Design and Fabrication of Nonuniform Helical Antennas for Detection of Side-Channel Attacks in Computer Systems

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***Abstract*—This paper presents a design, fabrication and measurement results of a helical antenna that has variable pitch angle and radius. These variations allow the nonuniform helix to be for 2–3 dB more directive compared to the optimal uniform helix of the same length (750 mm). A 3D printed support structure for the helix to be wound around is made out of ABS plastic and a 400 mm by 400 mm metal sheet is used as the ground plane. The design frequency is 2 GHz, the impedance bandwidth is 33% (1.8 GHz–2.5 GHz), and the axial ratio is less than 3.8 dB. The gain is 18.2 dBi and the two prototypes that are built match the simulation performance[1].**

***Index Terms*—nonuniform helical antenna, helical antenna, circular polarization, directive.**

I. Introduction

Side-channel attacks are a major concern for electronic security. They circumvent traditional security techniques by relying on observing confidential information via side-channels [1]–[3]. One of the challenges in studying the side-channel EM emanations is how to improve signal reception, especially at a distance. In this paper, we propose a nonuniform helical antenna design that allows us to receive signals at distances longer than one meter.

Helical antennas have been known for a long time as high-gain directional antennas, with circular polarization [4]–[13]. In [11], the optimal design of uniformly-wound helical antennas located above a large conducting plane is given. The design is presented for narrowband and wideband antennas.

To additionally increase the antenna gain without increasing the antenna length, helical antennas can be nonuniformly wounded, i.e., the radius and/or the pitch vary along the antenna [14]–[20]. In [14], it is shown that tapering the radius at the beginning and the end of the helical antenna improves matching and radiation properties of the antenna. In [15], it is demonstrated that the tapering can increase the bandwidth two times in comparison with the classical design. In [16], a nonuniform helical antenna is designed such that it has a flat circular reflector and a constant radius. Numerical and experimental data are presented showing a significant improvement in gain compared to the classical antennas. In [17], in addition to the variable pitch, the radius exponentially increases along the axis of the helix. In [18], it is shown that nonuniformly-wound antennas can also be tailored to achieve a dual-band operation by adjusting the helix pitch and the wire length. Finally, in [19], nonuniform helical antennas without a ground plane are considered. The counterbalance is the first antenna segment, which is about one quarter-wavelength long. By optimizing the pitch and the radius, simulating the antenna by AWAS [20] and using the particle swarm optimization (PSO) [21] and Nelder-Mead simplex algorithm [22], high-gain antennas are obtained. Regarding the performance, these antennas can compete with the classical antennas that have large ground planes, or even outperform the classical antennas for longer overall antenna lengths.

In contrast to the previous designs, in this paper we consider a nonuniform helical antenna located above a large ground plane. As in [17, 19], both the pitch and the radius are nonuniform, but in contrast to previous papers, we fix the overall axial length of the antenna and optimize the pitch and the radius in order to maximize the antenna gain. We have designed, fabricated, and measured a nonuniformly wound helical antenna with a flat square ground plane. The current in the helix creates two radiated waves. One wave travels upwards from the plane. The other wave travels downwards, towards the ground plane, it is reflected from the plane, and catches up with the first wave. Thus, the antenna gain is improved for 2–3 dB over the classical design. This is approximately the same enhancement as if a two times longer helical antenna were employed.

The rest of the paper is organized as follows. Section II defines geometrical and electrical parameters of the helical antenna and presents the design approach. Section III presents simulations results and Section IV describes the structural design. Section V presents experimental verification of the proposed antenna design, and Section VI concludes the paper.

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II. Nonuniform Helical Antenna Design

In this paper we consider a nonuniform helical antenna located above a large ground plane. Similarly to designs in [17, 19], both the pitch and the radius are nonuniform (as shown in Fig. 1). In our design approach, we fix the overall axial length of the antenna and optimize the pitch and the radius in order to maximize the antenna gain. The antenna is analyzed using programs [20], [23], [24].

The conductor is a copper wire, whose radius is r. Skin-effect losses in the wire are included into the numerical models. It was found that thicker wires yield higher gains due to lower losses. However, if the wire radius is too large, the wire is hard to handle, both numerically in the analysis and when assembling the antenna. Hence, we have selected a technically optimal wire radius.

