Open Access CAD, EM tools, and examples for teaching microwaves

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***Abstract*—The paper presents an open access software platform for electromagnetic (EM) teaching and dissemination of microwave technology results. The platform is developed within the H2020 MMAMA project. Its core is a licence-free GUI, wherefrom different EM and multiphysics solvers can be launched, under different licence schemes. The tools are supplemented with an expandable database of modelling examples and results, documented in the standardised MODAand Gwyddion formats. The presented examples range from the Basic Microwave Course, whose elements have been used for 25 years in teaching at the Warsaw University of Technology, to the modelling of calibration standards for microwave microscopy of materials.**

Keywords—open platform, open access tools, open innovation environment, EM modelling, coupled processes modelling, teaching microwaves.

I. Introduction

Teaching microwaves supported with visualisation tools gains continuously growing popularity. Visualising the invisible [1], as electromagnetic (EM) waves with EM simulation software [2-4], catalyzes the understanding of the EM field theory among students and young engineers. Such a teaching approach is frequent at universities and increasingly accepted in industry However, it is strongly dependent on accessibility of teaching releases of commercial simulation software, which, even if available, are typically restricted to university usage. This hinders continuous education of individuals employed in commerce as well as the invaluable simulation-supported teaching at companies, especially small and medium enterprises (SMEs), which should be a driving force of innovation in Europe and throughout the world.

Increasing the accessibility of the results of publicly co-funded research has become one of the desirable outcomes of R&D projects supported by the European Commission (EC). Its research actions aim at fostering collaboration and competitiveness by supporting, on one hand, mechanisms like Marketplaces [5] or Test Beds [6], which however operate on commercial bases. On the other hand, a significant attention is given to popularise the development of simulation tools with a focus on open access modelling platforms or in more general terms, open innovation environments. The modelling platforms are foreseen to implement research results of the projects' consortia and deliver them for the usage of a wide scientific community, including universities as well as industry.

In this paper, we present our open access modelling platform, developed within the EC H2020 MMAMA project [7]. The platform is hierarchical to enable a continuous learning process, for students and engineers of different levels of expertise. It starts from the analysis of basic microwave phenomena and directs the user towards advanced problems, coupling electromagnetics with other physical or chemical processes. Such a learning path is possible due to common, open access graphical user interface (GUI), which allows easy switching between different solvers or different problem complexities or different licence schemes, with no necessity to learn a new tool, which is a typical constraint for both newcomers to the field and overloaded design engineers.

The paper is organised as follows. In Section II we present the basic blocks of the open platform. Section III describes selected examples of application from the area of microwave microscopy of materials, as advanced in the MMAMA project. Section IV concludes with an outline of the on-going works of the MMAMA consortium and our invitation for collaboration addressed to other consortia.

II. Open Platform GUI and Solvers

The concept of the modelling platform presented herein is based on the idea of delivering open access modelling tools, spanning across different science domains, which brings the opportunity of easy and continuous learning and skills enhancement process, eliminating expensive time overheads related to familiarising with different user interfaces. This goal is achieved by developing a common GUI, linked with different simulation tools and a database of examples. Such an approach enables not only a convenient way of solving various types of coupled and linked EM and multiphysics problems but also a robust cross-comparison of different solvers. The conceptual diagram of the open platform, together with relevant access schemes, is presented in Fig. 1. The consecutive blocks of the platform are described in the following sections.

A. Graphical User Interface: Licence-Free Time-Unlimited

The core unit of the open modelling platform is GUI (Fig. 2) [8-9], which is common for all solvers available within the platform. The GUI is implemented as a workbench for the open source FreeCAD general purpose parametric 3D CAD modeller [10]. FreeCAD is a feature-based parametric modeller having a modular software architecture, which enables providing new functionalities without modifying the core system. This allows taking advantage of professional CAD geometry preparation and modification capabilities and enhancing them with dedicated functionalities for the purpose of modelling physical processes. One of the main objectives that is met, ensuring operation flexibility, is industrial adequacy achieved through import and export of popular CAD (e.g. *.stp, *.iges, etc.) and Gwyddion files. A set of intuitive and user-friendly menu options and dialogues allow for convenient choice of appropriate meshing, solver, or simulation options.

The proposed GUI is a fully operational CAD-based tool for simulation project preparation, with unlicensed, time-unlimited access, and unrestricted availability. To boost the learning process, it delivers a set of libraries gathering simulation examples modelled with the tools being accessible within modelling platform.

