On the Design and Simulation of Antennas on Ultra-thin Flexible Substrates

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Abstract ─ Flexible wireless systems are rapidly evolving in a wide spectrum of applications such as medical, entertainment and sport facilities. The aim of this paper is to investigate whether the ultra-thin substrates along with their permittivity are essential for the initial design stage of a flexible antenna, which is a key element of any wireless system, or it is merely a supporting structure. Three state-of-the-art simulation tools are used to evaluate the scattering parameter, S_{11} which are then compared against precise measurements conducted inside an anechoic chamber. These methods are the Finite Integration Technique (FIT) based Time Domain Solver (TDS) and the Finite-Element Method (FEM) based Frequency Domain Solver (FDS) of CST Microwave Technology and the (FEM) based HFSS of ANSYS. This paper attempts to provide an answer as to whether the substrate and other geometrically small features such as the feeding structure should be sufficiently discretized or else conventional default adaptive meshing should be enough. Three different flexible antennas with two fabrication techniques and feed lines have been used in the simulations and measurements.

Index Terms ─ CST, flexible antenna, HFSS, substrate, ultra-thin.

I. INTRODUCTION

The past decade has witnessed an ever-growing demand for flexible wireless devices in medical, entertainment, military, sport and personal communications. Furthermore, the electronics market is moving towards flexible displays due to their low profile, low cost, portability and light weight [1-3]. However, literature lacks research on the role of the substrate during the initial design stage, commonly conducted by simulations and the associated challenges faced since commercially available flexible substrate exist in heights ranging from 25 μm up to 130 μm, to mention a few.

This paper mainly focuses on the role of the substrate on the operating frequency bands of flexible antennas, expressed in terms of the frequency spectrum of S_{11}, with ultra-thin substrates. Three antennas are designed, fabricated and tested to bench mark the three simulation approaches used in this paper. It should be noted that the existing literature does not address this important issue in spite of the obvious discrepancies we observed between measured and simulated spectrum of S_{11} [1-8], to mention a few. Indeed, a close scrutiny of prestigious journals and flagship conferences revealed obvious discrepancies between measured and simulated values of S_{11} for antennas of widely different geometries, fed by different techniques. This motivated us to further investigate this important design issue and to aid researchers in the field of flexible antenna design. It should be emphasized that the dispersion caused by the variation of the real and imaginary parts of the permittivity of the substrate must have not been considered in the simulations reported in this paper due to the unavailability of the pertinent data from the manufacturer. However, it is expected that the effects of such dispersion as well as numerical dispersion caused by the finite-size of the mesh would not significantly alter the observation and conclusions reported in this paper.

II. THE FABRICATED PROTOTYPES

A printed trapezoidal monopole antenna has been chosen due to its wide bandwidth and geometrical symmetry which allows simulating only half the geometry. Photolithography microfabrication technique is used to fabricate this antenna.

The antenna geometry and prototype are shown in Fig. 1. The antenna consists of two parts: the radiating patch which is trapezoidal in shape and the coplanar feeding line. Copper is used for the conducting parts. The substrate is Rogers R03035 with a dielectric constant, ε_r=3.5, $tan\delta$=0.05, and thickness of 130 μm.

The second antenna is geometrically nonsymmetrical. It consists of a strip-loaded CPW-fed pentagonal antenna [9] prototyped using the 2831 Fujifilm material printer with silver nano-particles [10]. The antenna was printed on a polyimide substrate, ε_r=4.3 and a thickness of 25 μm. The antenna geometry and prototype are shown in Fig. 2.

