Semiconductor-Substrate Integrated 3D-Micromachined *W*-band Helical Antennas

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***Abstract*— This paper investigates for the first time concepts of *W*-band dielectric-core helix antennas which are fabricated by three-dimensional micromachining into the volume of a semiconductor (high-resistivity silicon) wafer substrate. The maximum antenna gain is achieved by free-etching the antenna but loading the core of the helical antenna with a dielectric-rod tailor-made out of the substrate, and by properly modifying the geometry of the substrate-integrated ground plane. The simulation results show that an optimized antenna concept has a return loss S11 of -22.3 dB at the nominal frequency of 75 GHz, and a 3dB-bandwidth of 2.5 GHz. For the whole band from 69 to 84 GHz, the reflection coefficient is better than -10 dB. A maximum gain of 13.2 dB and a half-power beamwidth (HPBW) of smaller than 40° are obtained for a single antenna. The front-to-back (F/B) ratio is better than 23.5 dB with an axial ratio of 0.94. An eight-element helix line array is demonstrated and has a maximum gain of 22.3 dB with a HPBW of 7° in the *y-z* plane and an F/B ratio of 23.71 dB.**

I. Introduction

Helix antennas offer many advantages over other antennas such as high gain, wide operational bandwidth and circular polarization. As future wireless and remote-sensing technologies are moving towards to higher and higher frequencies, the dimensions of helix antennas becomes more feasible to be fabricated on the same wafer of an integrated circuits as an on-chip antenna or even an integrated antenna array. There is only one previous publication on on-chip helix antennas, and which was designed only for *C*-band, and had very limited performance [1].

This paper reports for the first time on the concept of integrating an axially-radiating helical antenna into the volume of a semiconductor-grade wafer substrate, by 3D micromachining, investigated for *W*-band where typical wafer thicknesses of 500-650 µm fit the diameter dimensions of *W*-band helix antennas. In contrast to the conventional on-chip antennas which normally utilizing only the surface of the substrate, the proposed antenna concept utilizing the volume of the wafer results in a compact high-gain 3D helical radiator.

II. On-Wafer Square Helix Antenna with Tailor-Made Dielectric Core

Square helix antennas loaded with dielectric core were well studied and demonstrated to have an excellent performance [2]. At 75 GHz, size and cross-section of the square helix structure are feasible to be implemented on a standard-thickness silicon wafer with a cleanroom micromachining process.

Figure 1 show a perspective model of an eight-turn on-chip helix antenna fabricated on a high-resistivity silicon substrate (HRSS). The antenna is composed of a gold square-cross-section helix, partially embedded in a 870-µm-thick HRS wafer. 2-µm-thick gold patterns on top of front and back side of the wafer are connected by 40×40-µm^2 through silicon vias (TSVs) to form the helix structure. The separation between each helix turn is 1020 µm. To eliminate the reactance part of the input impedance of the antenna [3], a part of the silicon wafer inside the core of the helix structure with a major part of the surrounding must be completely removed (Fig. 1), which can be done by standard isotropic plasma-micromachining process, resulting in a well-matched pure resistive input impedance of 220 Ω. A 8-mm-long ground plane of the helix radiator is designed by vertically embedding a gold layer in the substrate which is perpendicular to the wafer plane. This ground layer can be fabricated in the same process step as the through-wafer vias which are utilized for the antenna coil.

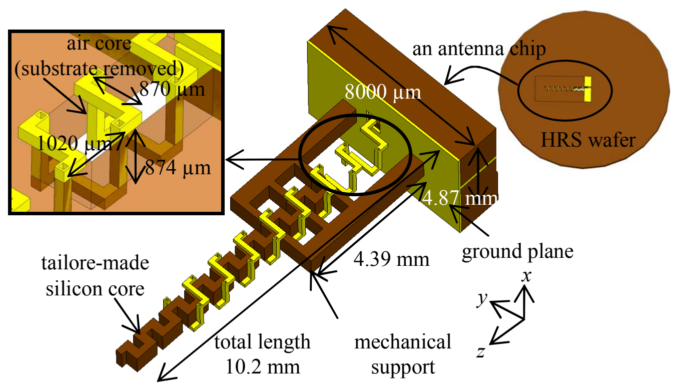

Fig. 1. 3D model of a helix antenna designed for the nominal frequency of 75 GHz. The silicon beams are required as a mechanical support for a stable positioning of the antenna.

The simulated S_{11} of the helix antenna in Fig. 1 is plotted in Fig. 2. This antenna design offers a reflection coefficient of -25.4 dB at the nominal frequency of 75 GHz and lower than -10 dB from 69 to 86 GHz. Fig. 3 shows simulated radiation patterns with maximum gain performance at 75 GHz. This antenna design is well directive and has a maximum gain of 12.2 dB for front radiation with a F/B ratio of 19.95 dB. The biggest side-lobe of 1.4 dB at ±50° from the front radiation is offered on the *x-z* plane, while on *y-z* plane the side lobe level is -0.62 dB at the direction of ±48°. The HPBW of this antenna structure is 40°, both on *x-z* and *y-z* plane, and the axial ratio of 0.94 is offered at 75 GHz.

