Micro-fabricated High-impedance Surface for Millimeter Wave Beam Steering Applications

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***Abstract*—A multi-layer high-impedance surface has been micro-fabricated and measured in W band. It consists of an array of capacitors placed on a dielectric substrate with a ground plane. Reconfigurability of the effective surface impedance of this structure can be enabled by applying control voltage to the tunable capacitors. Tunable impedance surfaces can be used in phase shifters for a phased array antenna, and directly as a smart beam steering surface.**

I. Introduction

High-impedance surfaces (HIS), since their introduction in 1999 [1], attract much attention due to their promising applications, such as improvement of the radiation pattern of an antenna and suppression of the surface wave [1], beam steering [2] and phase shifting [3]. Recently, we have proposed to use MEMS fabrication technique to produce reconfigurable HIS where the effective surface impedance can be controlled by applying voltage to MEMS capacitors [4]. In contrast to, e.g., ferroelectric devices, MEMS allow to develop phase shifters and other components of low loss even at the millimeter wavelengths. Nevertheless, MEMS phase shifters based on switching the length of the transmission line may be not convenient in phased array antennas due to the large size, and besides they provide a discrete phase shift only. In this paper we report the measurement results of a micro-fabricated HIS, which can be used for developing low loss analog type phase shifters or smart beam steering surfaces.

II. Multi-Layer High-Impedance Surface

The proposed multi-layer HIS consists of an array of electrically small MEMS capacitors placed on a dielectric substrate with a ground plane and coupled to each other in the direction of ***E***-field, see Fig. 1. Since the size of the MEMS capacitors is much smaller than the wavelength of the field above the structure, its electromagnetic response can be described in terms of the effective surface impedance. The input impedance of the grounded dielectric substrate, which thickness was chosen to be smaller than quarter of the wavelength, is inductive. Together with the capacitive array this forms a resonant structure. At a resonance frequency, the effective surface impedance of the structure becomes very large compared to the free space impedance, and the phase of the reflection coefficient changes from 180° (as it is for metal surfaces) to 0°, see Fig. 2.

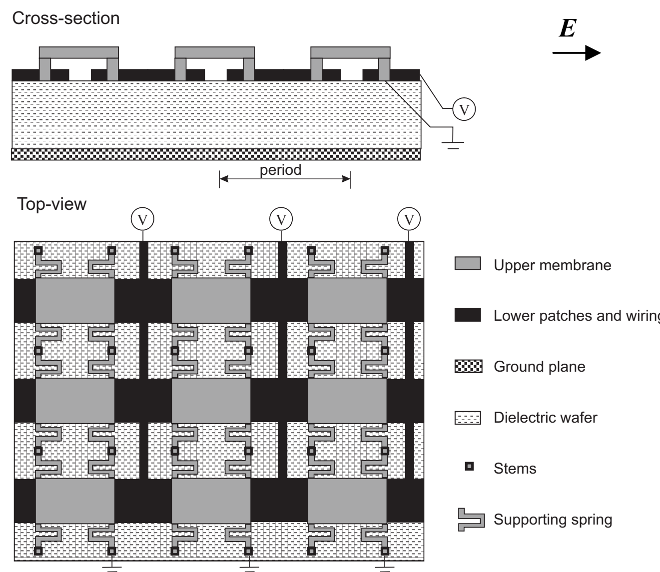

Fig. 1 Design of the reconfigurable MEMS-based HIS.

The phase of the reflection coefficient of the proposed multi-layer HIS plotted in Fig.2 is found from the effective surface impedance, which can be calculated through a parallel combination of capacitive impedance of array of membranes and patches, and inductive impedance of the grounded substrate, as we have shown earlier [5]. Due to the relatively large separation between neighboring patches and membranes chosen on the design stage, the main contributor to the capacitive impedance is the overlapping between the upper membranes and lower patches, while the grid capacitance of, e.g., the array of lower patches, is responsible for a few percent only of the total effective capacitance. In case of thin and low loss dielectric substrate, its effective impedance can be approximated as $Z_{substr}=j\eta_0 k_0 h$, where η_0 is the free space impedance, k_0 is the wave number, and h is the thickness of the substrate. Extracting effective total capacitance and total inductance from the surface impedance equation, allows calculating the resonance frequency of the structure:

$$f_{res} = 1/(2\pi\sqrt{L_{eff} C_{eff}}) \qquad (1)$$

If a control voltage is applied to the capacitors, the value of the capacitance changes, as well as the effective surface impedance. Due to this, the phase of the reflection coefficient of the structure and the phase factor of the propagation constant of the field above it can be controlled in analogue way by the applied voltage, see Fig. 3. This allows to integrate the proposed HIS to a metal or dielectric waveguide in order

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to obtain an analogue type millimeter wave phase shifter, which can be used for a phased array antenna. Optionally, the proposed HIS can be used directly as a smart reflecting beam steering surface if each row of the MEMS capacitors is controlled independently, and an electrically tunable gradient of the reflection phase is induced on the surface, see Fig. 4. Changing the gradient of the reflection phase throughout the surface will change the direction of the field reflected from the HIS.

