A Highly-Repeatable, Broadband 180º Phase Switch for Integrated MEMS Processes

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Abstract. A broadband 0º/180º phase switch based on a slotline-coplanar-waveguide cross loaded with two MEMS switches in opposed (ON/OFF or OFF/ON) states, is reported. The fabrication was made on high-resistivity silicon substrates using the FBK-irst and LAAS-CNRS surface micromachining processes, showing a high repeatability. The measured phase shift is 180º +0º/-7º in the extremely wide frequency range 1–30 GHz.

1. Introduction

Recent advances in two-state (0º/180º) phase switches have shown that uniplanar designs based on coplanar waveguide (CPW) [1], [2] feature a broadband phase-shift behavior with low insertion loss. In [1], a CPW/slotline design on alumina substrate using PIN diodes is reported, with a phase shift of 180º ± 2º and insertion loss ≤ 2.5 dB in the frequency range 24−37 GHz (42.6%). In [2], a phase switch based on switching between two out-of-phase back-to-back CPW-to-slotline transitions using two single-pole-double-through MEMS switches is presented, with a phase shift of 180º ± 5º and insertion loss ≤ 2 dB in the frequency range 14−20 GHz (35.3%). These figures are comparable or even better than those reported for microstrip-based MMIC phase switches [3] –[5]. In [3] an InP HEMT process is used, featuring a phase shift of 170º ± 10º and insertion loss of 3.5 ± 0.5 dB in the frequency range 26–36 (32.2%). The p-HEMT phase switch presented in [4] features a phase shift of 187º ± 7º in an ultra-wide bandwidth (0.5–20 GHz) with insertion loss of 3.7 ± 0.6 dB in the frequency band 6–20 GHz. The InP HBT phase switch presented in [5] features a phase shift of 180º ± 1º to 180º ± 5º with insertion loss of 2–5 dB in various 20%-bandwidth channels in the frequency range 30–100 GHz. Phase switches based on MEMS switches with electrostatic actuation [2], [6] present inherent low insertion loss and egligible DC-power consumption, which are attractive features for space applications. In [6] a distributed-MEMS phase shifter is reported, presenting a differential phase shift of 180º in a narrow band at 13.7 GHz, whereas in [2] the phase shift is broadband as described above.

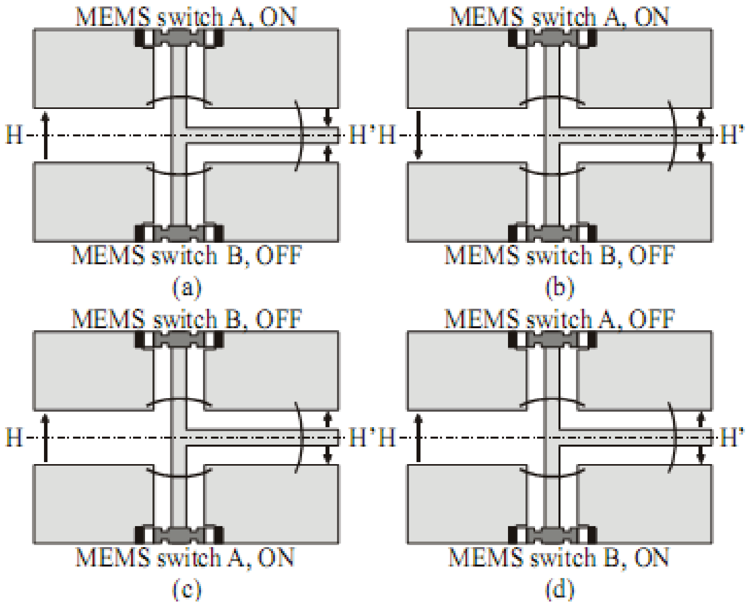


Fig. 1. Structure of the uniplanar 180º phase switch and its principle of operation. The arrows represent electric-field orientations. (a) One of the phase-switch states, with the exciting input slotline mode, and the obtained output CPW (even) mode. (b) Same MEMS switch states as in (a) but now reversing the sign of the incoming slotline field; by linearity, the output CPW field is reversed. (c) Same phase-switch as in (b) but mirrored along de H-H' axis. (d) Same phase-witch as in (c) but with the MEMS switches renamed (A↔B); thus, the other MEMS-switch state is obtained: the output CPW mode is sign-reversed with respect to (a), for the same field orientation of the input slotline mode.

