Multi-Domain Modeling of 3D Printed, Nanotechnology and Morphing/Origami-based RF Modules

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Abstract — This talk will address the major challenges for the multi-domain modeling of additively-manufactured RF modules given the surface roughness and non-uniformity issues as well as given the non-orthogonal fabricated geometries with fine details and liquid/solids combination. In addition, it will discuss issues having to do with shape-changing RF components and modules utilizing origami principles. Ways on coupling EM simulators with mechanical and hinging modeling tools will be shown for various benchmarking antenna, energy harvesting, nanotechnology and wireless sensing topologies.

Index Terms — Multi-Domain Modeling, 3D printing, Nanotechnology, Origami, FDTD, MRTD.

I. INTRODUCTION

State-of-the-art wireless sensing, communication and energy harvesting systems for Internet-of-Things, Smart Skins and Quality of Life applications require the effective modeling of complex structures that involve mechanical motion, wave propagation and solid-state effects. Due to computational constraints, most commercial simulators utilize various approximations in order to provide fast and relatively accurate results. The drawback of these approaches is that transient phenomena and nonlinearities are not modeled effectively, leading to the degradation of system-level performance. Alternatively, full-wave techniques provide higher accuracy but suffer from excessive execution time requirements, thus making their efficient numerical implementation very critical.

The Finite-Difference Time-Domain technique (FDTD) [1] is one of the most popular and versatile time-domain tools and has been applied to the discretization of Maxwell's, mechanical and solid-state equations. Curves and diagonal elements can be modeled using stair stepping. In addition, a wide variety of FDTD enhancements make possible the modeling of small gaps, multidielectric/membrane configurations and resonating passives. Macroscopic results, such as S-parameters and impedances, can be determined by probing and comparing voltages and currents at different points in the structure. The multiresolution time-domain (MRTD) technique [2] has provided a mathematically correct way to implement time and space-adaptive gridding, as well as to significantly decrease execution-time and memory requirements. MRTD is an adaptive generalization of the FDTD technique that is based on the principles of Multiresolution analysis and makes use of wavelets to alleviate the computational burdens of FDTD for complex or large structures, such as multilayer packages, MEMS or "morphing" RF structures, where the position of the boundaries is time-changing and the membrane thickness is much smaller than any other detail in the transverse direction. The MRTD technique allows the cell resolution to vary with both time and position. The wavelets can be used to represent higher levels of detail along with higher frequency content. As fields propagate through the structure the resolution can be varied to allow for the rapidly changing fields. For these reasons, FDTD and MRTD are presented in this paper for the simultaneous modeling of Maxwell's, mechanical and solid-state equations in high-frequency 3D printed, nanotechnology and morphing/origami benchmarking structures.

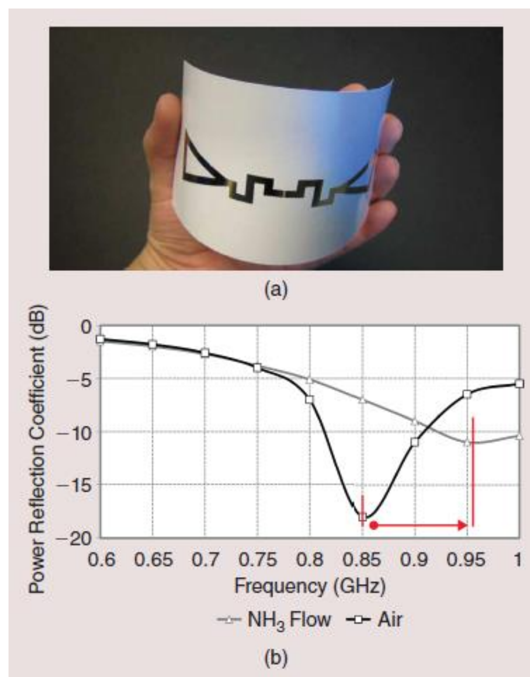

Fig 1. Inkjet-printed CNT-based wireless sensor.

II. MODELED HIGH-COMPLEXITY RF STRUCTURES

A. Inkjet-printed nanotechnology-enabled antenna-based wireless sensors for "smart skin" sensing and liquid sensing applications with unprecedented sensitivity characteristics.