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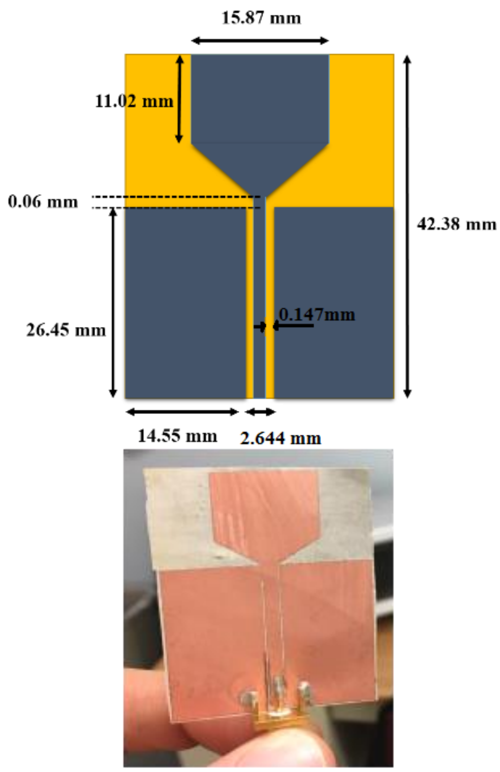

Fig. 1. Geometry and prototype of the trapezoidal flexible antenna.

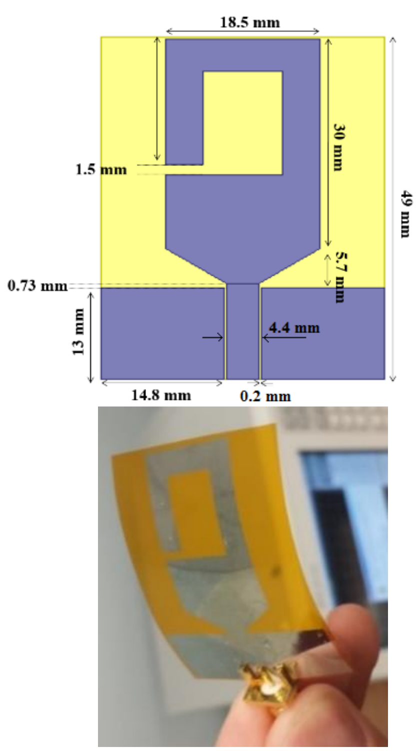

Fig. 2. Geometry and prototype of the strip-loaded CPW-fed pentagonal antenna.

The third antenna is a printed monopole fed by a microstrip line as shown in Fig. 3. This feeding technique has been chosen since the feed line lies partially above a grounded substrate which necessitates the role of the substrate. The substrate is Roger R03035, ε_r=3.5, $tan\delta$=0.05, and 50 µm thickness. The antenna is fabricated using photolithography technique with copper as conducting material. A perfect magnetic conductor boundary is used similar to the first antenna due to geometrical symmetry.

It should be emphasized that the three antennas considered in this paper are not optimized for large bandwidth, neither for a designated radiation pattern. Simple planar radiating and feeding geometries are chosen since our main focus is on the role of the substrate thickness.

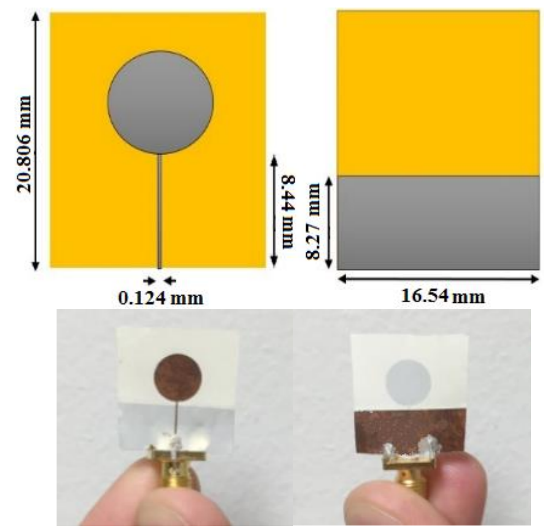

Fig. 3. Geometry and prototype of the circular monopole antenna with radius of 4.13 mm.