In this paper, we report a broadband, uniplanar phase switch based on a slotline-CPW cross with capacitive-contact MEMS as switching elements. Fig. 1 illustrates its principle of operation. The two MEMS switches are always in opposed states (ON/OFF or OFF/ON, where OFF is used here for not-actuated MEMS and ON for actuated MEMS), thus defining the two phase-switch states (0º/180º). The phase switch features frequency-independent 180º phase-shift properties provided that the structure is symmetric along the axis H-H'. The underlying multimodal theory and design procedure of the phase switch are not covered here since they are extensively studied in [7]. The RF MEMS switches are described in section 2 and applied to the phase switch design in section 3. Section 4 summarizes the main results.

2. Fabrication Processes and MEMS Switches

The phase switch was fabricated using two different surface-micromachining MEMS processes, the FBK-irst eight-mask process [8] and the LAAS-CNRS process [9], both on high-resistivity silicon substrate. The substrate resistivity is higher than 5 KΩcm for the FBK process and 2 KΩcm for the LAAS process. Fig. 2 shows pictures of the capacitive-contact switches used in the design. A bridge topology was selected, with a pair of electrodes located symmetrically. The switch-membrane dimensions and electrode area of 620×100 μm^2 and 2×180×100 μm^2 (for the FBK process), and 800×50 μm^2 and 2×130×210 μm2 (for the LAAS process), respectively. The actuation voltages are 50 V (FBK) and 35 V (LAAS).

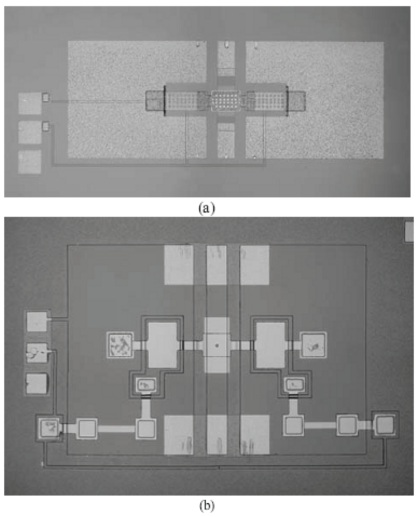


Fig. 2. Pictures (not to scale) of the capacitive-contact MEMS switches used in the designs. (a) FBK-irst process and (b) LAAS–CNRS process.

Fig. 3 illustrates the RF performance of the switches characterized up to 30 GHz with an AgilentTM N5242 network analyzer and a Cascade-MicrotechTM on-wafer probe station with ground-signal-ground probes. Within the phase-switch operating band (8-16 GHz), the FBK-switches OFF-state insertion loss is ≤ 0.3 dB and the return loss is ≥ 20 dB; the ON-state return loss is ≤ 0.5 dB and the isolation is ≥ 20 dB. For the same operating band, the LAAS-switches OFF-state insertion loss is ≤ 0.6 dB and the return loss is ≥ 20 dB; the ON-state return loss is ≤ 0.6 dB and the isolation is ≥ 15 dB.