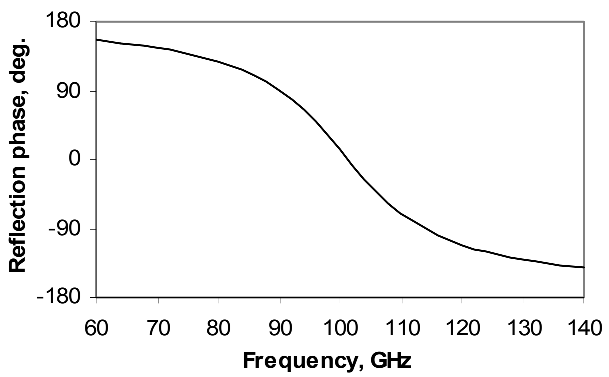

Fig. 2 Frequency dependence of the HIS reflection phase, calculated.

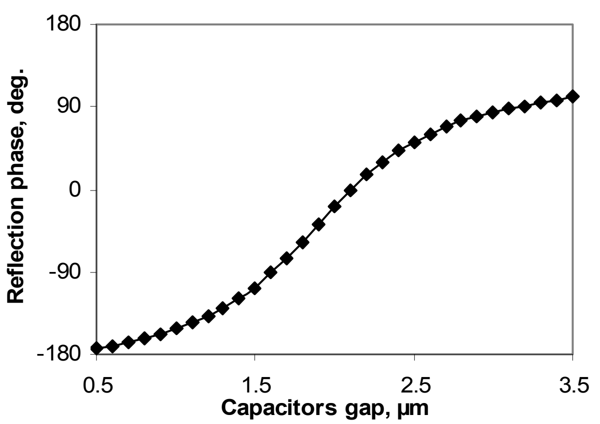

Fig. 3 Dependence of the HIS reflection phase on the gap of the MEMS capacitors controlled with bias voltage, simulated with Ansoft HFSS.

III. FABRICATION

Fig. 5 shows an outline of the process flow used to fabricate the HIS. First, the gold ground plane is sputtered on a silicon substrate (a). Then the dielectric AF45 glass layer is transferred to the ground plane and the lower HIS patches are fabricated on the glass by gold evaporation and lift-off patterning (b). The membrane layer is transferred by adhesive wafer bonding using a sacrificial bonding polymer which defines the gap of the capacitors (c). Finally the membrane layer is patterned and gold posts are erected by electroplating, after which the sacrificial polymer is stripped to release the membranes (d).

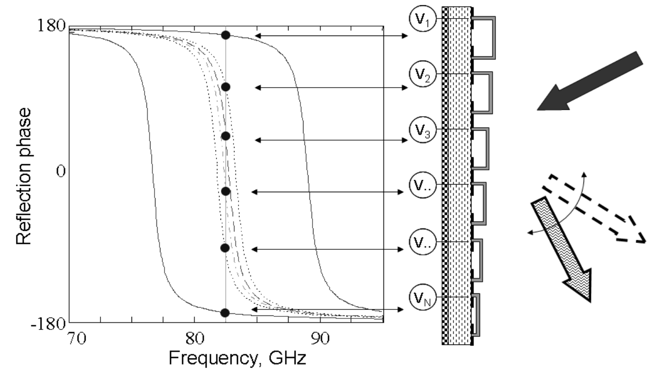

Fig. 4 Scheme of the electronic beam steering using MEMS tunable HIS. (Note that the gap of the tunable capacitors is greatly exaggerated.)

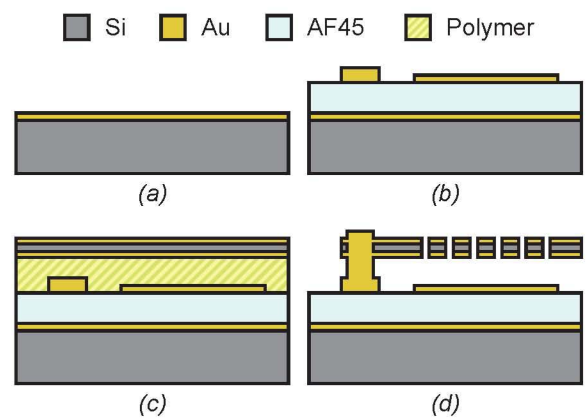

Fig. 5 HIS fabrication process.

A SEM image of a micro-machined HIS prototype consisting of an array of 200 × 52 unit cells is shown in Fig. 6. The pitch size of the individual unit cells is 350 µm, resulting in a total chip size of 74 mm × 22 mm. Large size of the HIS in one direction is required for a narrow beamwidth of the reflected signal in W band.

