A 5-17 GHz Wideband Reflection-Type Phase Shifter Using Digitally Operated Capacitive MEMS Switches

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Abstract

In this paper, a micromachined low-loss and ultra wideband reflection-type phase shifter (RTPS) is proposed. The phase shifter shows a constant phase shift from 5 to 17 GHz and consists of two cascaded reflection-type phase shifter. Low-loss reflection termination consists of digital capacitive switches, and air-gap overlay CPW couplers are used in order to employ the low-loss 3 dB coupling. The fabricated phase shifter showed the 5 discrete states, 0°, 22.5°, 45°, 67.5°, 90° respectively, the average insertion loss of 3.48 dB, and maximum rms phase error of ±1.80° for the relative phase shift from 0° to 90° over 5-17 GHz.

1. Introduction

Microelectromechanical systems (MEMS) technology has enabled low-loss RF switching devices with RF circuits. The RF MEMS switches have a low-loss, a low parasitic and a good linearity. Therefore, the RF MEMS switches result in low loss phase shifters at any frequency. Also, a very small up-state capacitance of RF MEMS switches makes better result in a wider band performance than the similar designs using solid-state devices [1, 2]. The RF MEMS phase shifters also result in a considerable reduction in the DC power for large phased arrays. Due to these advantages, they have been enabling components for low-loss phase shifters, which implement the telecommunication and radar applications. These phase shifters are based on true-time delay phase shift such as distributed loaded lines or switched lines, and show linear relationship between the phase and the frequency.

Another type of broadband phase shifter requires constant phase over a wide frequency range. The Reflection-Type Phase Shifter (RTPS) has been widely used for this purpose. The RTPS was first introduced by Hardin [3]. Hardin proposed a 1-stage reflection-type phase shifter using a single varactor diode as reflective terminations. Many authors have proposed the wideband RTPS [4,5]. However, these broadband concepts can only be applied to one phase difference state. Therefore, several broadband RTPSs should be cascaded to implement multi-bit phase shift, which result in an excessive loss.

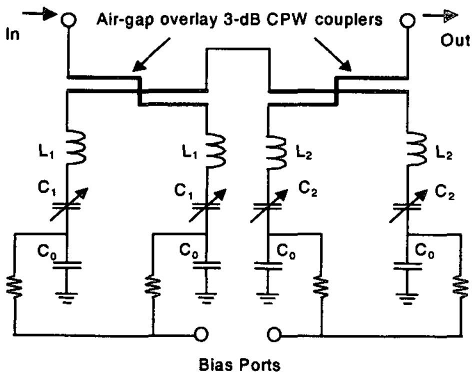
A Cascading two-matched RTPS for increasing the bandwidth was proposed by Lucyszyn [6]. In this method, the center frequency of the first-stage RTPS hump is set to a low-frequency end while that of the second one is set to a high-frequency end. In this way, a flat frequency response could be achieved over significantly wider bandwidth compared to the single RTPS. Based on this concept, a wideband cascaded CPW MMIC RTPS has been developed [7]. In this design, gate-to-source diodes of GaAs PHEMT have been used as varactors. The MMIC circuit exhibited low phase error of 5.5° over a wide frequency band from 27 to 47 GHz. However, the insertion loss was rather high (6.9 dB) due to a large series resistance of the PHEMT diode.

In this paper, a low-loss and ultra wideband reflection-type phase shifter (RTPS) using digitally operated capacitive MEMS switches has been successfully designed and fabricated for the first time. The fabricated phase shifter shows an average insertion loss of 3.48 dB, and maximum rms phase error of ±1.80° for the relative phase shift from 0° to 90° over 5-17 GHz.

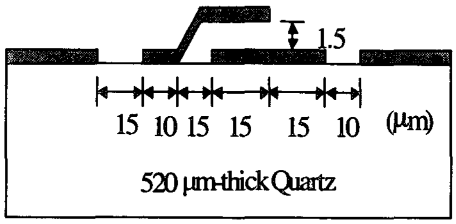
2. Design and fabrication

Fig. 1(a) shows the topology for the 2-stage cascaded reflection-type phase shifter [6]. Air-gap overlay CPW couplers were used for wideband 3-dB coupling and low loss at millimeter wave, and made by a standard MMIC air bridge process. The design of the coupler with a center frequency of 12 GHz was based on the Ka-band coupler presented in [8]. Other dimensions together with the coupled line structure are shown in Fig. 1(b) [7]. RF signals are transmitted through the CPW lines and an input signal power is divided through air-gap overlay 3-dB CPW coupler. The CPW transmission lines and capacitive MEMS switches were used as reflection termination inductors (L_1, L_2) and variable capacitors (C_1, C_2), respectively. C_0 is a metal-insulator-metal (MIM) capacitor and it is used to feed bias voltage and make RF short. The C_0 is much higher than the C_1 or the C_2. We feed bias voltage between an upper metal of MIM capacitor (or bridge structure) and a signal line, because the upper metal of MIM capacitor is connected to the bridge-type MAM capacitor. Namely, the RF signal line is ground of DC bias and the upper metal of MIM capacitor (or bridge structure) is a positive electrode.

