

## RESEARCH PAPER

# Analog-type millimeter-wave phase shifters based on MEMS tunable high-impedance surface and dielectric rod waveguide

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*Millimeter-wave phase shifters are important components for a wide scope of applications. An analog-type phase shifter for W-band has been designed, analyzed, fabricated, and measured. The phase shifter consists of a reconfigurable high-impedance surface (HIS) controlled by micro-electromechanical system (MEMS) varactors and placed adjacent to a silicon dielectric rod waveguide. The analog-type phase shift in the range of 0–32° is observed at 75 GHz whereas applying bias voltage from 0 to 40 V to the MEMS varactors. The insertion loss of the MEMS tunable HIS is between 1.7 and 5 dB, depending on the frequency.*

**Keywords:** Phase shifter, MEMS, millimeter waves, high-impedance surface, dielectric rod waveguide

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## I. INTRODUCTION

Millimeter-wave phase shifters are important components for a wide scope of applications such as automotive radars, high-capacity communication systems, satellite communication, etc. Existing millimeter-wave phase shifters change the phase by adjusting either the geometrical parameters of the device (e.g. changing the length of a transmission line using switches), or material properties of its components (e.g. by applying magnetic or electric field). Phase shifters based on switched networks and distributed transmission lines may be inconvenient, e.g. in phased arrays due to their relatively large size. Besides they provide with a discrete phase shift only, and of no more than 4.25 bits at frequencies above 60 GHz, e.g. [1–3], which restricts their usability. Using materials with controllable parameters (e.g. ferroelectrics) for phase shifter usually results in high insertion loss at millimeter wavelength frequencies, e.g. 10 dB for a continuous phase shift up to 220° at 60 GHz [4]. That is why we propose an approach that combines micro-electromechanical systems (MEMS) fabrication technology with the concept of artificial electromagnetic surfaces for realization of analog-type millimeter-wave phase shifters. MEMS technology

allows one to miniaturize electronic components, reduce their cost in batch production, and effectively compete with semiconductor and ferroelectric technology in terms of losses. Combined with the artificial electromagnetic surfaces, MEMS varactors enable tunability of unique engineered properties of these surfaces. Previously, we proposed the design of a novel MEMS tunable high-impedance surface (HIS), analyzed its electromagnetic properties analytically and numerically, studied possible applications, and fabricated and measured several non-tunable prototypes, as well as tunable MEMS capacitors [5–12]. In this work we present for the first time the measurement results of the MEMS-based HIS that is tunable in an analog way and is employed in an analog-type phase shifter.

## II. MEMS TUNABLE HIS

Conventional HIS [13] consists of a capacitive two-dimensional periodic grid of electrically small metal patches placed on a thin dielectric substrate with a ground plane. As the period of the structure is much smaller than the wavelength of the field above it, an effective surface impedance model can be used to analyze the electromagnetic behavior of the HIS. The grid of metal patches provides a capacitive response to the incident electromagnetic field, whereas the thin grounded dielectric substrate provides an inductive response. As a result, the HIS is a resonant structure, and at the resonance frequency the effective input impedance becomes very high, and the phase of the reflection coefficient changes from 180 to 0°. The HIS was proposed for such applications as an improvement of antenna radiation

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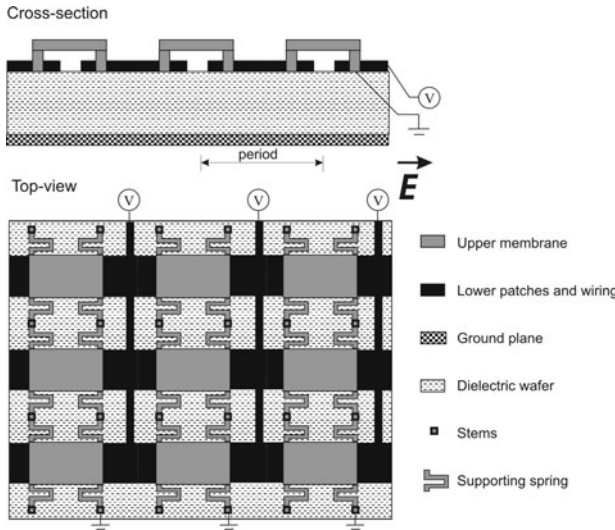


Fig. 1. MEMS tunable HIS (part of a large periodic arrangement is shown).

parameters, suppression of the surface waves, and leaky wave antennas [14, 15]. Tunable HIS controlled with diode varactors and InP quantum barrier varactors were utilized for demonstrating beam steering [16] and metal waveguide phase shifting [17], respectively. However, at W-band these tunable elements exhibit high losses. That is why we proposed to employ MEMS varactors for reconfiguring the HIS [5]. The MEMS tunable HIS, consequently, consists of a two-dimensional periodic arrangement of MEMS varactors placed on a grounded Si substrate with a period much smaller than the wavelength of a field above the HIS, see Fig. 1.

