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INTEGRATED SIMULATION OF A MEMS-BASED PHASED ARRAY ANTENNA

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Abstract. We address the problem of simulating the complete behavior of a phased array antenna, creating a map between constructive parameters and the radiated beam. In this manner, we can control the relationship between gain and cost, in terms of the design and operation of the antenna. In order to carry out this type of simulation, we decompose the full system into its main components, and apply different finite element tools to each of these: electromagnetic effects at microwave frequencies are modeled with commercial EM solvers, HFSS from Ansoft and Feko from EM Software & Systems-S.A.; on the other hand, the particular type of phase shifting device, namely a micro-electro-mechanical (MEMS) switch, is modeled with a multiphysics tool, CoventorWare from Coventor, Inc. This type of switches constitute a relatively new technology for radio-frequency (RF) communications, allowing very small dissipation rates at high frequencies, as compared to their solid-state counterparts. However, the full extent of this advantage can only be appreciated when all the costs are integrated into one single tool, which is precisely the aim of our custom-made graphical tool.

1 INTRODUCTION

Complete numerical simulation of antenna systems has always been a difficult task. By "complete", we refer to a tool that can map constructive parameters to far-field signals, thus giving constituting a virtual workbench for testing this type of systems.

The reasons for this difficulty lie in the fact that many different length scales and phenomena must be accounted for. In practice, separate tools are generally employed for each of these scales.

In this work we address such a simulation, for a phased array antenna based on micro-electro-mechanical switches. In order to attack this problem, we need to develop a strategy consisting of separate simulations for each of the components of the antenna, plus a tool that couples all of these simulations. In this way, the large numerical effort is tackled by individual, commercial tools, whereas the "stitching" is carried out by an application that is custom tailored to these effects.

We wish to emphasize that this work is being carried out at a recently established micro-fabrications facility at CNEA, directed at MicroElectroMechanical (MEMS) devices. In the near future, we will be able to fabricate and test all the components described in this paper. At the time of writing, we are optimizing processes for simple transmission line structures and radiation patches, whereas the fabrication of the more complicated devices (switches, phase shifters) has been carried out at the Fondazione Bruno Kessler in Trento, Italy. Simulation and design of all devices is carried out at CNEA, while testing is being done through a partnership between our group and the Universidad Nacional de San Martn (UNSAM).

2 PHASED ARRAY SYSTEMS AND MEMS SWITCHES

Phased array antennas construct radiation beams as a result of constructive interference from several radiation elements. By controlling the relative phase and physical separation among these elements, it is possible to concentrate the energy within beams of relatively small width[1]. More importantly, these parameters can be adjusted in order to direct and steer the beam in arbitrary directions, thus avoiding the need for moving parts in the antenna(Visser, 2005).

Given this advantage, compared to classical moving-dish steered antennas, phased array antennas avoid the energetic consumption associated with mechanical steering. Therefore, this technology has found its place in applications that demand a high level of energy efficiency, such as space communications and (in the near future) mobile telephony.

From a technological point of view, the main concern with phased array antennas rely on the phase shifters, i.e. the mechanisms for establishing the phase difference among elements. At relatively high frequencies - radiofrequency (RF) at the order of 1 to 10 GHz- the classical MOS-based shifters suffer from enormous dissipative losses(Goldsmith et al., 2001), thus annealing the advantage of using an array with this type of shifters.

Solution to this drawback has come from MEMS switches: systems that can commute (micro) mechanically, by moving a small membrane or connector in order to force the RF wave along one path or another. During the past decade, several different schemes and architectures have been developed, both in academic and commercial environments, and RF-MEMS switches is today a mature technology(Rebeiz, 2003).

[1]In the most general case, the amplitude of each element is used as another control parameter.

3 BEAM FORMATION

The global component of our simulation tool is a graphical user interface, built with the QT4 platform, coded in C++, wherein all the constructive parameters for the antenna can be entered, and the resulting beam is visualized.

Briefly, a beam formed by a phased array antenna is the result of multiple interference among the participating elements of the array. Thus, the intensity of the beam at probe point r, θ, ϕ is

$$E(r,\theta,\phi) = \sum_i \mathbf{f_i}(\theta,\phi)\frac{\exp\left(-j\mathbf{k_i}\cdot\mathbf{R_i}\right)}{R_i} \tag{1}$$

where i sweeps all the radiating elements in the array, $\mathbf{f_i}$ is the characteristic pattern for element i, $\mathbf{R_i}$ is the relative position for the probe point from element i, and $\mathbf{k_i}$ is the wave vector for a wave propagating from element i.

