Novel RF MEMS Mechanically Tunable Dielectric Phase Shifter

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***Abstract*—This paper presents three variations of novel single-stage digital passive RF MEMS phase shifters. Relative phase shift is achieved by moving a micromachined λ/2-long dielectric block by a MEMS actuator above a 3dimensional micromachined coplanar waveguide. The relative phase-shift of a single stage is determined by an artificially tailor-made dielectric constant of the block which is designed by a periodically etched pattern. The devices are fabricated and assembled by wafer-scale processes using bulk and surface micromachining. The measurement results show that already the first prototypes of the phase-shifter designs at the nominal frequency of 77 GHz have both in the up and in the down state a return loss better than -25 dB for 45ºand 30º phase shifter and better than -12 dB for 15º phase-shifter with an insertion loss better than -0.9 dB at 5 GHz bandwidth.**

The phase shifters also perform well from 10-100 GHz with the return loss better than -10 dB, an insertion loss of less than -1.5 dB and a fairly linear phase-shift for the whole frequency range.

I. Introduction And Background

PHASE shifters play an important role in wireless communication and radar systems. MEMS phase shifters in general are known for very low insertion loss and high linearity over a large bandwidth. However, at frequencies above 60 GHz, switched true-time delay phase shifters are not suitable anymore because of their poor performance in return- and insertion loss [1]. Distributed MEMS capacitive phase shifters [2] perform well in the W-band but consist of thin metal bridges which cannot handle large induced current densities, and are therefore limited to low power handling capability [3].

This paper introduces a novel digital-type microwave MEMS phase shifter which by its nature has a high power handling capability since no thin moving metallic membranes are employed. The power handling is only limited by the current handling capability of the coplanar waveguide (CPW) conductors and the heat sink capacity of the substrate.

II. Dielectric Phase Shifter

A MEMS electrostatic actuator, vertically moving a /2-long dielectric block above a 3dimensional micromachined CPW, tunes the propagation constant of the RF signal, resulting in a relative phase shift between the up and down-state is shown in Fig. 1.

A periodically etched-patterned high-resistivity silicon block is suspended over a 3D micromachined CPW connected to the anchor by four serpentine flexures. The length of the dielectric block is chosen to be half-wavelength at the nominal frequency of 77 GHz. In this case the reflected electromagnetic (EM) waves from the discontinuities at the beginning and at the end of the block are exactly out of phase (180º difference) and, thus, cancel each other.

Relative phase shift is obtained by moving the dielectric block over the high-impedance CPW (>50 Ω) resulting in different characteristic impedance of the t-line and propagation constant of the EM waves propagating along the t-line between up and down state. Periodically etched patterns of the dielectric block with three different sizes are introduced for tuning the effective dielectric constant resulting in relative phase shift of 45º, 30º and 15º. Short circuit of DC-actuation voltage between the dielectric block and the CPW in the down state is prevented by patterning an array of silicon nitride (Si_3N_4) distance keepers on top of the CPW metal line.

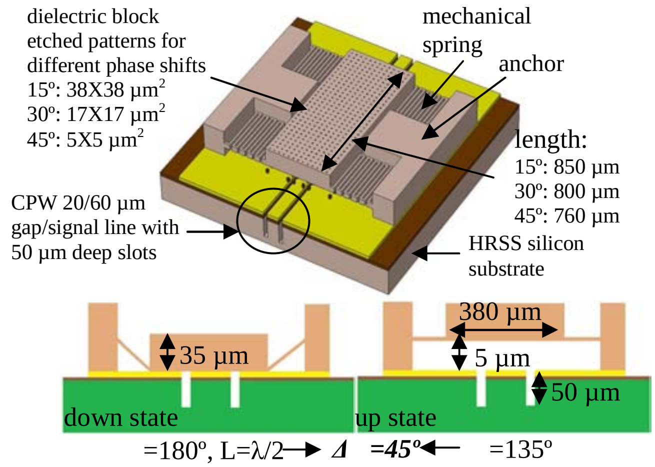

Fig. 1. Single stage phase shifter: cross-section and schematically functional drawing.

III. Fabrication Process

The process flow for fabricating the dielectric-loaded phase shifter is shown in Fig. 2. The fabrication starts with patterning the CPW of 1-μm gold layer with thin adhesive Ti-layer on the high resistivity silicon substrate. Additionally, the gaps between the signal line and the ground lines of the CPW are etched down into the substrate to create deep trenches. These slots decrease the effective permittivity of the t-line and thus make it more sensitive to the position of the dielectric block on top of the t-line, which creates a larger phase difference between the up and the down state of the dielectric block. Furthermore, the slots decrease the losses of the t-line. The thin Si_3N_4 layer is deposited on the t-line and patterned to create an array of the distance keeper. Subsequently, this wafer is bonded to a high-resistivity silicon-on-insulator (SOI) wafer for patterning springs, anchors, and movable dielectric block by adhesive polymer boding. The bulk material is removed from the bonded SOI wafer and the SiO_2 layer is used as oxide masks for further processing. Deep reactive-ion etching (DRIE) steps are performed to create the mechanical springs and dielectric block. The structure is finally released by a time-controlled O_2-plasma etching process. The phase shift in a single stage is determined by artificially tuning the dielectric constant of the silicon block by varying the size of the etch-holes, Fig 3.

