Beam Steering with MEMS-based HIS on a lossy Sillicon Substrate at 80 GHz

Zhou Du, Dmitry Chicherin, Antti V. Räisänen
Department of Radio Science and Engineering / SMARAD, Aalto University
P.O. Box 13000, FI-00076, AALTO, Finland
zhou.du@aalto.fi, dmitry.chicherin@tkk.fi, antti.raisanen@aalto.fi

***Abstract*-We have studied MEMS-based high impedance surface (HIS) on a lossy silicon substrate as a beam steering reflective surface for millimetre wave applications. The steering mechanism is based on inducing the effective surface impedance throughout the structure controllable by MEMS varactors for changing the reflection phase distribution on the surface. Reflection phase properties of a single unit cell of the periodic structure are analyzed analytically and numerically. Normalized radiation pattern of a strip consisting of elements with different impedance is analyzed numerically for oblique incidence. The steering range is achieved from -45° to 45° with respect to the normal direction.**

I. Introduction

Since its first proposed in 1999 by Sievenpiper [1], the high impedance surface (HIS) has been developed for various applications since it was first proposed in 1999 [1], for instance for antennas [2] and radar absorbers [3] phase shifters [4, 5], etc.

Beam steering based on HIS has demonstrated by changing the reflection phase difference between two adjacent elements of the HIS array, in order to steer the reflecting beam direction by controlling the phase gradient throughout the surface [6]. Generally, the tunable phase gradient can be achieved by varieties of methods, and in [6] diode varactors were placed between each two elements. The resonance frequency in the HIS can be tuned by adjusting the capacitance values of diodes, which consequently changes the reflection phase.

Microelectromechanical systems (MEMS) components has demonstrated exceptional performance at RF and millimetre wave frequencies, including low insertion loss and high isolation. This is the reason we have proposed to use MEMS varactors for developing reconfigurable HIS operating at millimetre wave range [7].

Proposed multi-layer MEMS tunable HIS (see Fig. 1), consists of an array of electrically small MEMS tuneable capacitors, placed on a grounded dielectric wafer, in which the upper membrane is formed by three layers (Au + Si + Au) and is suspended by springs. Upon application of a bias voltage between the membrane and the bottom plate of the MEMS varactor, changes the distance between them, which in turn, change the effective capacitance of the whole structure affecting the resonance frequency of the HIS.

II. Characterization of Unit Cell Structures

As the MEMS-based HIS is a periodical structure (consists of at least 5 x 5 cells), it is handy to consider a unit cell structure for describing the structure dimensions and analysing its electromagnetic performance with appropriate boundary conditions. The 3-D view of the unit cell structure is shown in Fig. 1.The periodic length and width of the unit cell is 350 µm.

A. Equivalent Circuit of the Unit Cell

Due to its feature size is much smaller than the wavelength, the equivalent input impedance of MEMS-based HIS Z_{tot} can be interpreted as the parallel connection of the capacitive grid impedance Z_g, the parallel-plate capacitive impedance Z_{pp} and thin grounded dielectric inductive impedance Z_s.

$$Z_{tot} = (Z_s^{-1} + Z_{pp}^{-1} + Z_g^{-1})^{-1} \quad (1)$$

This equivalent circuit can be used to calculate the reflection coefficient of the incident electric field at the reflecting surface in terms of Z_{tot} and Z_0, which is the free space impedances for TM mode and different incident angles as in [8]:

$$Z_0 = \eta_0 \cos\theta \quad (2)$$

where η_0 is the plane wave impedance in free space.

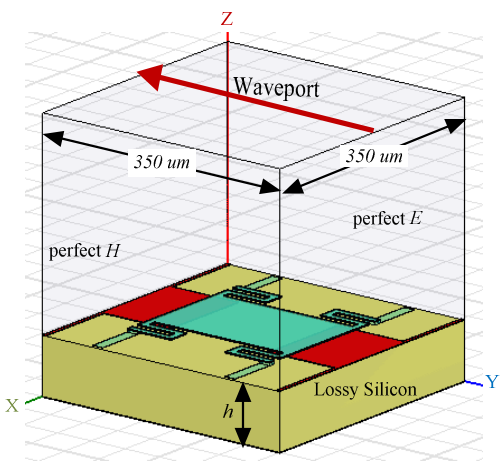

Fig. 1. 3-D view of the single unit cell structure of MEMS-based HIS.