III. SIMULATION PROCEDURE

The first step is to find whether mesh seeding is critical in the simulation stage or not. Because of substrate and feeding width/gaps, a hexahedral mesh of at least four cells are taken along the height, length, and width of the substrate to capture the field in the TDS. For the FDS and HFSS, however, the tetrahedral mesh allows only a local mesh refinement along the substrate height of 10µm due to limitations inherent by these two solvers. The mesh used to simulate this antenna in the time-domain solver of CST Microwave Studio will be elaborated in detail. The rest of the simulations are conducted using a similar meshing approach. In Fig. 4 we show the structure of the mesh used. A total of 37, 104,270 cells are used to provide sufficient representation of the geometry given the extremely large aspect ratio between the horizontal and vertical extent of the antenna. A hexahedral mesh in which Lines per wavelength=40, Lower mesh limit=200, Mesh line ratio limit=200, and a PEC refinement factor of 6 has been adopted.

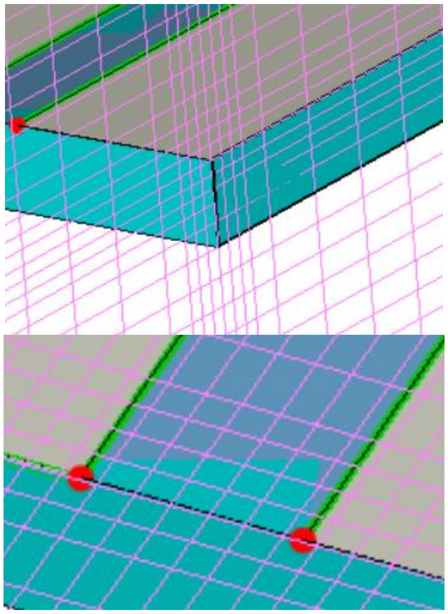

Fig. 4. Meshing scheme of the substrate and feed gaps of the trapezoidal antenna shown in Fig. 1.

The trapezoidal antenna shown in Fig. 1 is considered first. Results for S_{11} versus frequency obtained from measurements using the prototype are compared against simulated results as seen in Fig. 5. The measured results show two bands over which S_{11} is less than -10 dB. The first band extends from 2.93 GHz to 4.87 GHz; the second from 5.72 GHz to 6.71 GHz. With the exception of the TDS, the rest of the simulations reveal single band operation as seen in the figure caption. It is clear that TDS correctly predicts the existence of two separate bands albeit to the noticeable shift, particularly for the first band. Results obtained from the FDS and HFSS show a fair agreement with the measured value of the lower frequency of the first band, 2.93 GHz. However, both were unable to capture the higher end of the band, 4.87 GHz which the TDS predicted with 8% shift.

The second issue is whether the substrate is essential in the design stage or just acts as a supporting structure. As previously mentioned, we should emphasize that numerous papers ignore the presence of the substrate material in simulation and simply replace it by air or follow the default settings of CST and HFSS. If air is assigned as the substrate material, results shown in Fig. 5 obviously show unacceptable results. This observation should motivate researchers to consider the substrate dielectric constant when evaluating the operating frequency range of flexible antennas.

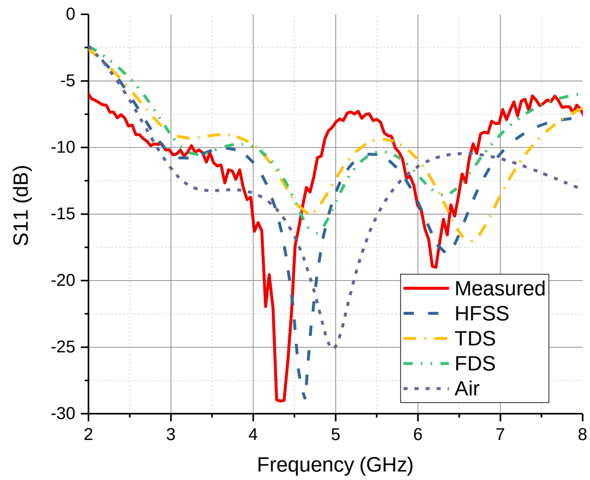

Fig. 5. Measured and simulated S_{11} for the trapezoidal antenna: measured bandwidths (2.93 GHz to 4.87 GHz) and (5.72 GHz to 6.71 GHz), TDS (4.04 GHz to 5.29 GHz) and (5.83 GHz to 7.36 GHz).