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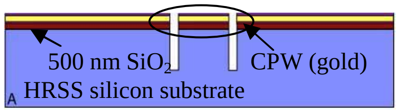
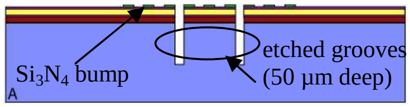
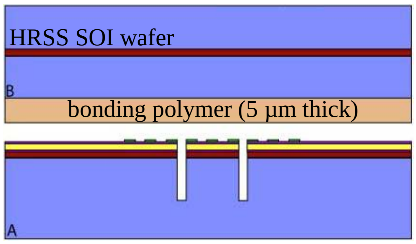


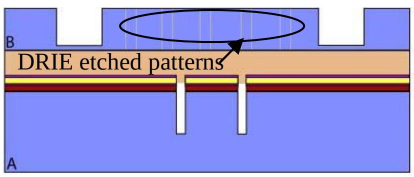
(a) Patterning CPW and 50-µm etch grooves



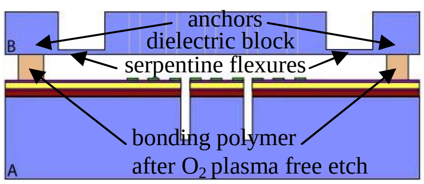
(b) Patterning Si_3N_4 bump array



(c) Polymer bonding with HRSS SOI wafer



(d) Patterning springs, anchors and etched patterns



(e) Releasing structure with O_2 plasma

Fig. 2. Process flow

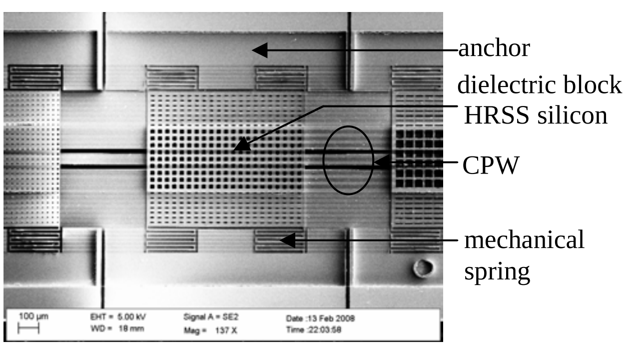
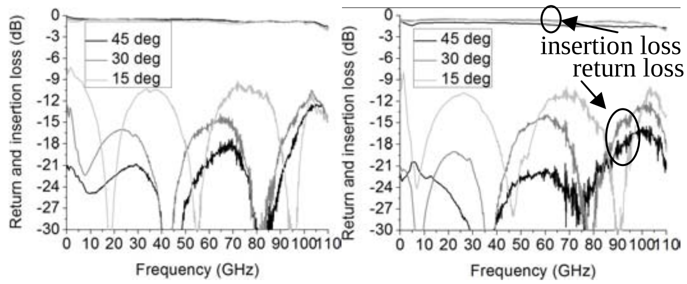


Fig. 3. SEM picture of fabricated 30º stage phase shifter between 45º (left) and 15º (right) stages.

IV. Measurement Results

Fig. 4 shows the return and insertion loss of the dielectric-loaded phase shifter in the up and in the down state, respectively. The measurements show that the return loss is better than -10 dB from 10-100 GHz in both up and down state. The maximum insertion loss is -1.7 dB occurred in the down state position due to the material loss of the silicon substrate. At the designed frequency with 5 GHz bandwidth the return loss is better than -25 dB for 45ºand 30º phase shifter and better than -12 dB for 15º phase shifter with the insertion loss less than -0.9 dB.

Fig. 5 shows the relative phase shift versus frequency. This dielectric phase shifter performs a decent linear phase shift. For loaded t-line length of 760 µm, this phase shifter produces 592º phase shift per cm. Calculating from the measured insertion loss a phase shift of 30º/dB at 77 GHz is obtained. The actuation voltage characterized was determined by white-light interferometry to be 29 V.



(a) up-state (b) down-state

Fig. 4. Return and insertion loss of the 15º, 30º and 45º phase-shifters

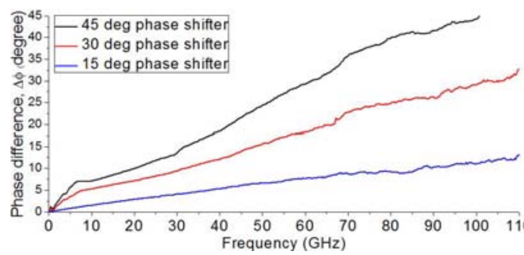


Fig. 5. Phase shifts between the up-state and the down-state for the 15º, 30º, and 45º stages.

V. Conclusions

A novel phase shifter concept based on dielectric-loaded of the 3D micromachined CPW is introduced. The relative phase shift is controlled by vertically moving a dielectric block resulting in changing of the propagation constant of the EM wave between up and down state.

Acknowledgement

This work is part of the SARFA project and receives funding through the NORDITE Scandinavian ICT program by VINNOVA, TEKES, and RCN.

We would like to thank to the VTT Technical Research Centre in Espoo, Finland, for the assistance with the RF measurements.

References

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