In [3] FDTD and MRTD were introduced for the first time in the integration of a conformal radio frequency identification (RFID) antenna with a single-walled carbon nanotube (SWCNT) composite (Fig.1) in a chipless RFID node for toxic gas detection establishing the foundation for the first ever sub-parts-per-billion (ppb) antenna-based wireless sensors. The electrical performance characterization of the inkjet-printed SWCNT film was also reported for the first time up to 1 GHz. The whole module was realized by inkjet printing on a low-cost paper-based substrate. The electrical conductivity of the SWCNT film changes in the presence of very small quantities of toxic gases like ammonia and nitrogen oxide, resulting in the variation of the backscattered power level, which can be easily detected by the RFID reader to realize reliable wireless toxic gas sensing. The applied time-domain techniques were instrumental in the optimization of the response time as well as in the accurate evaluation of the sensor's sensitivity over a broad frequency range.

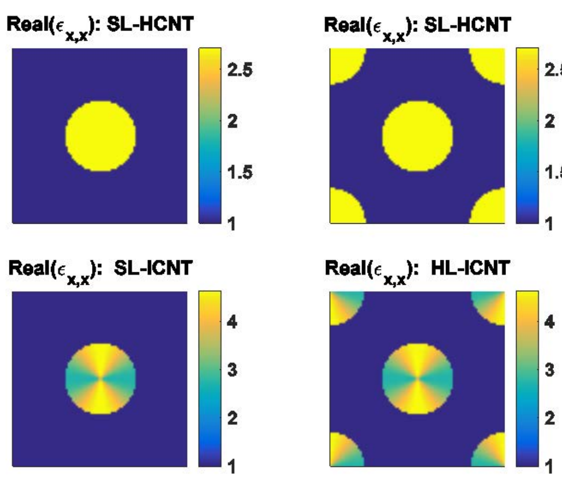

Fig 2. Lattice arrangement of CNT's: SL-HCNT: Square Lattice Homogeneous CNT, SL-ICNT: Square Lattice Inhomogeneous CNT, HL-HCNT: Hexagonal Lattice Homogeneous CNT, HL-ICNT: Hexagonal Lattice Inhomogeneous CNT (only the $\epsilon_{x,x}$ permittivity tensor element is shown).

According to [4] the CNT's permittivity tensor is spatially varying and is given in cylindrical coordinates by: $\hat{\epsilon}(\omega) = \epsilon_{\perp}(\omega)\left(\hat{\theta}\hat{\theta} + \hat{z}\hat{z}\right) + \epsilon_{\parallel}(\omega)\,\hat{r}\hat{r}$, where $\epsilon_{\perp}$, $\epsilon_{\parallel}$ is the permittivity measured when the direction of the electric field is perpendicular, parallel to the tube axis (z) respectively, at frequency ω. The values of $\epsilon_{\perp}$, $\epsilon_{\parallel}$ used are obtained from [5]. Therefore the modeling of CNT's requires a rigorous solver for Maxwell's equations formulated for anisotropic media. For this the Finite- Difference Frequency Domain method (FDFD) is used, where PML's are used to truncate the computational domain in the z-direction and Bloch periodic boundary conditions are used in the x, y directions. The FDFD anisotropic algorithm is implemented according to [6], with the modification that instead of the FDFD-Uniaxial Perfect Matching Layer (UPML) in [6], the SC-PML [7] is used since it is proven [8] that it leads to a linear system of equations with a matrix of a better condition number than the UPML case, which is solved iteratively.