The bias voltages applied to a MEMS varactor controls its capacitance value by changing the gap between the upper membrane and lower patch, affecting accordingly the effective input impedance of the whole structure. Fig. 2 shows frequency dependence of the effective surface impedance of the HIS. The phase of the reflection coefficient of the MEMS tunable HIS for different values of the gap between the upper membranes and lower patches is given in Fig. 3.

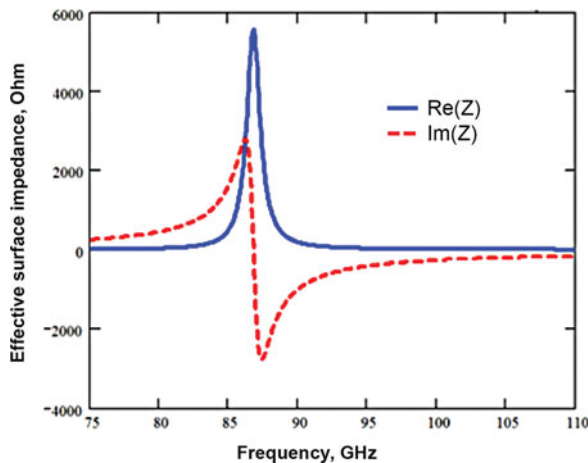


Fig. 2. Real and imaginary part of the effective surface impedance of the MEMS based HIS, calculated.

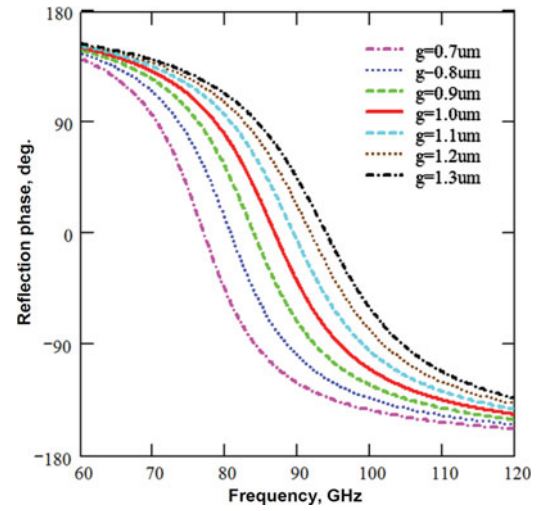


Fig. 3. Reflection phase of the MEMS tunable HIS for different values of the gap  $g$  between the upper membranes and lower patches, calculated.

### III. ANALOG-TYPE PHASE SHIFTER

#### A) Design

The MEMS tunable HIS can be used to control the phase factor of the propagation constant of a dielectric rod waveguide (DRW) placed adjacent to the HIS at a distance  $d$ , see Fig. 4, forming thus an analog-type phase shifter as soon as the bias voltage changes the capacitance value of the MEMS varactors gradually. The value of the phase shift is proportional to the length  $w$  of the HIS. The device can be used as a dielectric rod antenna with integrated phase shifter if the wave radiates to the free space from Port 2. Furthermore, a phase array antenna can be formed by placing  $n$  DRW one above another and adjacent to  $n$  HIS controlled individually. These HIS can be fabricated on a single chip will dramatically reduce complexity and, consequently, the cost of the array antenna.

Simulation results of the phase shift of the DRW with adjacent MEMS tunable HIS, when the gap of MEMS varactors changes from 2 to 1.2  $\mu\text{m}$  is shown in Fig. 5, demonstrating promising phase shifting potential. Previously we also fabricated a non-tunable prototype of the MEMS-based HIS for the DRW phase shifter, measuring S-parameters with HIS and a copper plate adjacent to the DRW for assessing the maximum achievable phase shift while tuning the structure from a high-impedance state to a low-impedance state [12].