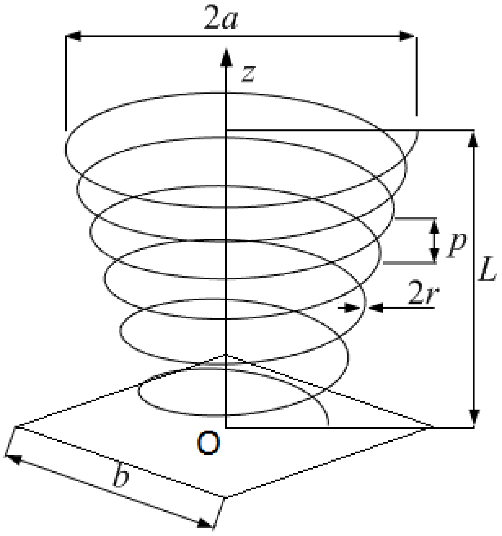

Fig. 1. Sketch of a nonuniform helical antenna.

We deliberately design a helix that significantly radiates downwards, i.e., that has a strong backward wave. The polarization of the forward wave is opposite to the polarization of the backward wave: one wave has the right hand circular (RHC) polarization, and the other wave has the left hand circular (LHC) polarization. When the backward wave is reflected from the ground plane, the polarization of this wave is switched. Hence, the forward wave and the reflected backward wave have identical polarizations. These two waves have similar intensities and are almost in phase. Consequently, when the backward wave is reflected from the ground plane and superimposed with the forward wave, the antenna gain is increased for about 2–3 dB. This increase is practically the same as if the overall antenna length were doubled.

The drawback of this design is that the ground plane must be sufficiently large to pick up the backward wave: the size b of the ground plane should be several wavelengths.

In order to double-check the optimization, the simplex optimization algorithm [22] is used with [20] and PSO [21] with [23]. As in [19], the antenna is divided into several sections. Variations of the pitch and the radius are described by linear functions of the axial coordinate (z) along each section (i.e., piecewise-linear distributions are assumed). In the optimization, the coefficients contained in these functions are modified.

Some of the solutions that we have found are very sensitive to the tolerance of dimensions and they are narrowband. Hence, we have discarded them. Some solutions have large variations of the pitch and the radius. Hence, the description of the optimal design is cumbersome. Therefore, we have selected simple variations as preferable for the design. Excellent results, not far from the best ones obtained in all our optimization trials, were obtained when the pitch and the radius were described by single linear functions of the z-coordinate.

In the numerical optimization we have neglected the influence of the supporting structure for the helix wire. Therefore, for the experimental model, we have designed a dielectric structure that has a negligible impact on the antenna characteristics. The optimal antenna was manufactured and measured.

III. Simulation Model

The design frequency is chosen to be 2 GHz and the height is chosen to be 750 mm (i.e., about 5 wavelengths).

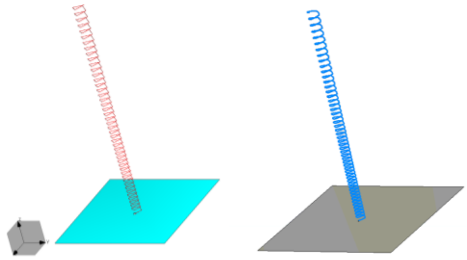

Fig. 2. WIPL-D and CST models of the nonuniform helical antenna.

In order to simplify the mechanical construction and reduce the influence of the dielectric, helix turns are square-like (Fig. 2 and 9). The radii of the helix turns and the pitch change linearly from the ground to the top of the antenna. The wire radius is 0.6 mm (diameter 1.2 mm, approximately AWG 17). In the simulations, the conductivity of the wire was taken to be 14 MS/m, which is about 4 times lower than for copper. The reason for decreasing the conductivity is to approximately take into account the effect of the surface roughness (which may increase conductor losses about 2 times at 2 GHz).

The optimal antenna has about 45 turns. The distances between the nodes and the antenna axis increase linearly from 17.76 mm at the bottom up to 22.91 mm at the top of the helix (whose elevation above the ground is precisely 748.8 mm). The pitch increases from 11.97 mm at the bottom up to 22.13 mm at the top. Reducing the side of the square ground plate (b) decreases the average gain in comparison with an infinite ground. We chose a side length of 400 mm as a compromise. Figures 3, 4, and 5 compare simulated axial ratios, peak gains, and radiation patterns obtained using WIPL-D [23] and CST [24].