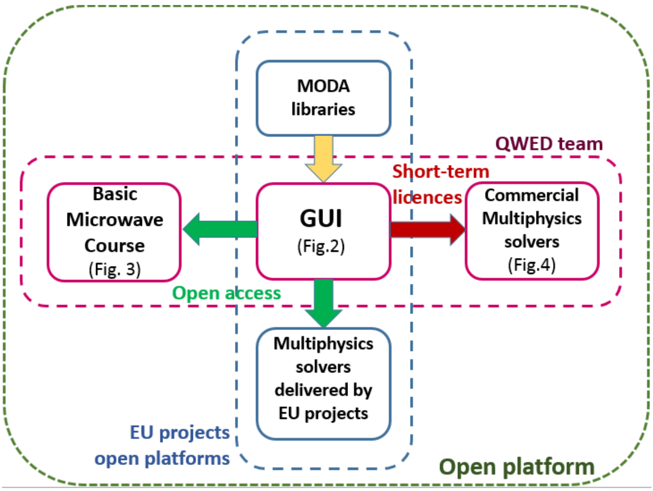

Fig. 1. Diagram of the open platform – elements and access schemes.

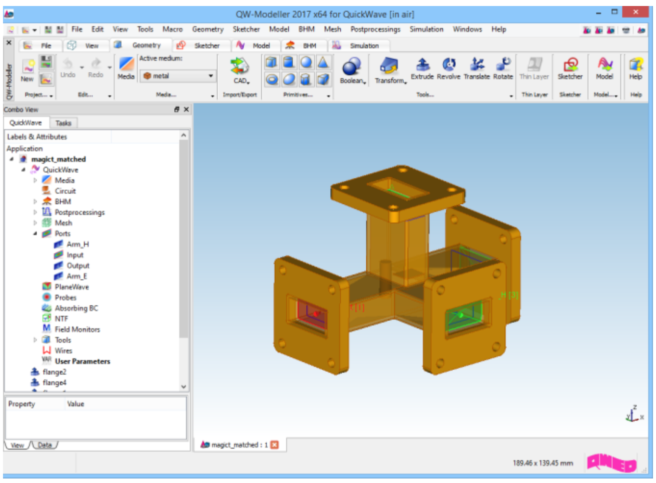

Fig. 2. Main window of the open access modelling platform GUI.

B. Basic Microwave Course: Free Time-Limited Licence

The goal of the open access modelling platform is to facilitate using EM modelling in physics and microwave technology courses (as successfully implemented at the Warsaw University of Technology since 1995, now [11-12]). The modelling platform enables analysis of the EM phenomena with the aid of the finite difference time domain (FDTD) solver [2]. The access to the solver is delivered through the so-called STUDENT Release [13], with a free, renewable three-month licence. The option of license prolongation, not preconditioned with any additional obligations, allows covering the duration of a typical academic course. Worth mentioning at this point is that the STUDENT Release is not restricted to academia, facilitating the use by the broader group of engineers. It has also been recently promoted to chemists and physicists within European initiatives such as the European Materials Modelling Council (EMMC) [14] or AMPERE [15].

The analysis of chosen EM phenomena can be conducted with the Basic Microwave Course that is delivered within modelling platform [16]. Short theory background is supplemented with simulation scenarios (with additional guidelines for project preparation), which are contained in the GUI libraries and are currently dedicated to plane wave propagation, rectangular and circular waveguides. The user is guided through investigation of relations between wavelength and frequency or medium parameters, wave behaviour when propagating in lossy media or when impinging on media boundaries (Fig. 3).

Flexibility of this solution comes from the possibility of analyzing also user-defined scenarios prepared in the GUI and run with the delivered FDTD solver. Thereby, the user is allowed to extend the spectrum of considered EM phenomena.

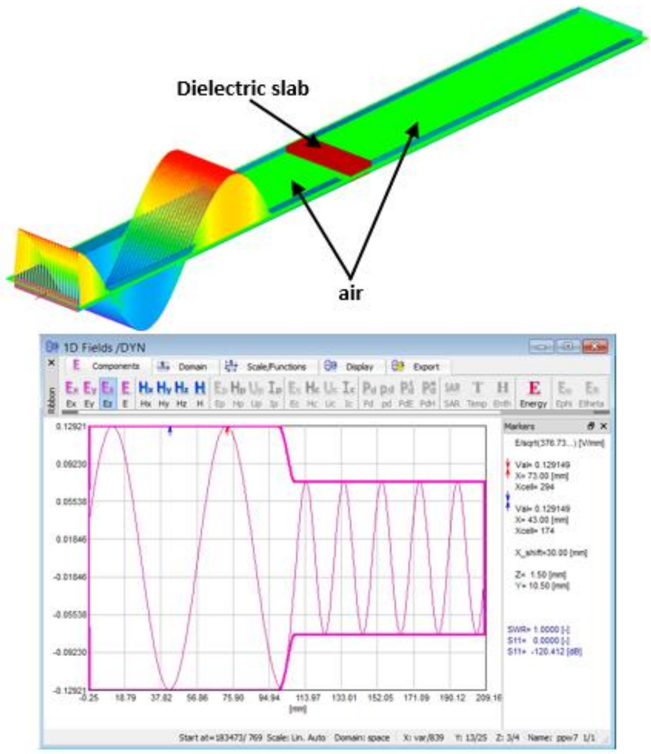

Fig. 3. Plane wave impinging on a material boundary – exemplary simulation scenario (quarter wavelength transformer problem).

