CPW's ground to be performed afterward. The contact-hole etching (2 μm × 2 μm) is done for metal plating for connection between the

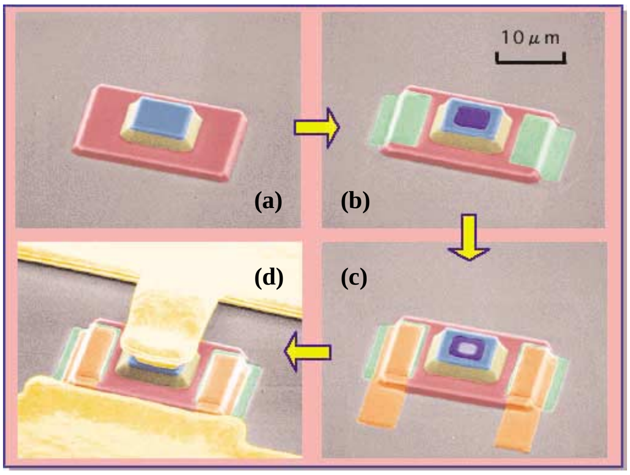

Fig. 2 SEM photographs of the PIN-diode placed in the gap between signal line and ground plane of CPW. The images have been taken in four stages with being the process in progress from (a) to (d).

PIN-diode and the CPW. (d) An air-bridge and the CPW are made with an Au electroplating process. The air gap under the bridge is 5 μm in height to suppress the parasitic capacitance. The cathodes located on both sides of the anode are connected to the CPW's ground plane with an overlay interconnect metal, and the anode is connected to the edge of the CPW's signal line with an Au plated air-bridge.

Figure 3 shows the DC I-V characteristics of the parallel pair PIN-diodes, which are drawn repeatedly for eleven samples. Each diode has 5 μm × 15 μm p-ohmic contacts. We confirmed that the linearity of the forward I-V characteristics is maintained up to at least 400 mA. A forward current of 10 mA is obtained at 1.3 V. Their reverse breakdown voltages are more than 45 V, and they also have good uniformity as well as forward bias. The breakdown voltages are at a reasonable level estimated based on the thickness of the i-layer (1.5 μm). It should be noted that our PIN-diodes have a very low leakage current of less than 0.05 nA at -5 V, which is the bias voltage for the arm in the ON-state.

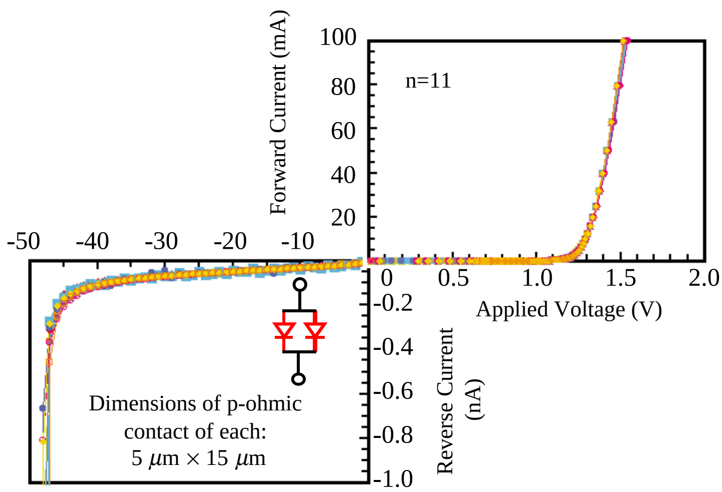

Fig. 3 I-V characteristics of the parallel pair PIN-diodes.

4. Circuit design

Figure 4 shows the photograph of a fabricated 76-77 GHz double-shunted SP3T GaAs PIN switch MMIC. The actual chip size is 2.2 mm × 1.4 mm and 1.85 mm × 1.2 mm in effectiveness. Two pairs of switching PIN-diodes are shunt-connected at the area indicated by ellipses A and B in Fig. 4. In other output arms, the shunting has been done in a similar situation.

Figure 5 shows a schematic diagram of the SP3T switch circuit. To realize

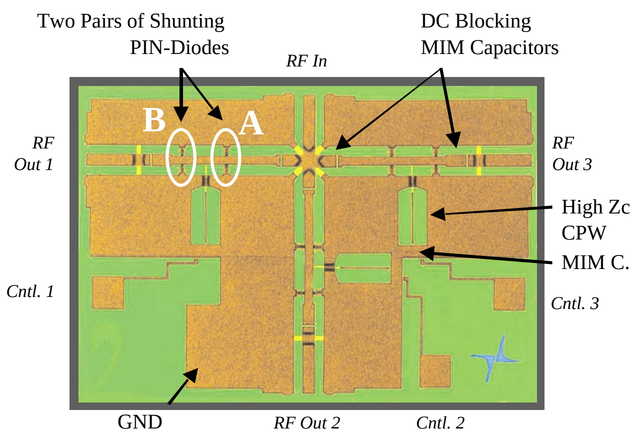

Fig. 4 Photograph of a fabricated 76-77 GHz double-shunted SP3T GaAs PIN switch MMIC. The actual chip size is 2.2 mm × 1.4 mm (1.85 mm × 1.2 mm in effectiveness).