For far-field observation, $R_i \simeq R - \hat{\mathbf{r}}\cdot r_i$, with $\mathbf{R}$ a conveniently chosen center for the antenna and $r_i \ll R$ the position of element i with respect to this center, and the radiated field becomes

$$E(r,\theta,\phi) = \mathbf{f}(\theta,\phi)\frac{\exp\left(-jkR\right)}{R}\sum_i a_i \exp\left(-j\mathbf{k}\cdot\mathbf{r_i}\right) \tag{2}$$

where $\mathbf{k}$ points from the center of the array, and the complex numbers a_i are the control parameters for each element.

Furthermore, for identical elements equally spaced at distances d_x and d_y, and without phase shifts ($a_i = 0$), we obtain (for a fixed distance R),

$$E(\theta,\phi) \propto F_x(u(\theta,\phi)F(v(\theta,\phi)) \tag{3}$$

with $u = \sin\theta\cos\phi$, $v = \sin\theta\sin\phi$, and

$$\begin{aligned} F_x(u) &= \left|\frac{\sin\left(N\pi d_x u/\lambda\right)}{\sin(\pi d_x u\phi/\lambda)}\right| \\ F_y(v) &= \left|\frac{\sin\left(N\pi d_y v/\lambda\right)}{\sin(\pi d_y v/\lambda)}\right| \end{aligned}$$

These last expressions are characteristic for the interferometry patterns in phased array antennas. Essentially, they control the main features that are present in any antenna beam (sidelobe levels, beamwidth, power loss, etc) as a function of the distance between elements.

Steering this same pattern is achieved in a straightforward manner: setting a uniform excitation $|a_i| = 1$, with fixed shift difference between consecutive elements,

$$a_{m,n} = \exp\left(-2j\pi\left(\frac{d_x u_0 m + d_y v_0 n}{\lambda}\right)\right) \tag{4}$$

results in a radiation pattern as in eq.3, but centered at $\theta_0 = \sin^{-1}(\sqrt{u_0^2 + v_0^2})$, $\phi_0 = \tan^{-1}(v_0/u_0)$.

Another important aspect of beam formation is the capacity to implement different numerical strategies aimed at optimizing specific magnitudes of the beam. These are called "array synthesis", which are pre-established recipes aimed at optimizing certain aspects of the beam (for example, narrowness, sidelobe levels, etc.), or else obtaining a best fit for a prescribed beam form.

Our graphical tool allows us to form beams in a custom manner, in any of four ways:

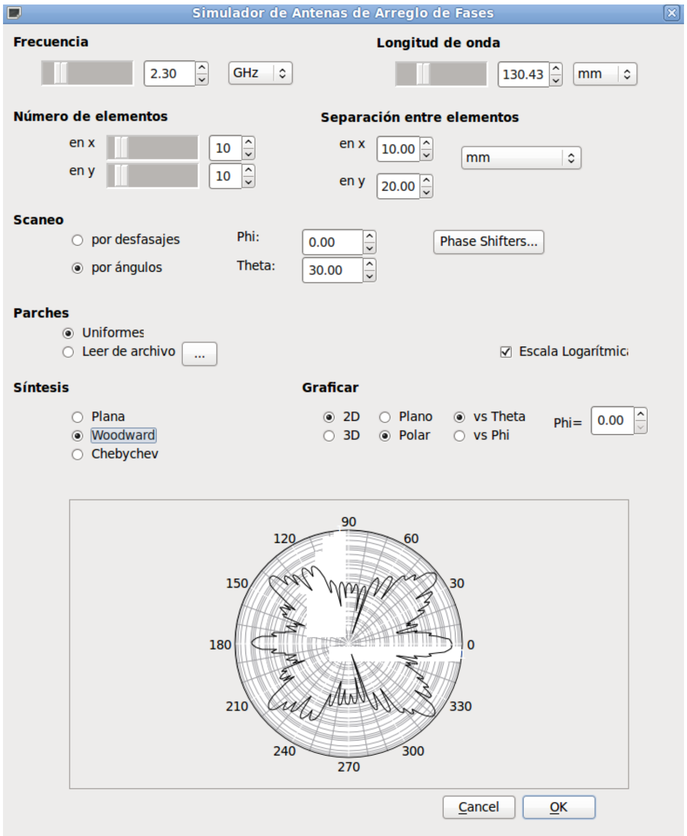

Figure 1: Graphical interface for the phased-array antenna simulation tool.