IV. Structural Model

Starting from the optimized numerical model of the antenna, we have developed a supporting structure for the helix wire. Due to its low losses, ABS plastic has been chosen as the material for the supporting structure. Since the geometry is complex, the 3D printing using ABS plastics has been chosen as a viable solution.

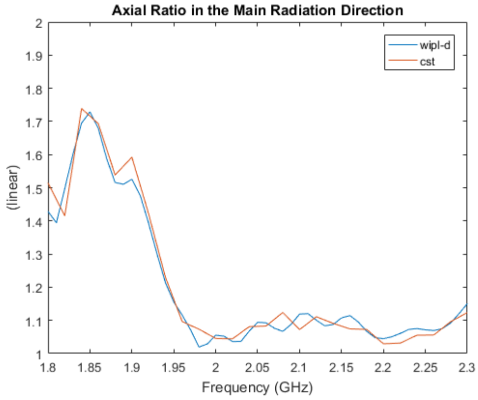

Fig. 3. Simulated boresight axial ratio.

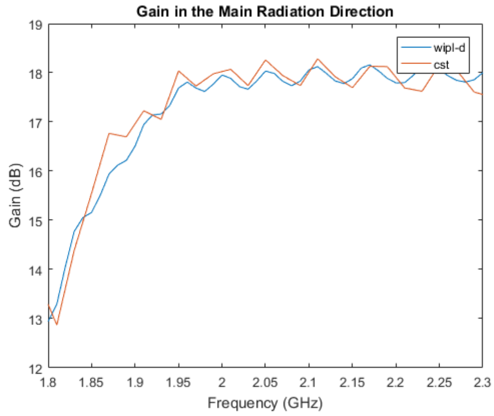

Fig. 4. Simulated boresight gain.

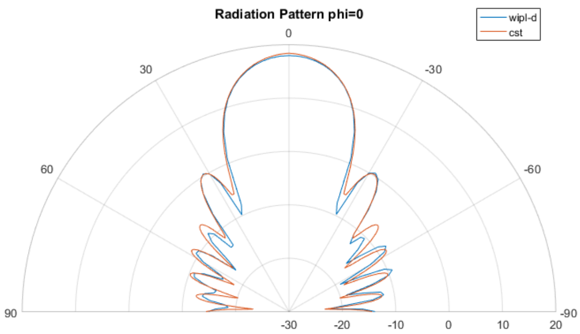

Fig. 5. Simulated radiation pattern at center frequency.

The supporting structure consists of a central mast, of diameter 8 mm, with “branches” (cylinders) that hold the corners of the helix turns.

The model for the 3D printing of the supporting structure was tailored in software Blender [25]. Due to the limitation of the 3D printer used, the structure is divided into three parts (Fig. 6). The length of each part is approximately 250 mm. The parts have small grooves and appropriate bumps for interconnecting the parts.

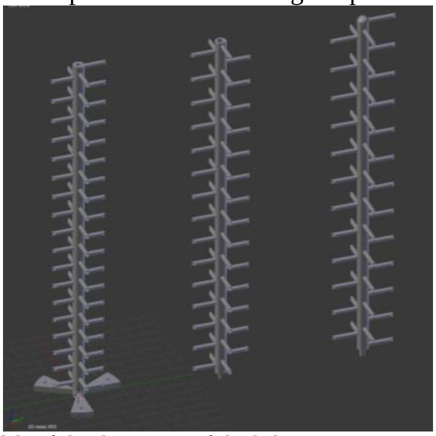

Fig. 6. Models of the three parts of the helix supporting structure for 3D printing.

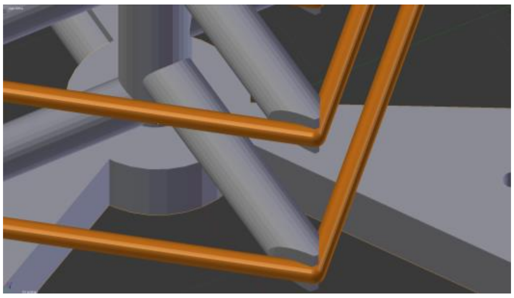

Fig. 7. The first two turns of the helix with the supporting structure.