#### B) Fabrication

A prototype of the MEMS tunable HIS with  $24 \times 120$  MEMS varactors placed on a silicon substrate with the period of

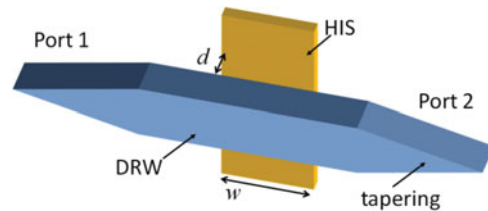


Fig. 4. Phase shifter based on a MEMS tunable HIS of width  $w$  adjacent to a DRW at a distance  $d$  (3D view).

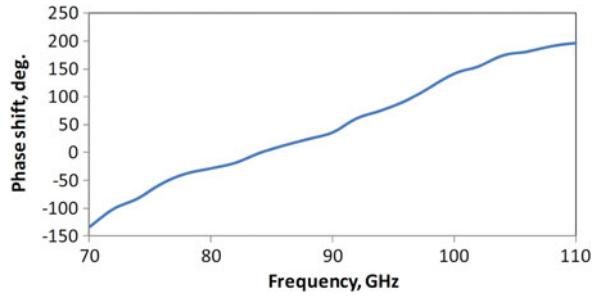


Fig. 5. Simulated phase shift of the DRW with adjacent MEMS tunable HIS.

250  $\mu\text{m}$  and total size of  $6 \times 30 \text{ mm}^2$  has been fabricated, see Fig. 6. All varactors are connected by bias voltage lines to two contact pads.

In order to increase the tunability range of the MEMS varactors, special actuation electrodes of the thickness smaller than the thickness of the lower patches are introduced into the HIS model, which do not affect performance of the HIS according to the both analytical and numerical analysis. For a simple parallel plate MEMS varactor, the gap between the upper membrane and lower patch can be decreased continuously by the bias voltage applied to them only by one-third of its initial value  $g$  to  $g_{\min} = g \times 2/3$  [18]. If more bias voltage is applied, the membrane collapses to the lower patch, consequently the maximum achievable capacitance ratio is 1.5. On the other hand, if the additional actuation electrode of small thickness  $t_e$  comparing with the thickness of the lower patches  $t_p$  is used for bias voltage, see Fig. 7, then the rule of

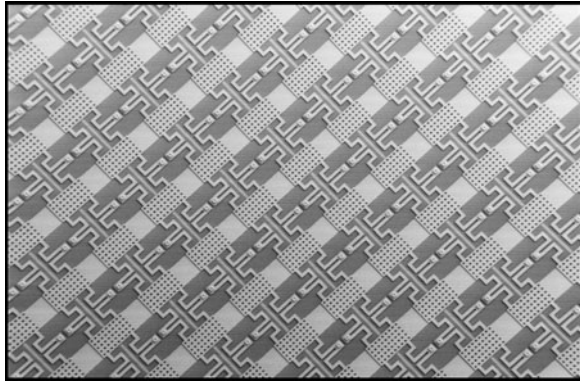


Fig. 6. SEM image of the fabricated prototype of MEMS tunable HIS.

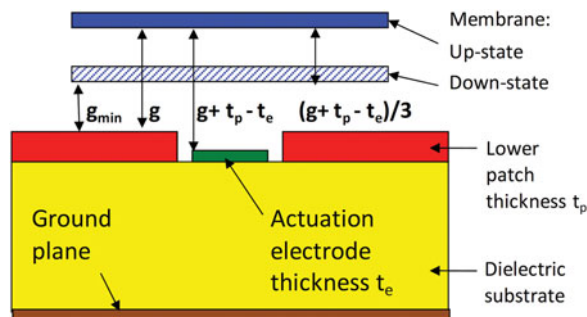


Fig. 7. Schematic overview of a single cell of the MEMS-based HIS for extended tuning range (side view).

two-third is applied for the larger gap  $g + t_p - t_e$ , and consequently the maximum achievable capacitance ratio is

$$K = \frac{g}{g - \frac{1}{3}(g + t_p - t_e)}. \quad (1)$$

For  $g = 1 \mu\text{m}$ ,  $t_p = 1 \mu\text{m}$ , and  $t_e = 0.2 \mu\text{m}$ , the capacitance ratio is 2.5.

### C) Measurements

The MEMS tunable HIS is placed adjacent to the silicon DRW matched to WR-10 waveports of a vector network analyzer for measuring S-parameters. The bias voltage from 0 to 40 V is applied to all MEMS varactors simultaneously. An analog-type phase shift is detected at Port 2 of the DRW, see Fig. 8, where the phase of  $S_{21}$  of biased phase shifter is referenced to the  $S_{21}$  at 0 V. The measured frequency dependence of the phase shift at, e.g. 40 V bias voltage, corresponds to the simulated results, see Fig. 5.