1. setting the desired angles, and computing the necessary phase shifts;
2. fixing the phase shifts, computing the scan angles;
3. choosing a prescribed array synthesis method (up to date, only Woodward synthesis has been incorporated(Mailloux, 2005));
4. establishing each of the shifts individually.

Apart from the phase shifts themselves, the application permits input of other constructive parameters, such as amplifiers and radiation elements. In this sense, the tool is quite simple, from a numerical point of view. The usefulness, and uniqueness, of this tool relies essentially on the capacity to control the input parameters according to the particular design needs within our group. This is the reason why we cannot use tools developed by others (for example, (Keizer, 2000)), or the ones incorporated into commercial applications, like HFSS.

4 NUMERICAL SIMULATION OF COMPONENTS

The simple schematic for phased array beam forming, shown in the previous section, is a standard theoretical description. In a real antenna, the design and simulation of this type of antennas demands a consideration of the limitations, input and output requirements for each component of the antenna.

Therefore, the tool mentioned above is basically a skeleton, which binds together the separate models for the individual components of the antenna, which are described in the following

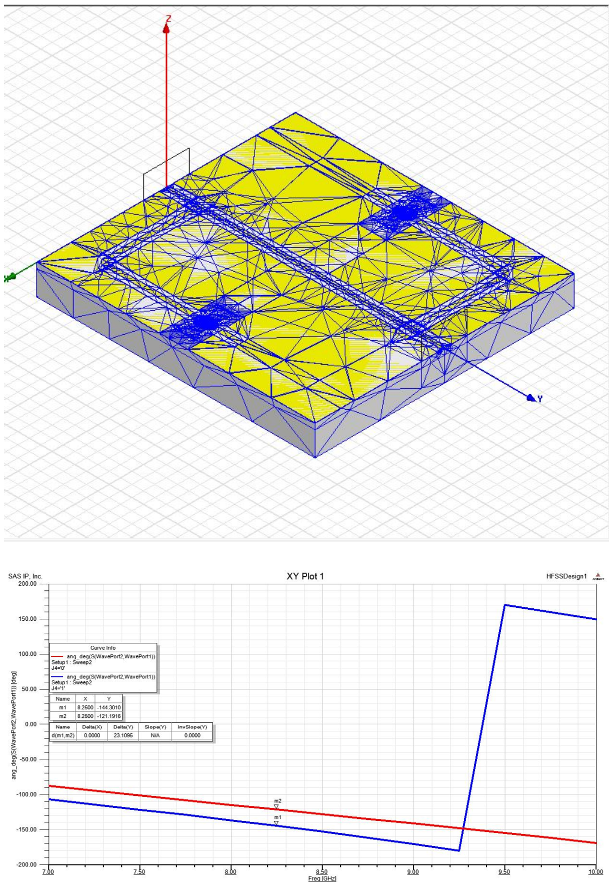

Figure 2: HFSS modeling for a piece of a reflective charge phase shifter: setup (top), and resulting S-parameters, showing the desired phase shift between an actuated and non-actuated states

paragraphs. In order to achieve an important capacity to develop phased antennas, it is imperative to fill up the libraries for these components.

Figures of gain as a function of cost are computed in a bottom-up strategy, by composing the individual costs and gains of each component, as well as the interface between each subsequent pair. The manner of connecting among the different structures is through standard circuit parameters, such as S, Y or Z parameters, which are produced by the simulation tools that follow.

4.1 Phase shifters

By far, the most important elements in a phased array antenna are the phase shifters. They determine the manner in which relative shifts among the radiative elements are established, and therefore the particular technology of a phased array antenna refers to the type of phase shifter being used.