The second antenna was tested as well and the results are shown in Fig. 6. Results obtained from HFSS show better agreement than TDS and FDS for the first resonant band (1.36 GHz to 1.59 GHz) but significantly differs from the second measured resonant band (3.20 GHz to 6.04 GHz). However, the TDS and FDS provide excellent agreement for the second band. It is again noticed that air cannot replace the substrate to predict the measured performance.

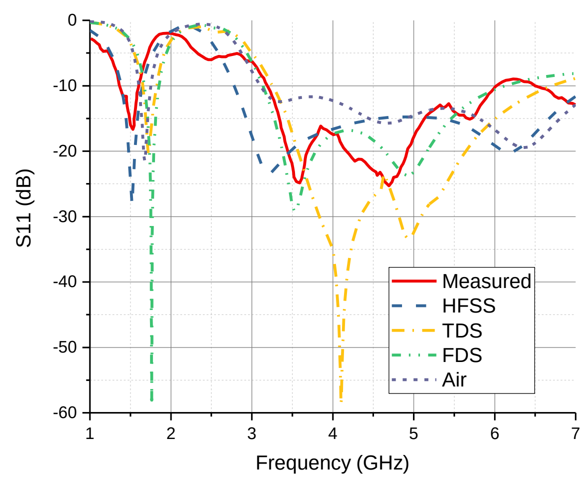

Fig. 6. Measured and simulated S_{11} for the strip-loaded CPW-fed pentagonal antenna: measured bandwidths (1.36 GHz to 1.59 GHz) and (3.20 GHz to 6.01 GHz), HFSS (1.40 GHz to 1.64 GHz), TDS (1.65 GHz to 1.82 GHz) and (3.25 GHz to 6.70 GHz), FDS (1.67 GHz to 1.85 GHz) and (3.13 GHz to 6.31 GHz).

The results of the third prototype are shown in Fig. 7. The first measured frequency at which S_{11} drops below -10 dB is at 5.44 GHz. HFSS yields a close value of 5.73 GHz while the values obtained from TDS and FDS are 6.26 GHz and 6.184 GHz, respectively. However, all simulations provided bandwidths well above the measured value of 8 GHz. Using air as a substrate provided erroneous results. It should be noted that the SMA for the prototype did not completely align within the 0.124 mm wide microstrip feed line. Another important issue is there is a common region in the substrate that is sandwiched between the partial ground and the microstrip line with a length of 8.27 mm may pose a challenge in the discretization and numerical simulations. This observation led us to conclude that microstrip-fed flexible antenna shown in Fig. 3 is more challenging to simulate as compared to the CPW-fed antennas in Figs. 1 and 2.

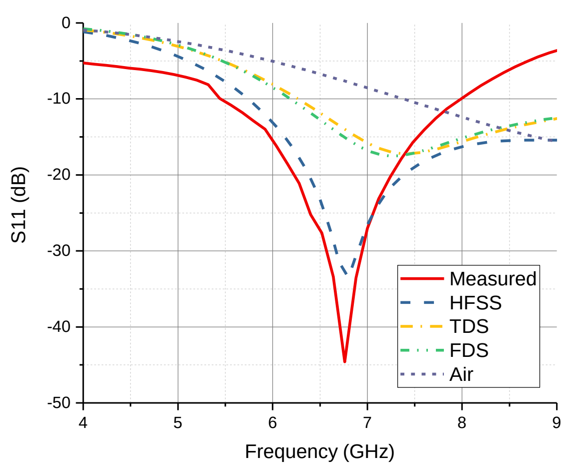

Fig. 7. Measured and simulated S_{11} for the circular monopole antenna: measured bandwidth (5.44 GHz to 7.96 GHz).

IV. CONCLUSION

The paper concludes that the substrate should be taken into consideration in the initial design of flexible antennas, at least for the feeding structure, and it is not merely a supporting structure. It was noticed through extensive simulations that appropriate manual meshing is essential to get the S_{11} spectrum closer to the measured values, and hence to reach the targeted design. Ignoring the substrate or replacing it by air provides erroneous results.

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