B. Surface Impedance Tuning

The HIS is a resonance structure, and at the resonance frequency the phase of the reflection coefficient becomes zero degree. Theoretically, the reflection phase of a tuneable HIS at

any fixed frequency varies continuously from -180° to +180° with continuous change of the capacitance value. In reality, it does not perform likewise. The main reason is due to the metal membranes become instable at two thirds of initial height [9]. Therefore, the beam steering mechanism should be adapted to this limitation.

The beam steering can be achieved by programming the gradient of the reflection phase as a function of gap between the membrane and lower patches, which influences the effective surface input impedance:

$$R = (Z_{tot} - Z_0)/(Z_{tot} + Z_0) \quad (3)$$

where R is the reflection coefficient of the HIS.

We have simulated the structure using full wave 3-D simulation software Ansoft HFSS, to analyze the tunability range. To keep the resonant frequency at the desired 80 GHz, the substrate height 75 µm is chosen as constant and the gap is varied according to each substrate separately. The simulated structure is a single unit cell which is placed at the bottom of a vacuum section which has two perfect electric boundaries on two opposing walls in X-Z planes and two perfect magnetic boundaries in Y-Z planes. The boundary conditions are imaging the unit cell to form a double periodic array of infinite extent. A TM mode plane wave with electric field parallel to y-axis as is excited on top of the vacuum section.

The reflection phase is recorded at the surface as a function of frequency by exciting a wave to the top of the vacuum section, since it is the normal way to find the frequencies where the surface works as intended. This is sufficient to explain tendency of the variation of reflection phase due to the change of the geometry, i.e. the thickness h of the substrate and gap g between membrane and lower patches.

Besides that, during the whole simulation campaign, there are couple of considerations should be taken into account in order to obtain more practical results. e.g. dielectric losses and surface roughness, etc.

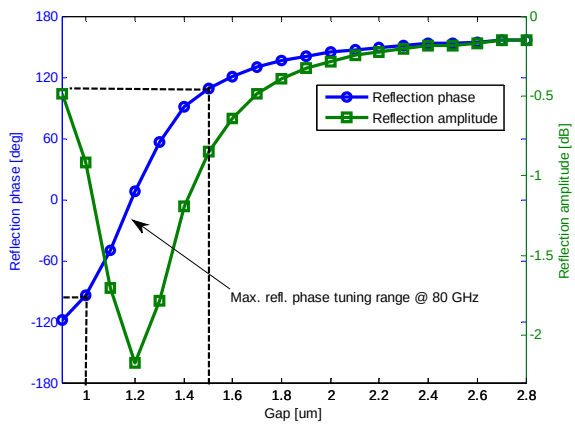

Fig. 2. Reflection phase and amplitude for the single unit cell as a function of gap between membrane and lower patches, simulated

Dielectric loss indicated by a finite loss tangent, tanδ, rises proportional the operating frequency. The loss tangent of silicon is 0.005 @ 1 GHz and 0.015 @10 GHz, respectively. In practice, the surface of the conductor will not be perfectly plannar. Since the current flows in a thin sheet near the surface (within a skin depth or so), the roughness of the surface causes the current to travel a longer path through the lossy conductor. This increases conduction loss. In this paper, loss properties during the simulation are: tanδ = 0.015, surface roughness = 3 nm.

Fig. 2 shows simulation results of the phase and amplitude of the reflection coefficient of the single unit cell of HIS for different values of the gap of the MEMS varactor. It indicates that, for the structure with 75 µm thick substrate, the reflection phase is varied from approximately +108.7° to -93° (which is also the maximum tuning range achieved), with the gap changing from 1.5 µm to 1 µm, according to the mentioned restriction of MEMS tunability. The bandwidth of the HIS (i.e. frequency range when the reflection phase is within -90° … +90°) is proportional to the ratio of the effective surface inductance and effective surface capacitance, whereas effective surface inductance is proportional to the substrate thickness when it is smaller than the guided wavelength.

