A Compact V-Band 2-Bit Reflection-Type MEMS Phase Shifter

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***Abstract*—Air-gap overlay CPW couplers and low-loss series metal-to-metal contact microelectromechanical system (MEMS) switches have been employed to reduce the loss of reflection-type MEMS phase shifters at V-band. Phase shift is obtained by changing the lengths of the open-ended stubs using series MEMS switches. A 2-bit (135°) reflection-type MEMS phase shifter showed an average insertion loss of 4 dB with return loss better than 11.7 dB from 50 to 70 GHz. The chip is very compact with a chip size as small as 1.5 mm $\times$ 2.1 mm.**

***Index Terms*—MEMS switch, reflection-type phase shifter.**

I. Introduction

REFLECTION-TYPE phase shifters using switches and couplers are suitable for monolithic applications due to the small size compared with the distributed phase shifters. However, their millimeter-wave application has so far been limited due to the increased losses of the couplers and switches at high frequencies. Microelectromechanical system (MEMS) technology brings low-loss possibility, and can thus be effectively employed to reduce the loss of the reflective phase shifters at millimeter-wave frequencies.

The switch benefits most from the MEMS technology as can be judged by the reported low-loss characteristics of the micromachined switches [1]–[3]. When the loss of the switch is minimized with the help of MEMS technology, the loss of the coupler becomes major loss contributor in the reflection-type switches. For example, a 4-bit X-band reflection-type MEMS phase shifter using microstrip Lange couplers and capacitive shunt MEMS switches showed a low average insertion loss of 1.4 dB at 8 GHz, out of which 1 dB was attributed to the loss of the cascaded Lange couplers [4]. The problem becomes more serious for CPW couplers. A 3-dB MMIC CPW Lange coupler with a 5 μm gap between the coupled lines on a GaAs substrate showed insertion losses higher than 1 dB at the center frequency of 20 GHz due to field crowding at the edges [5].

Recently, the authors developed a low-loss air-gap overlay CPW MMIC 3-dB coupler fabricated with MEMS technology [6]. The air-gap offset broadside coupling between two lines offers tight coupling and reduces the conductor loss by redistributing currents over broad surfaces. Similar approaches to reduce the conductor loss in the uniplanar transmission lines have also been demonstrated in the authors' previous work [7], [8].

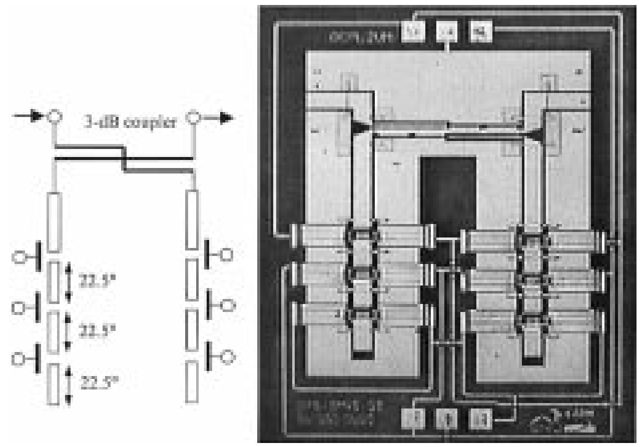

Fig. 1. Schematic and photograph of 2-bit (135° at 60 GHz) reflection-type MEMS phase shifter.

In this work, MEMS technology is applied to reduce the loss of the millimeter-wave reflection-type phase shifters. Metal-to-metal contact series MEMS switches are employed for low-loss switching of the line lengths, and the air-gap overlay CPW 3-dB couplers are used to minimize the loss of the couplers.

II. Design

A 2-bit (0°–45°–90°–135°) reflection-type phase shifter was realized using the air-gap overlay CPW 3-dB coupler and metal-to-metal contact series MEMS switches. Fig. 1 shows the schematic and the photograph of the phase shifter. For phase shift, open-ended lines consist of three line sections, each with an electrical length near 22.5° at 60 GHz, separated by series MEMS switches. The signal propagates through the switchable lines and reflects from the end of the open stub. If the phases of the reflected waves from both arms are the same, the signals add in phase and appear at the output of the air-gap overlay coupler. By actuating each pair of metal contact switches along the separated lines, the electrical length of each arm can be changed by 22.5°, resulting in subsequent S_{21} phase shift of 45° at 60 GHz. All the line lengths of the both arms are tuned for maximum relative phase shift at the center frequency of 60 GHz, resulting in a wideband phase shift flatness [9]. The chip size is only 1.5 mm $\times$ 2.1 mm, showing that this kind of phase shifter is well suited to V-band compact array antenna systems.