There are three main types of phase shifters, according to their topology(Rebeiz et al., 2002):

- Reflective charge, in which signals are driven through reflective circuits, and the phase is controlled by their lengths(Malczewski et al., 1999).
- Switched line, whereby signals are conducted along paths with different physical lengths(Kim et al., 2001).
- Distributed loaded line, whereby the phase is controlled by varying the optical parameters -generally the characteristic capacitance - of the line(Barker and Rebeiz, 1998).

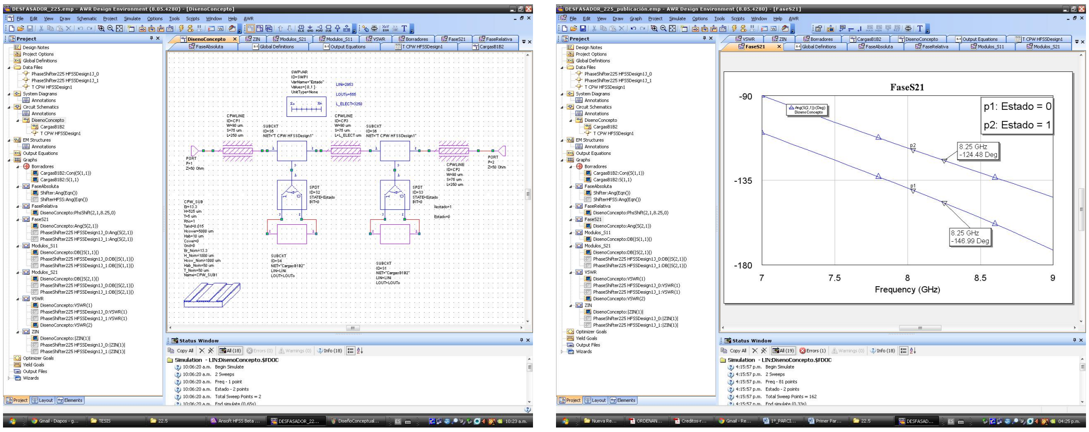

Figure 3: Schematic simulation for a 22.5^o loaded line phase shifter in AWR Microwave Office, with sub-models coupled to HFSS simulations shown in Fig.2: setup (top), and phase results for S12 parameter (bottom)

In each of these types of architectures requires a specific type of switching element. In our case, we have concentrated on shunt MEMS switches, for reasons explained in the following paragraph.

As a first application, we have designed and simulated, and fabricated a reflective charge type of phase shifter, for commuting at 180^o, 90^o and 45^o, as well as a loaded line model for 22.5^o. We have also simulated distributed structures for 11.25^o and 5.625^o, although these have not been realizable in a circuit design according to given design rules.

Precise simulation of these phase shifters involves several stages: on one side, very accurate electromagnetic simulation for the behavior of specific elements, such as the directional coupler(Larosa et al., 2010), switches and bits of transmission line are carried out within a finite element solver, such as HFSS from Ansoft (Fig.2); later, these models are incorporated into a schematic simulator, such as Microwave Office from AWR (Fig.3), which can couple these structures into a circuit model, and output the desired magnitudes (phase shifts, loss, etc.) as S-parameters or equivalent magnitudes.

4.2 RF-MEMS switches

Following the discussion in the previous section, the MEMS switches are fundamental for the efficient operation of the antenna. These switches can be grouped into two main categories, according to their functionality:

- Series-Contact, which act as a simple on/off switch, with a metallic contact between two pieces of transmission line, and can be used for the first two types of shifters mentioned above. The advantage is given by their straightforward design, but applications are limited because the metal contact produces large heat dissipation, and may lead to stiction effects (whereby the switch remains “stuck” in the lower position) and shorter lifespan (Rebeiz et al., 2002).