Special care was taken for the places where the wire touches the plastics. Those places were made as wedges with an appropriate gutter on the places where ABS touches the wire. This is done to minimize the influence of the plastic on the wire capacitance. Details of the two first helix turns are shown in Fig. 7. The supporting structure without the wire and with visible wedges and gutters is shown in 8.

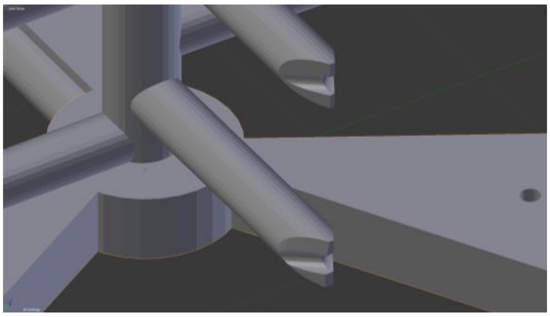

Fig. 8. Detail of the supporting structure.

These three parts, manufactured by a 3D printer, were glued together. A female thread M3 (i.e., the standard 3 mm thread) was made in each foot of the supporting structure. Thereafter, we wound the wire on it. Glue was applied to every fourth helix turn in order to keep the wire securely positioned on the supporting structure. Finally, the supporting structure with the winding was fixed to the ground plane using three M3 screws.

The ground plane is made of a 2 mm thick aluminum sheet. There are three holes of a 3 mm diameter, rotated for 120 degrees, for screws that hold the helix supporting structure. There are two additional holes with female threads for M2.5 screws that hold the SMA connector, and an additional hole for the SMA central pin, whose diameter is 4.0 mm.

The assembled prototype of the antenna is shown in Fig. 9.

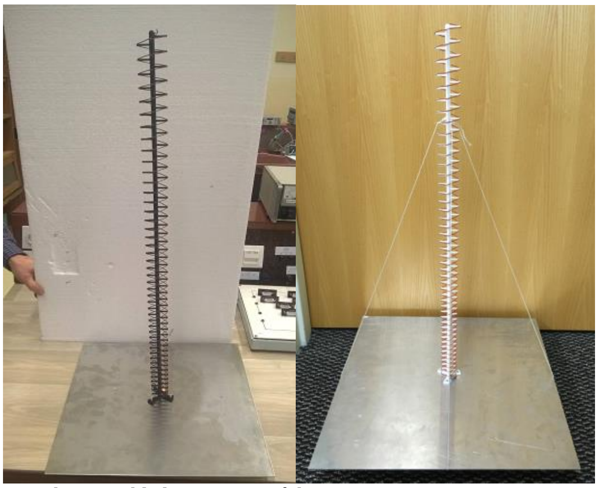

Fig. 9. The assembled prototypes of the antenna.

Antenna matching was performed by a copper foil soldered to the two straight segments closest to the SMA connector, as shown in Fig. 10. The foil was folded experimentally with the goal to tune the antenna to the coaxial feeder in a wide frequency range [26], [27].

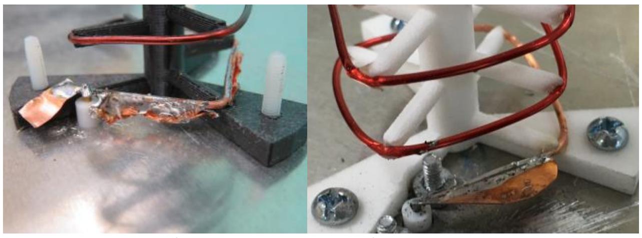

Fig. 10. Matching of the helix by a copper foil.

V. Model Validation via Measurements

The copper foil matching has resulted in better than −10 dB reflection coefficient between 1.8 GHz and 2.5 GHz. The comparison of the simulated and measured reflection coefficients is shown in Fig. 11. Due to the handmade and experimental nature of the matching taper, it is not possible for the two curves to match one another precisely. However, it can be seen that the simulation and the measurement agree at the beginning of the operation band (1.8 GHz), and the reflection coefficient remains below −10 dB.