III. Beam Steering of Impedance Surface

MEMS tuneable HIS can be used for electronic reflective beam steering by inducing reconfigurable surface impedance by applying different bias voltage to different rows of elements of the MEMS varactors array. Since full-wave simulation of electrically large reflective surface with electrically small features of MEMS varactors is practically computationally impossible, a simplified model of a surface with 40 impedance strip lines of 0.35 x 0.35 mm^2 is used (see Fig. 4).

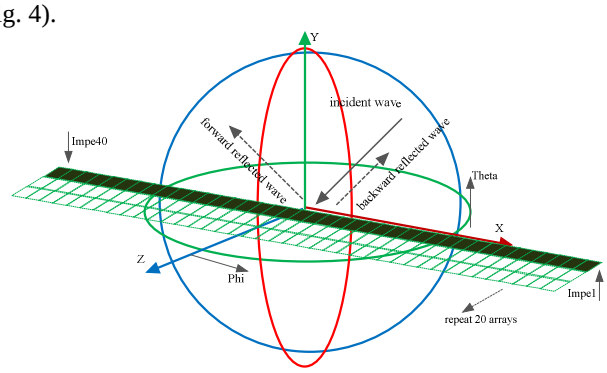

Fig. 3. 45° off broadside incidence were excited to the surface consisting of 40 different impedance elements.

The strip line structures are placed in the open boundary conditions, and the radiation pattern of the reflected beam has been simulated for 45° incidence. Configuring the surface so that different strips have different impedances and different phase of the reflection coefficient obtained from Eq. (3), the reflected beam can be steered by changing the gradient of the surface impedance. To reflect a beam of normal incidence in the direction θ from normal, the phase difference between adjacent strips should be [10]:

$$\Delta\Phi = kb\sin(\theta) \quad (4)$$

where $k = 2\pi/\lambda$ is the free space wavenumber and b is the strip width (which corresponds to the period of HIS).

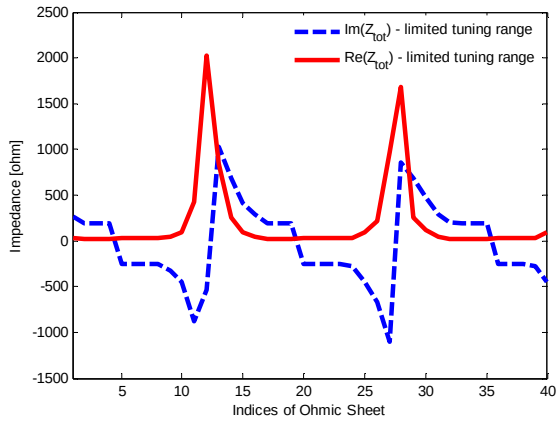

Fig. 4. The required impedances with incident angle from 45° and reflective beam to be steered to 0°.

Fig. 4 shows an example of the required impedances of each surface element according to the incidence and angle to be steered to. A series of normalized radiation patterns for several steering angles are shown in Fig. 5. As a reference, we have also simulated the radiation pattern of the surface with equal impedance (50 ohm resistance). As expected, for oblique incidence of 45° the strongest lobe is the main steering lobe according to the programmed reflection angle, i.e. -30° and 0°. A strong forward reflected wave side lobe can be observed through these simulation results, which is due to the specular reflection law occurred when a wave impinged to a flat surface. The limited tuning range does not produce a perfectly linear phase gradient, as the phase is truncated at extreme values. This problem is most severe at the 2π discontinuities, and as a result the radiation patterns have additional higher forward reflected wave side lobes (see Fig. 5). Opposite phase gradient is needed when beam is steered to the opposite direction. The surface can steer to any angle between these extremes, i. e. ±45°.