The schematic view of the capacitive MEMS switch is shown in Fig. 2(a). The capacitive MEMS switch is a metal-air-metal (MAM) capacitor, and it acts as a variable capacitor where an upper metal (Au bridge) touches an insulator on bottom plate when a bias voltage is fed between the upper and bottom plate. This wideband reflection-type phase shifter utilizes a capacitive MEMS switch for varying capacitance ratio of MAM capacitors. The initial C_1 and C_2 (C_1 = 120 fF, C_2 = 180 fF) were determined over 5-19 GHz for the wideband relative phase shift flatness of the 2-stage cascaded phase shifter [6]. However, the initial value of capacitance 120 fF or 180 fF is too large to implement as one MAM capacitor. Thus we divided C_1 and C_2 into 4 small MAM capacitors, which are connected in parallel. The fabricated wideband phase shifter and 4 MAM capacitors are shown in Fig. 2(b). We can operate this phase shifter digitally by feeding the 4 small MAM capacitors individually.

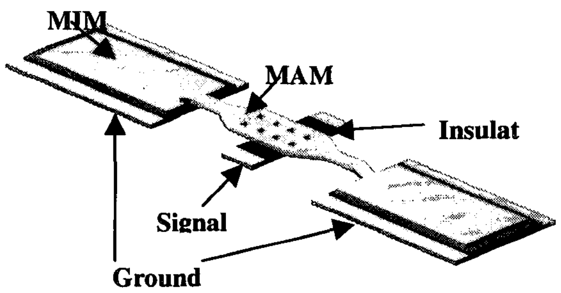


(a)

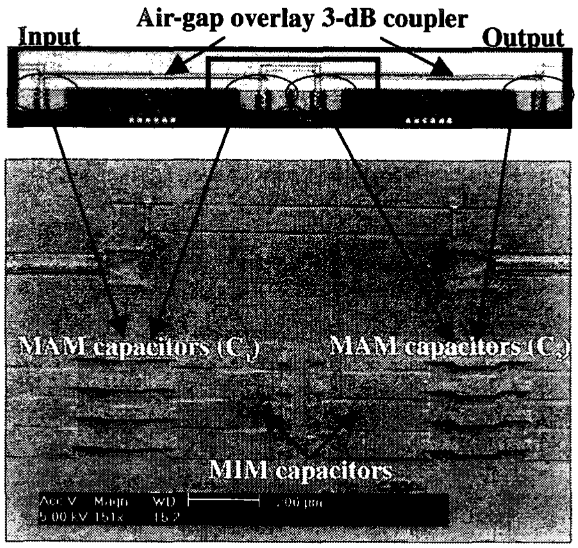


(b)

Fig. 1 Topology and dimension (a) Topology for 2-stage reflection-type CPW digital phase shifter (b) air-gap overlay CPW coupler



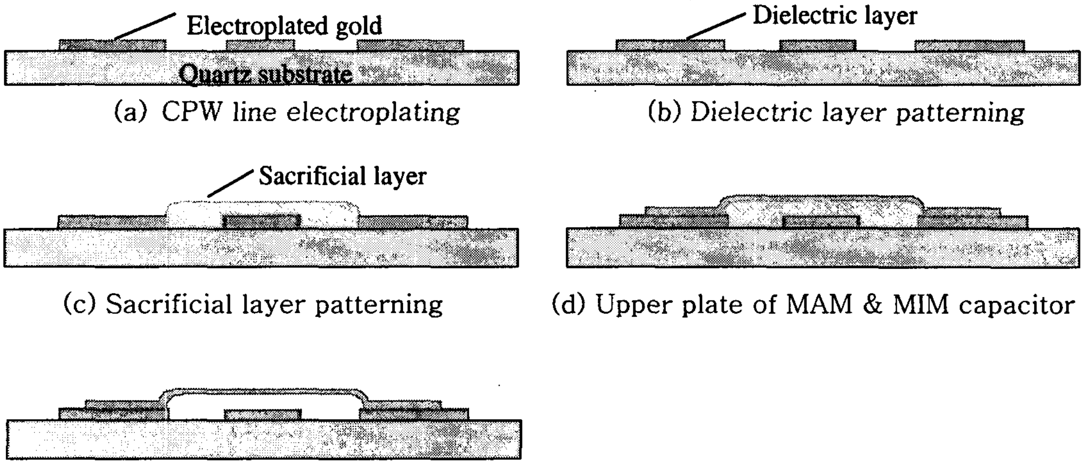
(a)



(b)