Dependence of the phase shift on the bias voltage is shown in Fig. 9 for 75 and 110 GHz, where the value of the phase shift is largest on the measured frequency range. The phase changes gradually from 0 to 13 and  $-32^\circ$ . Larger phase shift value can be expected with higher bias voltage, and in case the HIS is

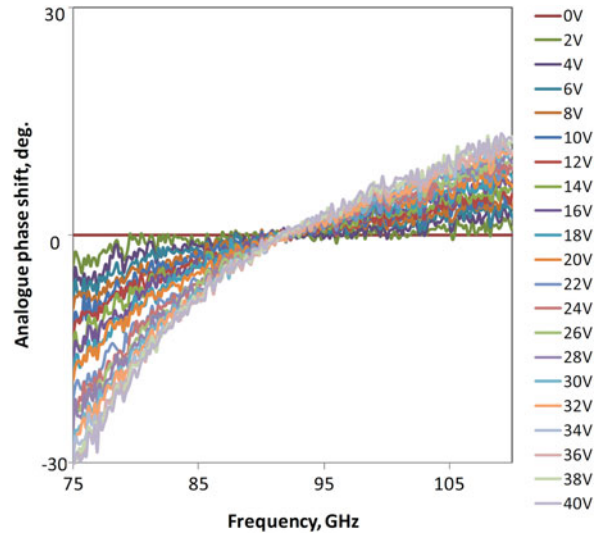


Fig. 8. Measured analog-type phase shift of the DRW with adjacent MEMS tunable HIS.

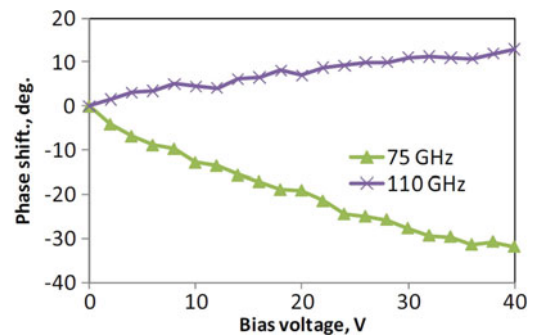


Fig. 9. Measured dependence of the phase shift on the bias voltage.

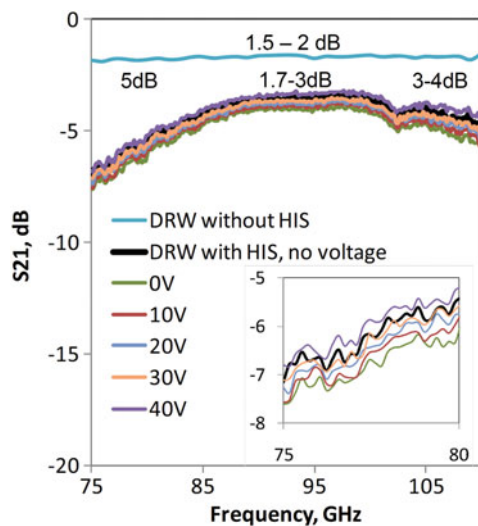


Fig. 10. Measured insertion loss of the phase shifter.

optimized so that the minimum phase shift would appear, e.g. at 110 GHz.

The  $S_{21}$  of the DRW and DRW with adjacent HIS is given in Fig. 10, showing that the insertion loss of MEMS tunable HIS as a phase shifting element is between 3 and 5 dB. Second fabricated prototype, showing larger phase shift of up to  $70^\circ$ , exhibited higher insertion loss. The losses can be decreased by optimized fabrication procedure, choosing better material of the DRW and improving matching of DRW to the WR-10 ports of the VNA. It has been shown that insertion loss of a DRW matched to WR-10 can be as low as 0.4 dB [19].

#### IV. CONCLUSION

We have designed, manufactured, and measured an analog-type millimeter-wave phase shifters. The phase shifter comprises of a MEMS tunable HIS placed adjacent to a DRW. The analog-type phase shift of up to  $-32^\circ$  has been demonstrated at 75 GHz by applying bias voltages from 0 to 40 V. Both the maximum phase shift value and the insertion loss can be improved by optimizing the design of the structure and the fabrication procedure. The proposed phase shifter can be used in a phase array antenna for millimeter-wave applications.

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