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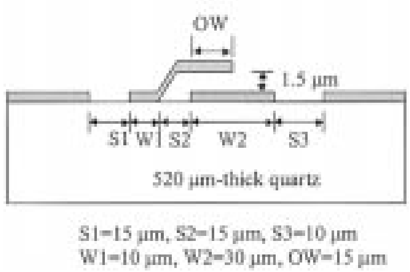
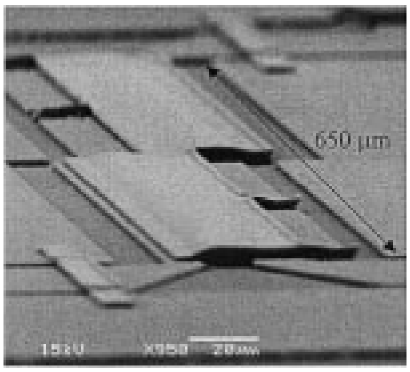


(a)



(b)

Fig. 2. (a) Schematic and (b) photograph of the air-gap overlay 3-dB CPW coupler.

III. Key Components and Fabrication

Overlay couplers and metal-to-metal contact series switches are the key components for the reflection-type phase shifters. Fig. 2 shows the simplified schematic and the photograph of the air-gap overlay 3-dB CPW V-band coupler that is basically scaled from the Ka-band coupler presented in [6]. The total length of the coupler is 650 μm. The offset coupling changes side at the mid point of the coupler, allowing easy access to balanced MMIC circuits. The structure is thus compatible with Lange couplers. For stronger support and prevention of bending, airbridge posts are placed at every quarter-length point along the length of the coupler. A commercial EM simulator, IE3D, was used for the design. The optimized parameter values, such as the overlap width (OW) of the coupled lines, are specified in Fig. 2.

The coupler is made up of the electroplated gold and is fabricated on a 520-μm-thick quartz substrate. The thickness of the bottom metal is 3 μm and that of the top metal is 2 μm. The air gap between the conductors is 1.5 μm. Fig. 3 shows the measured insertion loss of the coupler used in the reflective phase shifter. The switchable lines were removed from both arms, presenting open terminations. The input RF signal is, in this way, reflected from the coupled and the through port of the coupler and recombines in phase at the output port of the coupler. The insertion losses are 0.38 and 0.66 dB and the return losses are 17 and 18 dB at 40 and 60 GHz, respectively. This demonstrates very low loss nature of the air-gap overlay CPW coupler at V-band.

Fig. 4 shows the structure and operation of the metal-to-metal contact switch [3]. The process flow is summarized below. First, 3-μm-thick gold transmission lines are electroplated. To avoid dc voltage short, a 0.3-μm silicon nitride dielectric layer is deposited on the part of CPW ground plate to be used

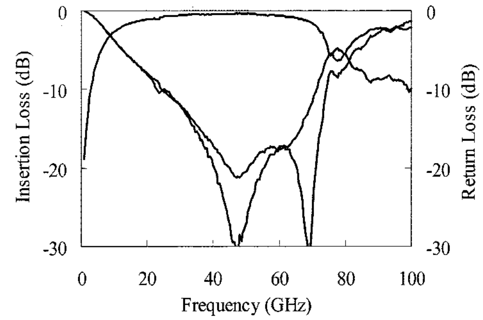


Fig. 3. Measured insertion loss and return loss of the air-gap overlay 3-dB CPW coupler with open termination.

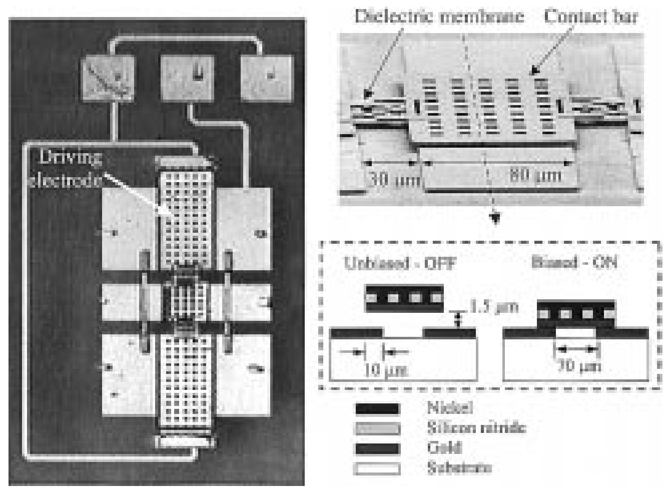


Fig. 4. Structure and photograph of the metal-to-metal contact switch.