Fig. 2 (a) Schematic view of capacitive MEMS switch (b) fabricated wideband phase shifter

The fabricated wideband RTPS consists of CPW lines, overlay 3-dB couplers, MIM capacitors and bridge-type MAM capacitors. First, gold is electroplated on a 500 μm-thickness quartz wafer to form CPW transmission lines after thermal evaporation of titanium and gold as an adhesion and a seed layer, respectively (Fig. 3 (a)). The thickness of electroplated gold is 3 μm. A 3000 Å-thick PECVD nitride (Si_3N_4) is deposited onto the electroplated gold to make insulators of MIM and MAM capacitor (Fig. 3 (b)). A 1.5 μm-thick sacrificial layer is patterned and cured after gap filling using photoresist. (Fig. 3 (c)). Next, gold is electroplated with the thickness of 1.5 μm to form a bridge structure of the MAM capacitive switch and an upper electrode of MIM capacitor (Fig. 3 (d)). Finally, the overhanging bridge is released when the sacrificial layer is removed using plasma ashing process (Fig. 3 (e)).

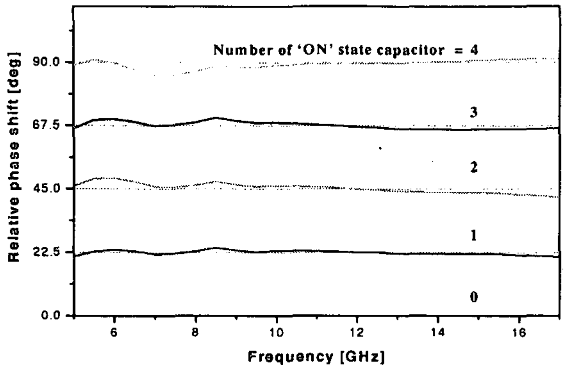


(a) CPW line electroplating
(b) Dielectric layer patterning
(c) Sacrificial layer patterning
(d) Upper plate of MAM & MIM capacitor
(e) Sacrificial layer ashing

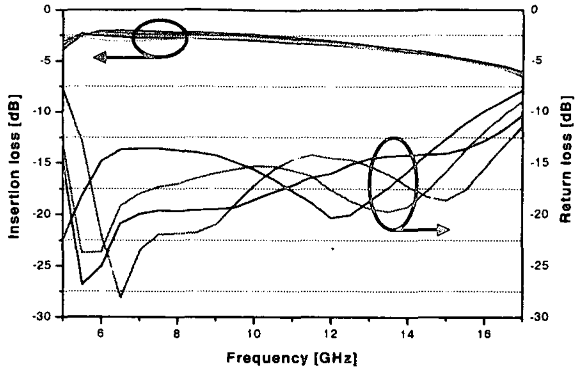
Fig. 3 Fabrication process

3. Results

When DC voltages are applied between an upper metal of MIM capacitor (bridge structure) and a signal line, the overhanging bridge-type capacitive switch touches down the bottom plate by electrostatic forces. It is 'ON' state when the bridge touches abruptly onto the dielectric layer on bottom plate, and the initial state without DC bias voltage is the 'OFF' state. The gap between the bridge and the bottom plate makes change in a capacitance at a reflective termination. The change of capacitance makes a phase shift of a transmitted signal and it is measured using a HP 8510 XF network analyzer. Fig. 4(a) shows the measured relative phase shift as a function of frequency for 5 states. The bias voltage for pulling down the MAM capacitors is 40V. When all the 4 MAM capacitors are 'ON' state, the relative phase shift is exactly divided by 4. Therefore, the 5 discrete states are 0°, 22.5°, 45°, 67.5°, 90° respectively, as the number of 'ON' state - MAM capacitors increase. The maximum rms phase error is ±1.80° for the relative phase shift from 0° to 90° over 5-17 GHz. Fig. 4(b) shows the insertion loss and return loss responses of this phase shifter. Over 5-17 GHz, the average insertion loss is 3.48dB and the return loss is larger than 10 dB. In comparison with the similar RTPS using the GaAs PHEMT varactor diodes showed average insertion loss of 6.9 dB [8], noticeable advantage is observed in terms of the loss and bandwidth.



(a)



(b)

Fig. 4 (a) Relative phase shift responses (b) Insertion and return loss responses

4. Conclusion

In this paper, we designed and fabricated a wideband reflection-type phase shifter using MEMS technology, and fabricated MEMS phase shifter shows constant phase shift from 5 to 17 GHz. The digitally operated capacitive MEMS switches with air-gap 3 dB overlay couplers help to reduce the insertion loss considerably compared with conventional RTPSs using the semiconductor varactor diodes. The phase shifter using capacitive MEMS switches has a low-loss and wide bandwidth. These results show that the micromachined phase shifter will be effectively used in microwave and millimeter wave telecommunication systems.

Acknowledgement

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