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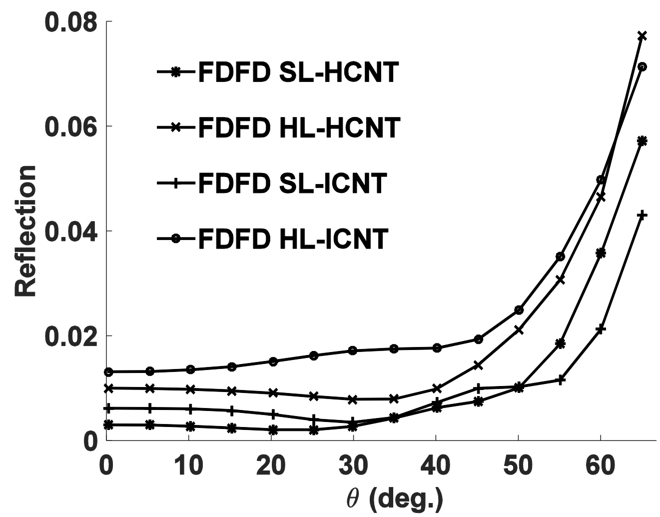

Fig 3. Reflection coefficient of the CNT lattice arrangements of Fig. 2, as a function of the polar angle θ of the incident plane wave. Design parameters: Incident Wavelength: $0.5\mu m$, Tube Diameter: $80nm$, Unit Cell Size (in x, y directions): $0.2\mu m$, Tube Length: $1\mu m$.

In Fig. 2 the various lattice arrangements (on the $x - y$ plane) of the CNT's considered are shown. In [5] the FDTD method was used, only for the SL-HCNT case and under the assumption that the permittivity tensor is diagonal and spatially homogeneous (within the effective medium theory), due to numerical problems present in the FDTD method for general anisotropic media and periodic Bloch boundary conditions. Using the solver developed in this work, CNT's can be analyzed for all cases of Fig. 2, as a function of the CNT's design parameters (volume fraction, tube length, tube distance, plane-wave incident angles). As an example in Fig. 3 the reflection of the CNT's for all cases of Fig. 2 is shown as a function of the polar angle θ and for azimuthal angle $\phi = 0$ for TE polarization.

In addition, FDTD and MRTD techniques were utilized in [4] to optimize the first-of-its-kind wireless passive sensing platform combining radio frequency identification (RFID), microfluidics, and inkjet printing technology (Fig. 4) that enabled remote fluid analysis and required as little as 3 µL of fluid. The demonstrated variable microfluidic capacitors, resonators, and RFID tags were fabricated using a novel rapid, low-cost, and low-temperature additive inkjet process, making them disposable. However, even with their disposable nature, the RF microfluidic devices exhibited repeatability and long-term reusability setting the foundation for fluid-tunable RF applications. The capillary effects as well as the liquid-reconfigurable frequency tuning of the proposed structure as well as the mechanical cracking due to flexing typical in wearable applications were accurately estimated including practical surface roughness, Young's modulus of elasticity and material properties. Monitoring fatigue cracking of large engineering structures is a costly and time-intensive process. [5] introduced the first low-cost inkjet-printed patch antenna sensor (Fig. 5) that can passively detect crack formation, orientation and shape by means of resonant frequency shifts in the two resonant modes of the antenna. For the first time, the effect of non-linear crack shapes on the parallel and perpendicular resonant modes of a patch antenna is quantified with simulation and measurement. This study presented a step towards fully integrated, low-cost, conformal and environmentally friendly smart skins for real-time monitoring of large structures.

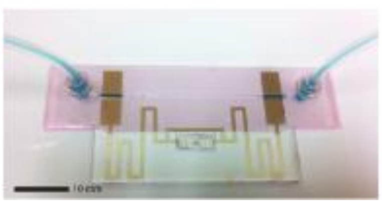

Fig 4. (a) Inkjet-printed liquid-reconfigurable wireless sensor.