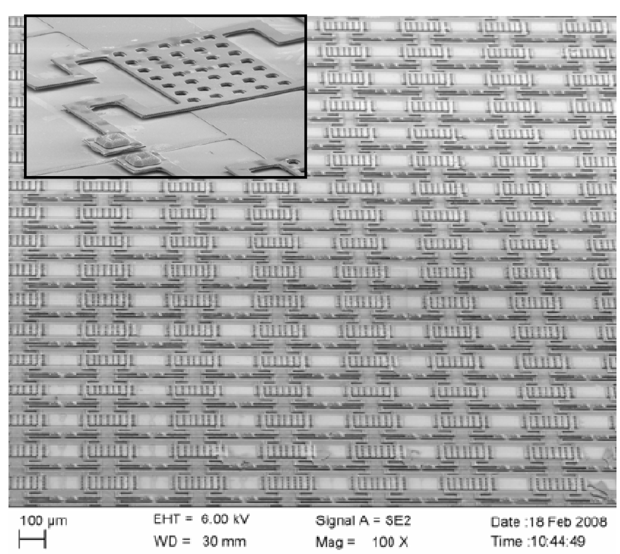

Fig. 6 SEM images of the fabricated prototype HIS devices.

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The HIS membranes consist of a double-side metal coated monocrystalline silicon layer, resulting in near-ideal flatness and high mechanical robustness of the membranes.

IV. MEASUREMENTS

Reflection coefficient of the fabricated HIS prototype was measured with HP 8510 VNA by placing it as a backshort of a rectangular metal waveguide WR-10, see Fig. 7. The phase of the reflection coefficient is changing from 140° to -94° and is equal to 0° at 112 GHz, proving that the structure behaves as a HIS, see Fig. 8. Plotted on the Smith chart, the measured S_{11} shows that the fabricated prototype is a resonant structure.

Losses of the HIS prototype appeared to be quite high: 18 dB at the resonance and 7 dB outside the resonance. Since the gap of the array of capacitors (where the amplitude of the electric field is largest) is filled with air and not with a lossy dielectric, the primary source of loss could be related to manufacturing nonidealities, which can be eliminated in the further development.

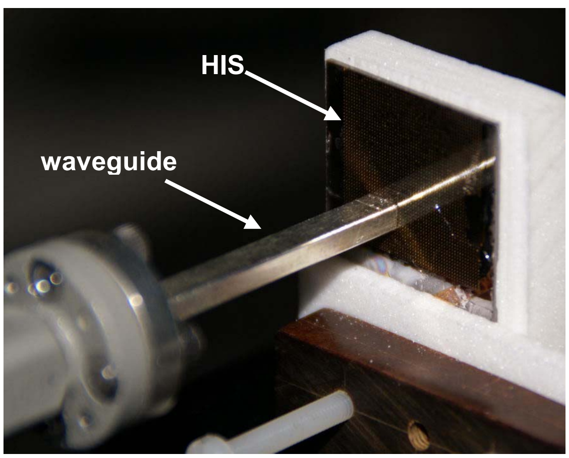

Fig. 7 Measurement setup.

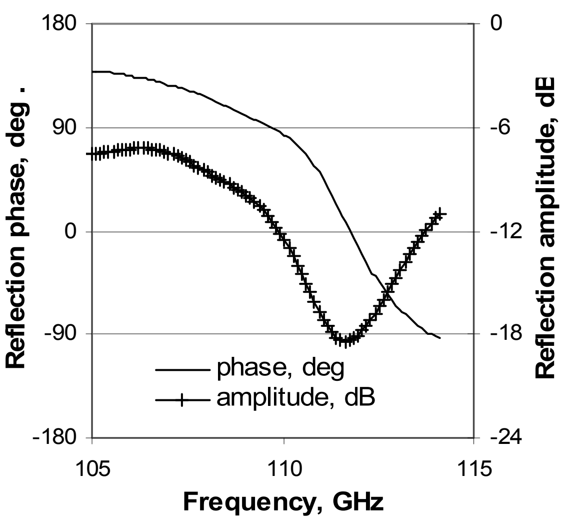

Fig. 8 Measured S_{11} of the micro-fabricated HIS prototype: frequency dependence of the reflection phase and amplitude.

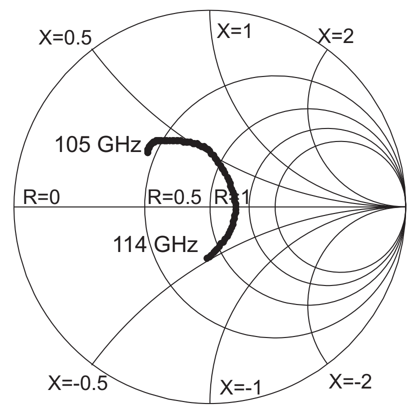

Fig. 9 Measured S_{11} of the micro-fabricated HIS prototype: Smith chart.

V. CONCLUSIONS

We have designed, analyzed, fabricated and measured a prototype of the multi-layer HIS. A sophisticated fabrication process allowed to obtain near-ideal flatness of the upper membranes. The measures reflection phase changes gradually from 140° at 105 GHz to 0° at 112 GHz, where the structure exhibits a pronounced resonance. Once the actuation of the MEMS capacitors is realized, the micro-fabricated HIS can be used for proposed applications as a phase shifting element or as a smart electronic beam steering surface. Next steps are the fine-tuning of the fabrication process in order to decrease reflection losses of the prototypes and realization of the voltage control of the surface impedance of the prototypes.

ACKNOWLEDGEMENTS

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