- Shunt-Capacitive, in which the switching mechanism is given by a moving membrane that can modify the capacity of a transmission line. This type of switches can be used for redirecting signals (with very high values of capacitance in the "down" state, i.e. a very small gap between the line and the membrane), as required by reflective and switched-line shifters; or as a tunable capacitance for the distributed type of shifters. Although more

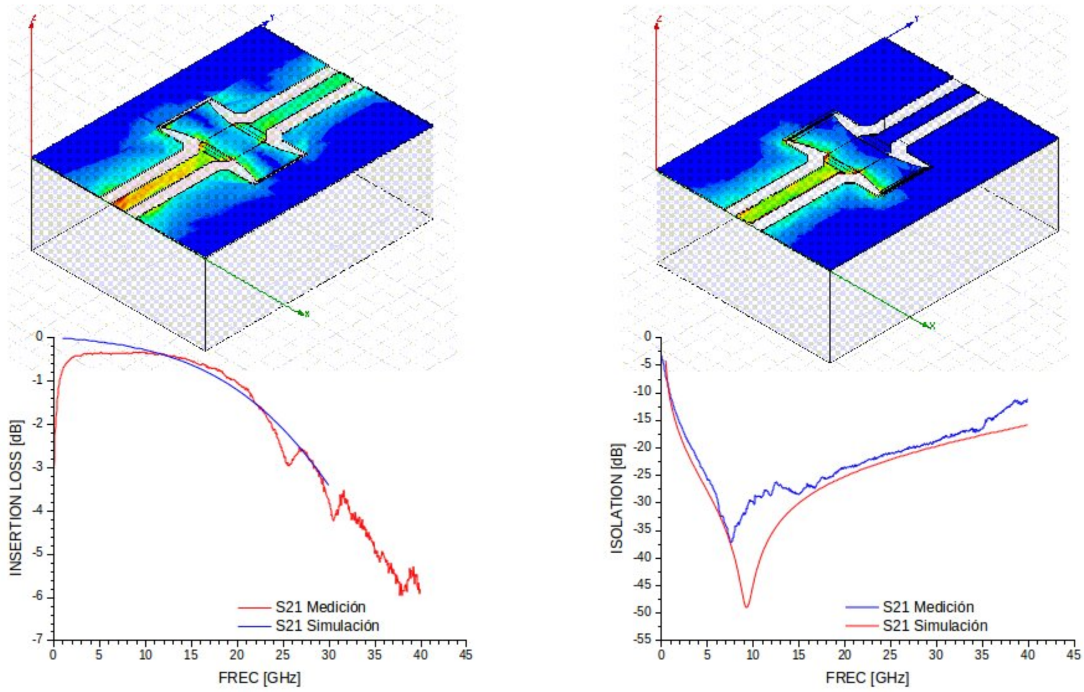

Figure 4: HFSS simulation of a shunt capacitive switch: “on” state (left), “off state (right).

cumbersome to design, they are comparatively more useful than the series switches, due to reliability and longer lifespan.

Precise modeling and simulation for these components must produce the two characteristics for the switch : the cost for mechanically actuating the switch, as well as the electromagnetic functionality of the possible states of the switch. These are given by isolation in the “off" state (generally measured as a very low S12 parameter), loss in the “on" state (generally measured as a S12 parameter close to unity).

The transition between these two states (i.e., the actuation of the switch) is known to have a hysteresis cycle: the pull-in voltage, necessary to lower the membrane, is higher than the lift-off voltage that must be applied in order to release the switch. Obtaining these values requires an adequate inclusion of mechanical effects (elasticity, stress gradients, Young modulus), as well as the electrical parameters.

Therefore, we observe that there are several different natures for the mechanisms involved in these switches, leading to different types of simulations:

- we employ a multiphysics tool (CoventorWare from Coventor) in order to address the actuation of the switch (Fig.4.2);
- we use an electromagnetic solver (HFSS from Ansoft, Inc.) for obtaining the isolation and insertion loss (Fig.4).

4.3 Radiation patches

The radiation elements are, by far, more conventional than the previous elements, in terms of well-established design and fabrication know-how. A particular choice of patches involves