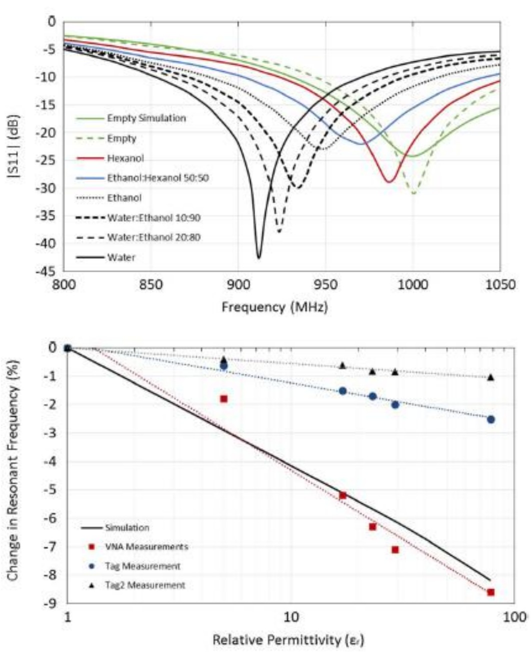

Fig 4. (b) Liquid-based reconfigurability/sensitivity

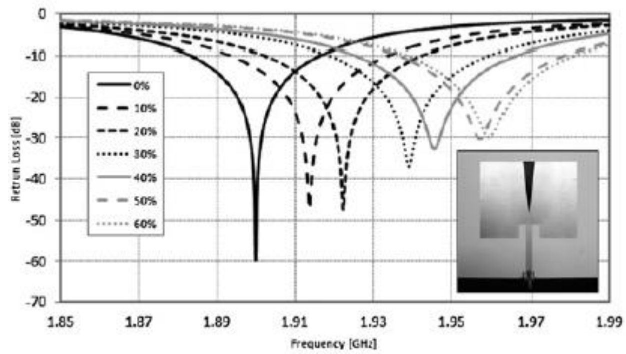

Fig 5. Crack-detection wireless strain sensor.

B. Inkjet-/3D-Printed Fully 3D antennas and antenna arrays with origami "morphing" topologies

Over the last 5 years, inkjet printing has been combined with 3D printing for the first ever realization of truly 3D antennas and antenna arrays in arbitrary 3D shapes. In [6], for the first time a 3D-printed cross-shaped "morphing" structure was modeled with multidomain simulation tools coupling mechanical and electromagnetic equations and built that folds to a cuboid in an "origami" fashion and retains its shape at room temperature (Fig. 6). Inkjet printing was used to directly fabricate antennas on the surfaces of the 3D-printed plastic, enabling a fully additive manufacturing of the structure. Multiple antennas on the cube's surfaces can be used for communication, sensing and RF energy harvesting of signals arriving from totally orthogonal directions, with the use of appropriate harvesters. In addition, a flexible 3D-printed strain sensor [7] was modeled and optimized through a combination of FDTD/MRTD relying on a 3D dipole antenna on an ECA stretchable conductor on a 3D printed NinjaFlex filament with an arbitrary positioned embedded rhombic cavity (Fig. 7) with an unprecedented capability of strain direction detectability over all 3 directions, while allowing for the easy integration of inkjet-printed electronics. The surface roughness issues along with very fine details 3-4 orders of magnitude smaller than commonly used discretization cells as well as drastically different time constants for the mechanical and electromagnetic effects necessitated the use of space-/time-adaptive simulation tools.

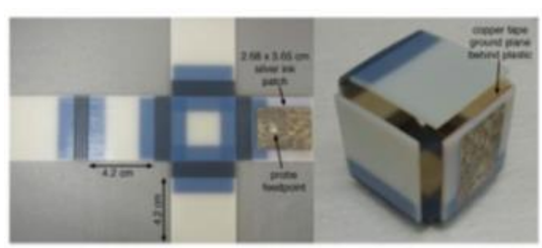

Fig 6. 4D printed "morphing" energy harvesting cuboid

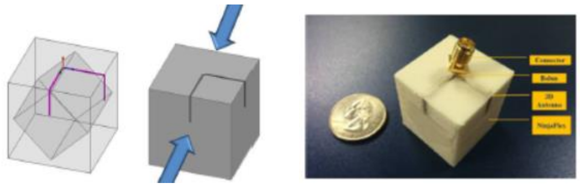

Fig 7. 3D printed strain sensor with embedded cavity

III. Conclusion

Numerous examples of the application of multi-domain modeling approaches (FDTD, MRTD) to state-of-the-art additively manufactured RF modules have been presented and the main modeling challenges have been identified. The accurate results derived from the coupling of electromagnetic, mechanical and solid-state equations have allowed for the optimization and successful implementation of the first fully printed flexible, stretchable wireless sensors, shape-memory “morphing” structures and energy harvesters for Internet of Things and Smart Skin applications.

IV. Acknowledgements

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