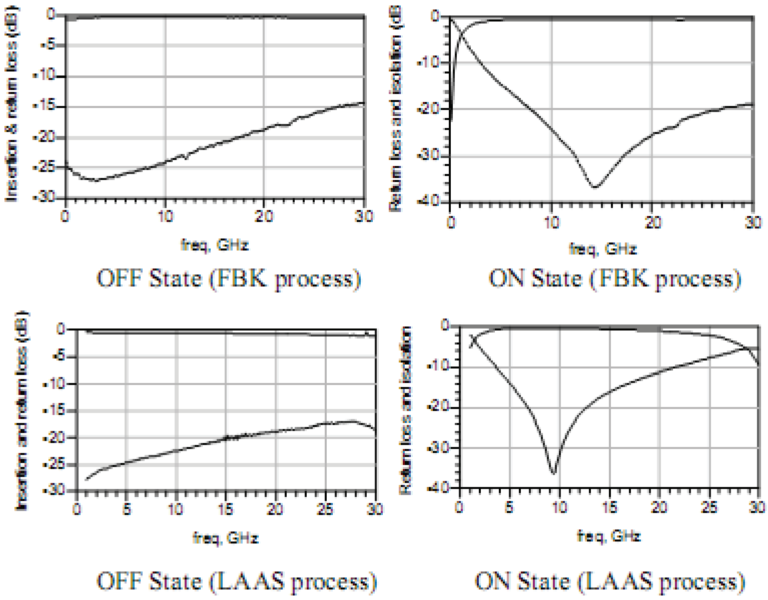
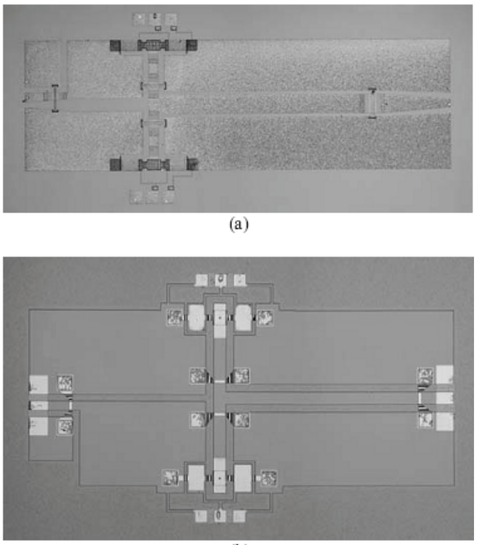


Fig. 3. Measured results of the capacitive-contact MEMS switches of Fig. 2.

3. 180º Phase Switch

A phase switch was designed. It uses the symmetric slotline-CPW cross shown in Fig. 1 loaded with capacitive MEMS switches in the two CPW opposed arms. Fig. 4 shows pictures of the fabricated phase switches using the two processes and the capacitive MEMS switches described in Section 2. Three devices were fabricated on different chips using the FBK process, and one device with the LAAS process. The design centre frequency is 12 GHz. The phase switch was simulated and designed using multimodal-analysis tools [7], which take into account the complex interaction between the CPW even and odd modes generated in the slotline-CPW cross. To obtain a perfect phase shift of 180º between the two phase-switch states, the CPW opposed arms must have equal lengths and be loaded with identical capacitive MEMS switches (but in opposed ON/OFF or OFF/ON states). Under these conditions, the 180º phase-shift is basically frequency-independent.

In Fig. 4, it is observed that a CPW-to-slotline transition of the type described in [10] is inserted prior to the slotline arm, in order to ease the phase-switch characterization using CPW ground-signal-ground wafer-probes.



(a)

(b)

Fig. 4. Pictures (not to scale) of the implemented 180º phase switches. (a) FBK-irst process and (b) LAAS-CNRS process.