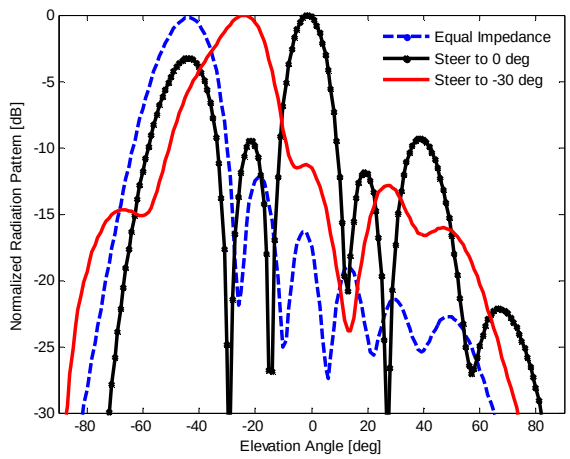

Fig. 5. The normalized radiation pattern of the surface at 80 GHz which is programmed for 0° and -30° with incident angle from 45°.

IV. Conclusion

The reflection property of the single unit cell structure of MEMS-based tuneable HIS with a lossy silicon substrate is analysed. Beam steering of simplified model of a large MEMS-based HIS at 80 GHz has been demonstrated numerically. By varying the bias voltage across the MEMS varactors, the reflection phase of the surface can be tuned. The reflection phase across the surface can be programed to produce a tunable phase gradient. The surface can steer to any angle between these extremes, i. e. ±45°.

Acknowledgment

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 224197 (TUMESA) and from the Academy of Finland under the Centre of Excellence in Research Programme.

References

[1] D. Sievenpiper, "High-impedance electromagnetic surfaces," Ph.D. Dissertation, Dept. of Elect. Eng, University of California, Los Angeles, 1999.

[2] F. Yang and Y. Rahmat-Samii, "Reflection phase characterizations of the EBG ground plane for low profile wire antenna applications," *IEEE Trans. Antennas Propag.*, vol. 51, pp. 2691-2703, Oct. 2003.

[3] A. Munir and V. Fusco, "Effect of surface resistor loading on high-impedance surface radar absorber return loss and bandwidth," *Microw. and Optical Tech. Lett.*, vol. 51, pp. 1773-1775, July 2009.

[4] J. A. Higgins, H. Xin, A. Sailer, and M. Rosker, "Ka-band waveguide phase shifter using tunable electromagnetic crystal sidewalls," *IEEE Trans. Microwave Theory & Tech.*, vol. 51, pp. 1281-1288, Apr. 2003.

[5] D. Chicherin, M. Sterner, J. Oberhammer, S. Dudorov, J. Aberg, and A. V. Räisänen, "Analog type millimeter wave phase shifters based on MEMS tunable high-impedance surface in rectangular metal waveguide," in *IEEE Int. Microwave Symp. Dig.*, Anaheim, CA, USA, May 2010, pp. 61-64.

[6] D. Sievenpiper, J. Schaffner, H. J. Song, R. Y. Loo, and G. Tangonan, "Two-dimensional beam steering using an electrically tunable impedance surface," *IEEE Trans. Antennas Propag.*, vol. 51, pp. 2713-2722, Oct. 2003.

[7] D. Chicherin, S. Dudorov, D. Lioubtchenko, V. Ovchinnikov, and A. V. Räisänen, "Characterisation and measurements of a multilayer high-impedance surface at W-band," in *Proc. 1st Int. Congress Advanced Electromagnetic Materials in Microwave and Optics*, Rome, Oct. 2007, pp. 891-894.

[8] O. Luukkonen, C. R. Simovski, A. V. Räisänen, and S. A. Tretyakov, "An efficient and simple analytical model for analysis of propagation properties in impedance waveguides," *IEEE Trans. Microwave Theory & Tech.*, vol. 56, pp. 1624-1632, July 2008.

[9] G. M. Rebeiz, *RF MEMS Theory, Design, and Technology*. Hoboken: John Wiley & Sons, 2003.

[10] R. D. Javor, X. D. Wu, and K. Chang, "Design and performance of a microstrip reflectarry antenna," *IEEE Trans. Antennas Propag.*, vol. 43, pp. 932-939, Sep. 1995.