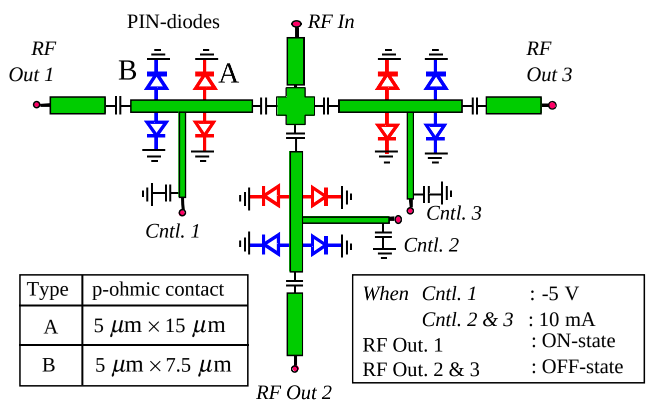

Fig. 5 Schematic diagram of the SP3T switch circuit.

good input and output matching, the type A diode pair has different dimensions from the type B diode pair. The type A diode pair has 5 μm × 15 μm p-ohmic electrodes, and the type B diode pair has 5 μm × 7.5 μm electrodes. The bias voltage applied on the control pad communicates commonly with four diodes, which are shunt-connected to each output arm, through the bias circuit. The bias circuit consists of a CPW 1/4-wavelength high impedance line and a shunting MIM capacitor and acts as the LPF. Each output arm has two DC blocking MIM capacitors at both ends. As shown in Fig. 5, for example, in order to turn on the RF output 1, a -5 V voltage should be applied on the control pad 1, and 10 mA currents should be provided into control pad 2 and control pad 3.

In this paper, we employ the most simplified diode models which are able to express the S-parameters used for 72-81 GHz accurately in a forward-biased state (10 mA) and in a reverse-biased state (-5 V). The equivalent circuits are shown in **Fig. 6**. The fundamentals are indicated in Fig. 6(a). The group of Ls, Rs and Cp is independent of bias conditions, though Rj and Cj vary with the bias condition. After elimination of negligible parameters by impedance comparison, the simplified model for the forward-biased PIN-diode is shown in Fig. 6(b), and the model for the reverse-biased one is shown in Fig. 6(c). The values of Ls, Ron and Coff are also indicated in Fig. 6. Ron and Coff are by no means inferior to the data previously reported. Especially, Ls is less than 8 pH and superior to any diodes for millimeter-wave switch MMICs.

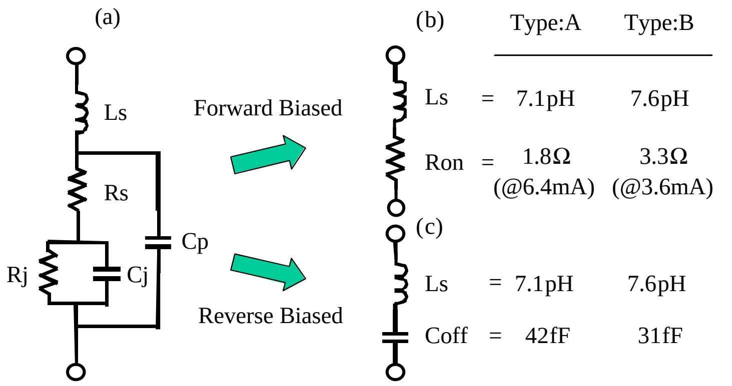

Fig. 6 Equivalent circuits for PIN-diodes. (a) fundamentals (b) simplified model for forward-biased PIN-diode (c) simplified model for reverse-biased PIN-diode.

Usually, almost all MSL-based shunt diode switch MMICs employ a low pass filter consisting of a series-L, a shunt-C (which is a capacitor for the reverse-biased diode), and a series-L to design the transmission impedance of the ON-state arm[4-7].