Since the antenna is electrically large (~5 λ), the antenna gain can be properly measured only in an anechoic chamber. However, for a quick, but accurate check, instead of using a chamber, we verified the antenna gain indirectly using the gain transfer method [28]. The transfer coefficient, s_{21}, was measured between the helix antenna and another well documented antenna, for which we have a very precise 3D model. The other antenna was a printed Vivaldi antenna and it has a linear polarization. The distance between those two antennas (i.e., the distance between two closest points of the antennas) was varied. Simulated and measured results are compared in Fig. 12.

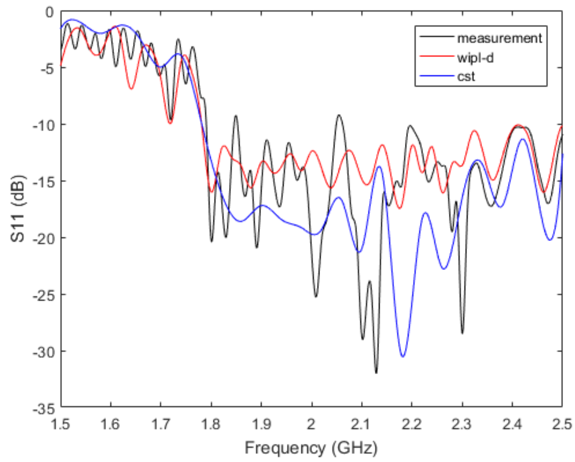

Fig. 11. Measured vs. simulated reflection coefficient.

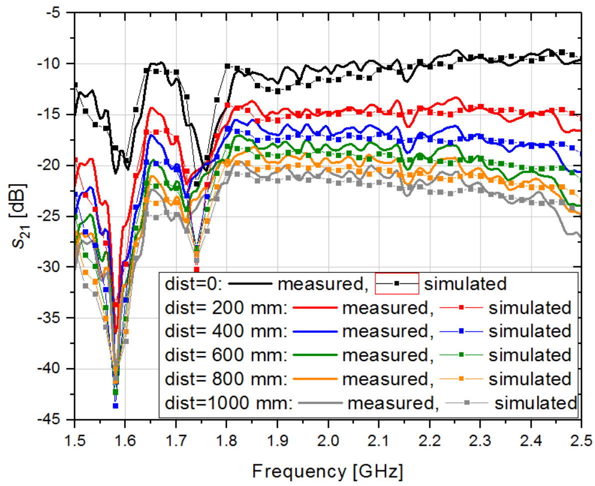

Fig. 12. Comparison of simulated (WIPL-D) and measured transfer between antennas.

From Fig. 12, it can be observed that the simulation and the measurement results match very well. The prominent dips in frequency are matched almost exactly.

Finally, the measured gain is shown in Fig. 13.

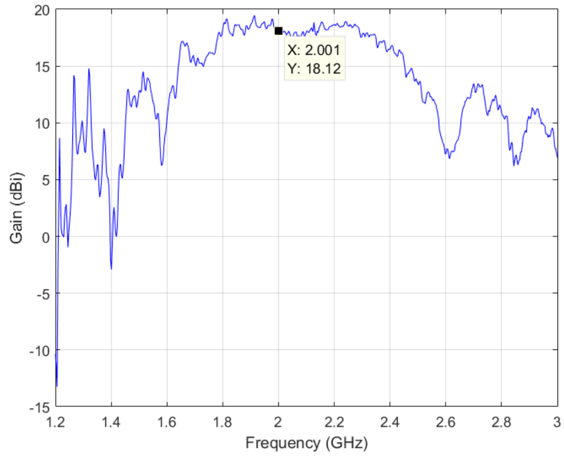

Fig. 13. Measured boresight gain of the nonuniform helical antenna.

VI. Conclusions

We have designed, fabricated, and measured a nonuniformly wound helical antenna with a flat ground plane. The current in the helix creates two radiated waves. One wave travels upwards from the plane. The other wave travels downwards, towards the ground plane, it is reflected from the plane, and catches up with the first wave. Thus, the antenna gain is improved for 2–3 dB over the classical design, which is approximately the same enhancement as if a two times longer helical antenna were employed.

The fabricated antenna has the following characteristics:

- central frequency: 2 GHz;
- operating band: 1.8–2.3 GHz;
- gain: 18 dBi;
- polarization: right-hand circular;
- ellipticity (axial ratio): <1.55 (3.8 dB);
- nominal impedance: 50 Ω;
- VSWR: <2.1;
- dimensions: 400 mm × 400 mm × 750 mm.

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