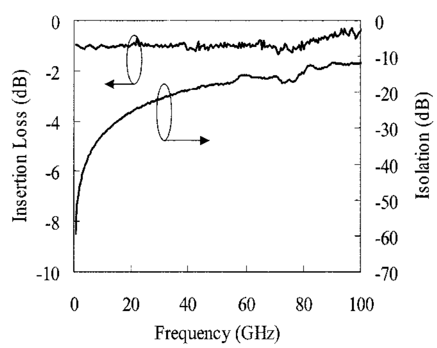


Fig. 5. Measured insertion loss and isolation of the metal-to-metal contact switch.

as the driving electrode. Photoresist is used as the sacrificial layer material. To increase the contact force in the actuation of the switch, the sacrificial layer on the contact part is slightly etched with anisotropic reactive ion etching, resulting in the smaller gap from the signal line compared with that between the driving electrode and ground plate. Next, contact metal is electroplated with a 2-μm-thick gold. A 0.5-μm-thick silicon nitride deposited using PECVD process is patterned as an insulating layer connecting the contact part and driving plate. The 2-μm-thick nickel metal structures for driving the electrode and the spring part are formed. Finally, the sacrificial layer is removed with oxygen plasma process. When a threshold bias is applied, the suspended driving electrode is pulled down so

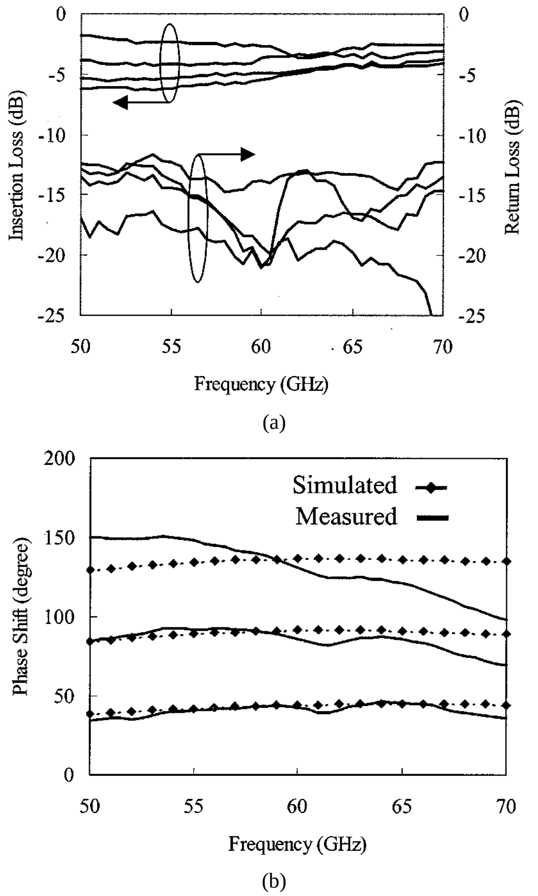


Fig. 6. Measured results of 2-bit (135° at 60 GHz) reflection-type MEMS phase shifter. (a) Insertion loss and return loss; (b) phase shift.

that the contact bar touches the signal line and the switch is on state. Mechanical actuation occurs at 35–40 V. Measured insertion loss and isolation of the fabricated switch are shown in Fig. 5. Isolation in off state is 15 dB and the insertion loss in on state is 1 dB at 60 GHz.

IV. Measurements

On-wafer RF measurements were made using a CASCADE probe station and an HP 8510XF network analyzer, which covers a wide frequency range from 45 MHz to 110 GHz. Line-reflect-reflect-match (LRRM) technique was employed using on-wafer standards for calibration. Measured S_{21} and S_{11} of the fabricated 2-bit reflection-type phase shifter are shown in Fig. 6(a). The return losses for all the switching states are better than 11.7 dB from 50 to 70 GHz and the average insertion loss is about 4.2 dB at 60 GHz. Fig. 6(b) illustrates the differential phase shift as a function of frequency for all the switching states. The measured average phase error for all the switching states is 4.6% at 60 GHz. Details of the phase shift errors and the losses at 60 GHz are listed as a function of the switching states in Table I. The loss can be represented as

$$\text{Loss (dB)} \approx 2.6 + N \tag{1}$$

TABLE I
Phase Shift Error and the Loss of the 2-bit Reflection Type MEMS Phase Shifter Measured at Each Switching State. The Data Are Measured at 60 GHz

Phase State	0.0°	45.0°	90.0°	135.0°
Measured	0.0°	41.5°	84.3 °	128.7°
Phase Error	0.0°	3.5°	5.7 °	6.3 °
Loss	2.6 dB	3.6 dB	5 dB	5.5 dB

where N is the number of switches that are on-state. The large loss (~6.2 dB) for some switching states at 50 GHz is attributed to the phase unbalance from the couplers and the lines.

V. Conclusion

The air-gap offset broadside coupling used in the overlay CPW couplers resulted in a very low loss of 0.66 dB at 60 GHz. MEMS series switches also showed a small insertion loss of 1 dB at 60 GHz. Combined effects of these two allowed 2-bit (135°) reflection-type phase shifters to show an average insertion loss of 4 dB with better than 11.7-dB return loss over a wide frequency range from 50 to 70 GHz. Compact size, low loss, and wide band characteristics make the phase shifters of this work a promising candidate for multibit-controlled phase shifters for V-band and above.

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