However, we employed an equivalent transmission line consisting of a shunt-C, a series-L, and a shunt-C. **Figure 7** shows equivalent circuits for the switch arm in the ON-state. Figure 7(b) indicates a transmission line

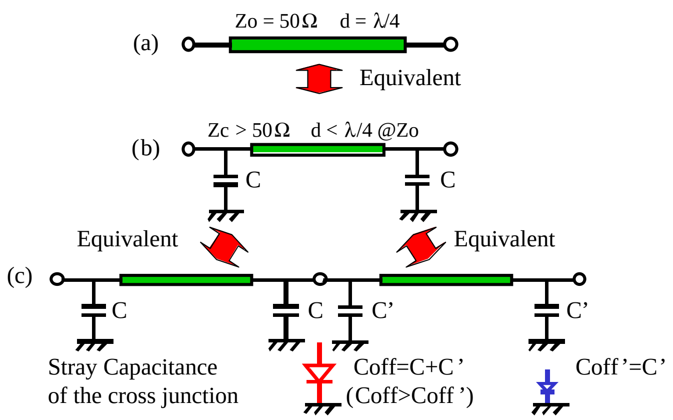

Fig. 7 Equivalent circuits for the switch arm in the ON-state. (a) fundamentals (b) equivalent transmission line to the fundamentals (c) switch output arm in the ON-state that has been designed to be a series of two equivalent transmission lines.

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equivalent to the fundamental one shown in Fig. 7(a). The series-L part is realized with a CPW line with a rather high Zc than Zo=50 Ω. Figure 7(c) shows the switch output arm in the ON-state. The structure consists of a series of two equivalent transmission lines which are indicated in Fig. 7(b). The left side shunt-C, series-L and shunt-C circuit consists of the stray capacitance of the cross junction, the high Zc CPW and a part of the Coff of the type A diode. The right hand shunt-C, series-L and shunt-C circuit consists of the remains of the Coff of the type A diode pair, the high Zc CPW and the Coff of the type B diode pair. The type A diode pair then has a larger Coff than the type B diode pair.

The smaller the Coff of the PIN diode is designed, the broader is the bandwidth in which the circuit is able to be equivalent to an excellent transmission line. Also, it is a necessary to realize broadband performance in which the Ls of the PIN-diode is sufficiently small. The strongest point of this circuit is its broader and excellent return matching in comparison with the L-C-L LPF-like circuit.

5. Fabrication

The outline of the process flow as well as the structure of the PIN-diode has already been introduced in **Chap. 3**. The wafer process is carried forward with the MBE wafer. The epitaxial layers are grown on the (100) S. I. GaAs substrate, which is 450 μm thick and 50 mm in diameter. The epitaxial growth has been done in the following sequence. (1) a 1-μm un-doped GaAs (buffer layer); (2) a 1.4-μm heavily Si-doped GaAs (n-ohmic contact layer); (3) a 0.2-μm moderately Si-doped GaAs; (4) a 1.5-μm un-doped GaAs; (5) a 0.05-μm moderately Be-doped GaAs; (6) a 0.15-μm heavily Be-doped GaAs; (7) a 0.1-μm more heavily Be-doped InGaAs (p-ohmic contact layer; indium mole-fraction of the InGaAs is 0.05).

All of the photolithography processes are carried out with an i-line stepper aligner. The minimum dimension of the contact hole pattern on the PIN-diode is 2 μm × 2 μm. The aligner has the ability for resolution on two levels with a difference of more than 4 μm depth at the same time.

The mesa etching of 3.7 μm depth in total is carried out with a wet etchant. The etching depth is controlled with in an accuracy of 0.1 μm. The functions of the PECVD SiNx are threefold: (1) a double layered resist mask combined with a photo-resist to provide a fine profile for lift-off metals, (2) an insulator for forming MIM capacitors, and (3) passivation to cover the PIN-diode's surface. The thickness of the SiNx is commonly 150 nm.

An Au electroplating process is employed to define the air-bridge and the CPW of 4 μm thick; the other metal patterns are made by a lift-off technique. The AuGe/Ni/Au alloy system for the n-ohmic contacts and the Pt/Ti/Pt/Au non-alloy system for the p-ohmic contacts have been in use. A low contact resistance of 5×10^{-7} Ω·cm^2 for the n-ohmic and 2×10^{-7} Ω·cm^2 for the p-ohmic has been realized.

6. SP3T switch performance

On-wafer measurements were made with Picoprobe W-band wafer probes that have integral bias-tees and an HP 8510B vector network analyzer (NWA) in the frequency range from 72 to 110 GHz. The SP3T switch MMIC has four ports but the NWA has only two ports. Two ports, which are not connected to the NWA, were then terminated with the wafer probes which have 50 Ω terminations.