The simulated and measured performances are depicted in Fig. 5. Simulations were performed using electromagnetic tools (MomentumTM from Agilent). The simulations agree well with the measured results; in general, Momentum simulations predict quite accurately the phase-switch behavior, though they tend to underestimate the insertion loss. From Fig. 5(a) (FBK process) the insertion loss is ≤ 3 dB for 9–16.5 GHz, with a minimum of 1.9 dB at 13.5 GHz. The amplitude unbalance between both phase-switch states is small in a very wide band (± 0.5 dB for 1–20 GHz). Moreover, the amplitude differences between the three FBK devices for each state is minimum (± 0.25 dB for 9–16.5 GHz), demonstrating a very small dispersion in the fabrication process. Return loss is ≥10 dB for 7.7–16.7 GHz, with a maximum of 25 dB at 12.8 GHz. The measured phase shift is 180º +5º/−2º in a very wide band (1–18 GHz). Regarding the measured results of the phase switch manufactured with the LAAS process (Fig. 5(b)), they show an insertion loss ≤ 4.3 dB in the frequency range 7–15 GHz, with a minimum of 3.2 dB at 12.6 GHz. The amplitude unbalance between both phase-switch states is small in an extremely wide band (± 0.5 dB for 1–30 GHz). The return loss is ≥ 10 dB in the frequency range 10–16 GHz, with a maximum of 18 dB at 14 GHz. The measured phase shift is 180º +0º/−7º, also in an extremely wide band (1–30 GHz), showing the basic phase-shift frequency-independence property of this kind of phase switches. The somewhat higher measured insertion loss for this process is due to the lower resistivity of the silicon substrate.

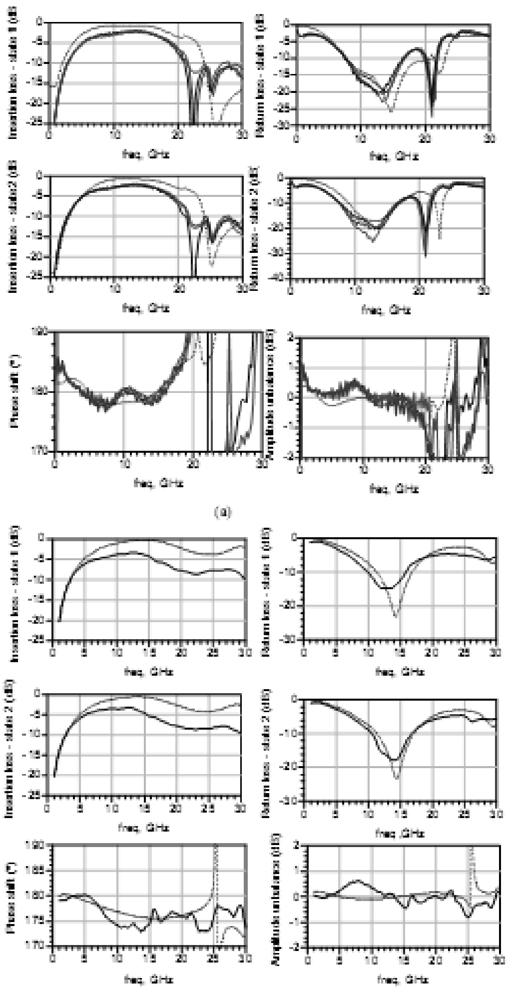


Fig. 5. Experimental results and electromagnetic simulations of the implemented phase switches: insertion and return loss for each state, phase shift and amplitude unbalance. (a) FBK-irst process. Solid line: measurements of chips 9A (red), 9B (orange), 10B (blue). Dotted line: electromagnetic simulation. (b) LAAS-CNRS process. Solid line: measurements. Dotted line: electromagnetic simulation.

4. Conclusion

In this paper, a broadband, uniplanar 180º phase switch, based on a slotline-CPW cross loaded with two capacitive MEMS switches in opposed states has been reported. The devices were fabricated on high-resistivity silicon substrates using two surface-micromachining processes (FBK-irst and LAAS-CNRS). The phase switches have proved to be highly repeatable over the two processes showing similar performance. They feature a 180º +0º/−7º phase-shift in an extremely wide frequency band (1–30 GHz) and insertion loss ≤ 3 dB in a 59% bandwidth (9–16.5 GHz).

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