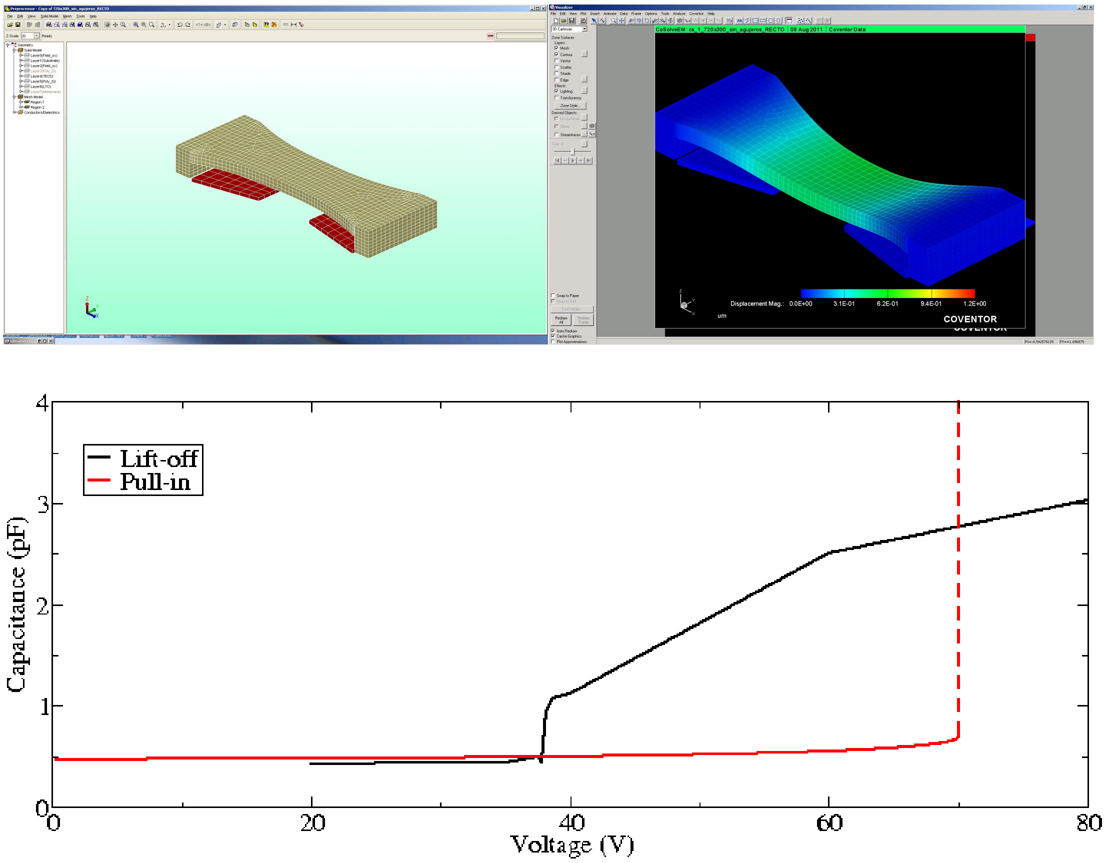

Figure 5: Coventor Finite-Element model for a shunt capacitive switch: model (top left), result visualization (top right), and plot of capacitance as a function of actuation voltage, for pull-in and lift-off.)

deciding the type of patches and materials to be used (metals and substrates). Generally, these are decided by the requirements in terms of frequency ranges, broadness, power, and cost.

Within our scheme for simulating the complete functionality of the antenna, the main difficulty resides in the mutual coupling among these elements: if the emission from each of them can be treated independently from the others, then their inclusion is quite straightforward, whereas comparatively elaborate schemes must be included if cross-impedance among elements must be accounted for.

At present, we are setting up a collaboration with a the Instituto Nacional de Radioastronoma (IAR) in La Plata, Argentina, a research institution that has ample experience in the design, fabrication and testing of antennas.

In the meantime, we have simulated some simple examples of radiation patches, designed for the vicinity of our frequency of interest, as can be observed in Fig.6

4.4 Auxiliary coplanar structures

For the interconnection of all the components mentioned above, we must take into account a wide range of transmission lines, impedance adapters, directional couplers, and other microwave devices, according to the necessities that appear as we construct the antenna. These models, generally developed in HFSS or similar tools, must also be included within the global simulation tool.