The transmission properties of eleven fabricated SP3T switches for the straight arm are shown in **Fig. 8**. In the range of 76-77 GHz, the insertion losses are 1.5 dB ± 0.2 dB and the isolations are 35 dB ± 3 dB. ON/OFF ratios of more than 28 dB are

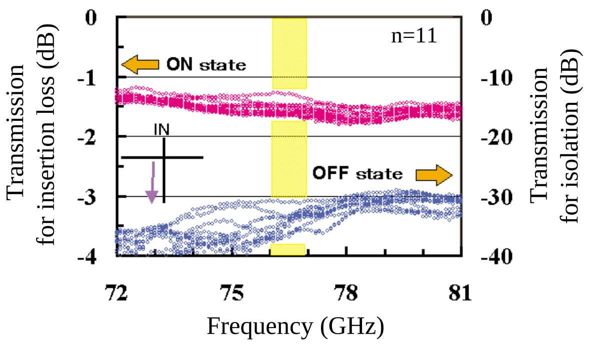

Fig. 8 Transmission properties of the fabricated SP3T switch for straight arm.

achieved in a 9 GHz bandwidth. For the bend arms, the isolation levels remain excellent, but the insertion losses degrade by only 0.3 dB.

The reflection properties of eleven fabricated SP3T switches are shown in **Fig. 9**. The upper side (a) shows the input reflection when the straight arm is in the ON-state, and the bottom side (b) shows the output reflection of the straight arm in the ON-state. In the range of 76-77 GHz, the input reflections are -23 dB ± 4 dB and the output reflections are -20 dB ± 2 dB. The center frequency was recognized to be about 3.5 GHz lower than the designed one due to the shift in diode parameters.

A summary of the 76-77 GHz switch characteristics in comparison with the target values is shown in **Table 1**. They are excellent properties and accomplish all of the targets. The excellent properties are maintained after the drive current decreases to 2 mA. The degradation levels are 0.3 dB for the insertion loss, 1 dB for the isolation and 0.5 dB for the reflections.

It was confirmed that the switch has a maximum handling power of more than 14 dBm, switching speeds of 2 ns for rising and falling and a delay time of 5 ns.

7. Summary

A 76-77 GHz high isolation single-pole triple-throw (SP3T) switch, which is specialized for use in an automotive holographic radar system, was implemented with coplanar waveguide (CPW) GaAs PIN-diode MMIC technology. A PIN-diode pair is shunt-connected in the gap between the signal line and the ground plane of the CPW to realize a very low Ls. The proposed switch provides more than 32 dB isolation, less than 2.0 dB insertion loss, less than -16 dB (input) and -18 dB (output) reflection simultaneously from 76 to 77 GHz, regardless of the combinations of bias states. The performance is sufficiently excellent for an electronically scanning antenna module.

(a)

(b)

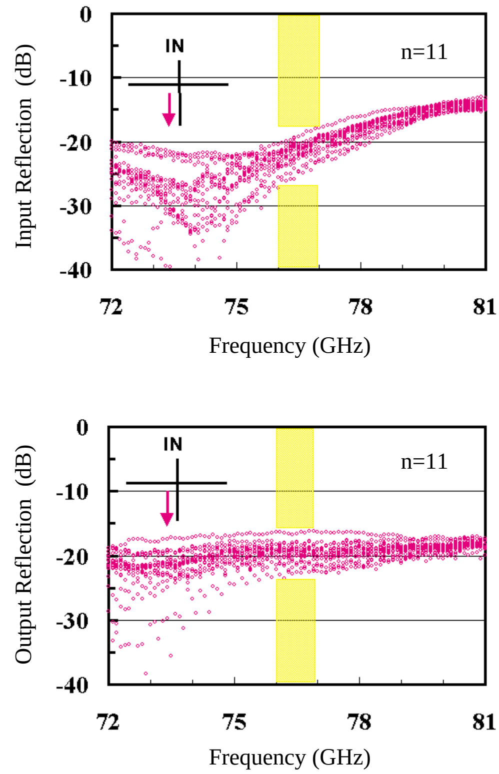

Fig. 9 Reflection properties of the fabricated SP3T switch. (a) Input reflection when the straight arm is in the ON-state. (b) Output reflection of the straight arm being in the ON-state.

Table 1 Summary of the 76-77 GHz switch characteristics in comparison with the target values. (n=11)

	(Target)	in all	Straight arm	Bend arm
Insertion loss	< 2 dB	< 2 dB	1.3 − 1.7 dB	1.6 − 2.0 dB
Isolation	> 30 dB	> 32 dB	32 − 37 dB	34 − 40 dB
Input reflection	< -15 dB	< -16 dB	-27 − -19 dB	-26 − -16 dB
Output reflection	< -15 dB	< -18 dB	-22 − -18 dB	-40 − -20 dB

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