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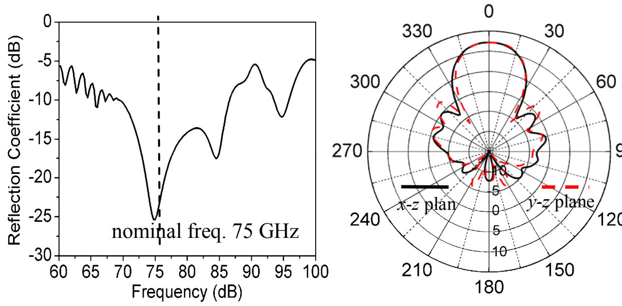

Fig. 2. Simulated S_{11} and maximum gain of on-chip square cross-section helix antenna in Fig. 1 from 60-100 GHz. The nominal of the antenna design is 75 GHz .

III. On-Wafer Square Helix Antenna with Tailor-Made Dielectric Core and Modified Ground Plane

In order to increase the antenna gain, a modified shape of the ground plane is recommended. Figure 3 presents a 3D model of the on-chip helix antenna with a modified ground structure to increase the antenna gain. The total length of the ground plane along *y*-axis is 7 mm with an additional ground of 5.5 mm on each side. The angle between the ground plane along the y-axis and the additional ground is calculated to be 105°.

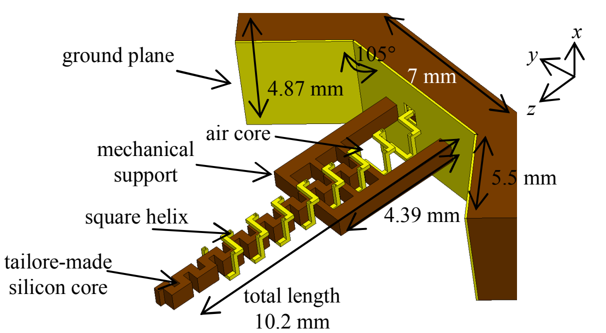

Fig. 3. 3D model of a helix antenna with a modified ground plane. The antenna is designed for the nominal frequency of 75 GHz.

Fig. 4 plots a simulated S_{11} and radiation patters of the helix antenna with a modified ground structure. The simulated S_{11} of -22.3 dB at 75 GHz and a 3-dB bandwidth of 2.5 GHz are offered. The antenna with modified ground plane has a maximum gain of 13.2 dB in the front-radiation direction, with a F/B ratio of 23.55 dB. The maximum side lobe of the antenna is -1.5 dB at ±48° from the front radiation on the *x-z* plane, while on the *y-z* plane the maximum side radiation is 3.43 dB at ±52°. On the *x-z* plane, the radiation HPBW of the antenna is 40°, while the HPBW of only 28° is offered on the *y-z* plane. The axial ratio of this antenna design is simulated to be 0.94 at 75 GHz.

To increase gain and directivity of the on-chip helix antenna, a linear antenna array was investigated by placing the antenna elements along the *y*-axis with a separation between each element of 0.925λ (3.7 mm). Fig. 5 presents the simulated radiation plot of the maximum again of a line antenna array with eight radiation elements. A maximum gain of 22.3 dB at 75 GHz is offered in the front-radiation direction and the F/B ration of the design is 23.71 dB. The highest side-lobe level of the antenna array is 7.9 dB at ±11.5° on the *y-z* plane. The antenna offers a HPWB of 40° on the *x-z* plane and 7° on the *y-z* plane.

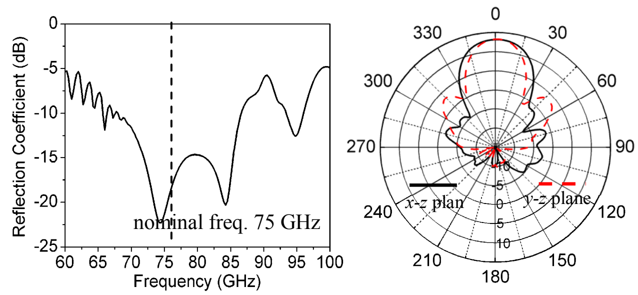

Fig. 4. Simulated S_{11} and maximum gain of on-chip square cross-section helix antenna in Fig. 3 from 60-100 GHz. The nominal of the antenna design is 75 GHz .

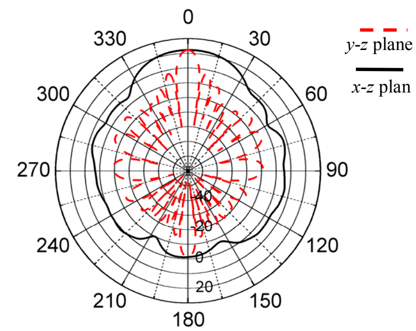

Fig. 5. Simulated radiation patterns of a linear helix-antenna array composed of eight radiation element in Fig. 3 at 75 GHz.

IV. Conclusions

This paper reports for the first time on a study of 3D-micromachined silicon-substrate integrated dielectric-loaded helix antennas designed for 75 GHz. This antenna design utilizes not only surface of the HRS wafer, but makes full use of the volume of the substrate. The simulation results look very promising for a high-gain on-chip helix antenna which can be fabricated by standard micromachining processes, including free-etching the antenna and parts of the core of the antenna. The influence of the ground layer geometry, which can be fabricated in the same micromachining processes as the antenna coil, for enhancing the maximum gain is investigated.

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