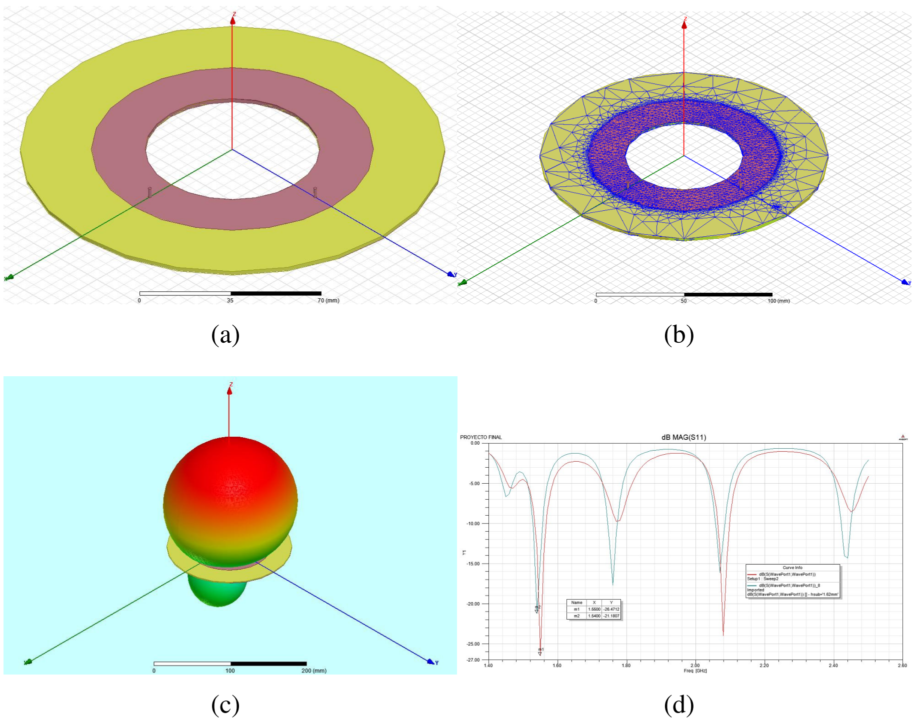

Figure 6: Finite Element modeling of a radiation patch in HFSS: setup (top left), meshing (top right), radiated beam at frequency of interest (bottom left), and S12 parameters as a function of frequency (bottom right).

5 CONCLUSIONS

We have shown a platform in which a phased array antenna can be numerically simulated, by decomposing all its elements into simple models. Within this environment, these models are coupled in a manner that allows a mapping between constructive parameters of the antenna and the resulting radiation beam. We have briefly discussed the main numerical strategies in dealing with each of the components of the antenna, namely: finite element methods for electromagnetic and electromechanical effects, plus specific tools for schematic simulation of large electrical structures. For these simulations, we have relied on commercial tools, such as CoventorWare, HFSS and Microwave Office. Present and future efforts are concentrated on filling up the libraries of elements, leading to richer explorations in parameter space.

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REFERENCES

Barker N.S. and Rebeiz G.M. Distributed mems true-time delay phase shifters and wide-band switches. *IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES*, 46(11):1881–1890, 1998.

Goldsmith C., Kleber J., Pillans B., Forehand D., Malczewski A., and Frueh P. RF MEMS: benefits & challenges of an evolving rf switch technology. pages 147–148. 2001. doi:10.1109/GAAS.2001.964365.

Keizer W. Phasim, an advanced phased array antenna software simulator. In *Phased Array Systems and Technology, 2000. Proceedings. 2000 IEEE International Conference on*, pages 477 –480. 2000. doi:10.1109/PAST.2000.859000.

Kim M., Hacker J.B., Mihailovich R.E., and DeNatale J.F. A DC-to-40 ghz four-bit RF MEMS true-time delay network. *IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS*, 11(2):56–58, 2001.

Larosa F.S., Fuentes L.A., and Bonaparte J.J. A mems x-band capacitive directional coupler. pages 24–29. 2010.

Mailloux R.J. *Phased Array Antenna Handbook, 2nd edition*. Artech House, 2005.

Malczewski A., Eshelman S., Pillans B., Ehmke J., and Goldsmith C. X-band rf mems phase shifters for phased array applications. *Microwave and Guided Wave Letters, IEEE*, 9(12):517 –519, 1999. ISSN 1051-8207. doi:10.1109/75.819417.

Rebeiz G., Tan G.L., and Hayden J. Rf mems phase shifters: design and applications. *Microwave Magazine, IEEE*, 3(2):72 –81, 2002. ISSN 1527-3342. doi:10.1109/MMW.2002.1004054.

Rebeiz G.M. *RF MEMS: Theory, Design and Technology*. John Wiley and Sons, 2003.

Visser H.J. *Array and Phased Array Antenna Basics*. John Wiley and Sons, 2005.