C. Multiphysics Solvers from EU projects:

The adopted concept of the open modelling platform allows conveniently extending its capabilities by adding different solvers, both, open access and commercial, enabling the analysis of more complicated coupled problems. To this end, solvers delivered by the European projects will be provided for on royalty-free basis for teaching and dissemination purposes. The first of this family is a coupled FEM solver for EM-semiconductor physics introduced in [17]. The classical EM wave simulators are capable of delivering results for the structures that are solely based on dielectrics and metals [18]. However, interaction between the external high frequency EM field and the charge carriers requires the conductivity within semiconductor domains to be defined locally. Therefore, charge transport simulations are needed in order to model the effects of highly nonlinear semiconductor properties and to accurately perform EM analysis of devices that involve semiconductor materials. This led to development of multiphysics simulations of drift diffusion equations coupled with Maxwell's wave equations for simulations of scanning microwave microscopy (SMM) of semiconductors within the MMAMA project [7]. In the following example, its basic FEM solver is applied to the classical EM problem, for comparison with an EM FDTD solver; examples of coupled simulations as presented in [18] are being added to the open platform database.

D. Interfaces to Commercial Multiphysics solvers

The open GUI is also linked to commercial solvers enabling the analysis of multiphysics problems beyond the scope of the open access tools. Here, representative examples are microwave heating scenarios, where a coupled EM-thermal solution is necessary [19]. The thermal part typically includes heat flow, load movement, and temperature variation of materials. The open platform GUI, next to typical parameters necessary to run EM simulation, delivers a set of dedicated dialogues enabling configuration of the coupled process, through determining heating times, dependence of electromagnetic and thermal media parameters on temperature or trajectory of the load movement. The access to commercial tools is through evaluation or short-term licenses. The modelling examples, including microwave heating problems (Fig. 4), are delivered in the GUI libraries.

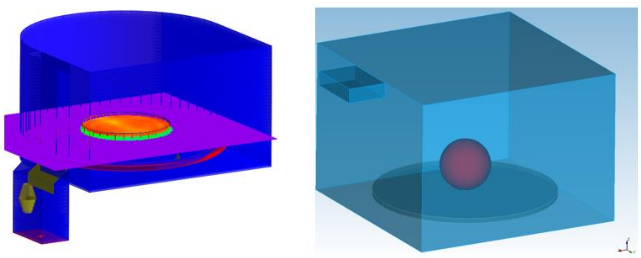

Fig. 4. Commercial microwave oven model courtesy of Whirlpool Sweden AB with distribution of power dissipated in heated beef, simulated by FDTD after [20] and a simple oven model also from [20], being added to the open platform.

III. Open Platform Models and Simulation Results

Our library of examples and simulations results aims to provide reusable and interoperable data. As such, a number of scenarios are borrowed from pre-existing teaching courses [16] or open literature [20]. New examples are defined as MODA fiches following the EC recommendation for documenting simulation problems [21-22]. In MODA, each User Case has an assigned physical model, treated with a specific computational solver and post-processors. The three User Cases of the MMAMA project [7] are a classical coaxial probe, a dielectric resonator, and an SMM probe (Fig. 5) of current research interest in e.g. nanotechnologies [23] and semiconductor [24] or biomedical [25] research .

An EM problem of an SMM tip in contact with a dielectric or metallic material under test (MUT) were considered in [18] by stand-alone FDTD and FEM solvers. Herein, the solvers launched from our open GUI are used to support the SMM calibration technique, in order to demonstrate the industrial relevance of the established platform.

For the purpose of SMM calibration, four different gold structures were fabricated by METAS using cleanroom technologies (material deposition, electron beam lithography, and etching). The panel on the left of Fig. 6 presents a top view scanning electron microscope (SEM) image of one of the four fabricated devices. As shown on the right of Fig.6, the devices are made of gold on a free SiN membrane. Each of them has a round gold pad with a radius *r1*, where the SMM tip lands on during SMM measurement. This gold pad is separated from the rest of the 100 nm thick gold film, which is grounded, by a dielectric region, where SiN surface is exposed (dark region in the SEM image). As listed in Table I, the four devices differ from each other by geometry (*r1* and *r2*), leading to the different impedance and capacitance values. The values of imaginary part of input impedance $\mathrm{Im}(Z_{in})$ are presented in Table I. The data obtained from a calibration technique are shown between those from FEM and FDTD modelling. The calibration algorithm is similar to the short-open-load method, used to calibrate a one-port Vector Network Analyser, as detailed in [23-24]. As required by this method, each calibrated value in Table I, e.g. 1731.7 Ω of Device 1, is obtained by employing $\mathrm{Im}(Z_{in}^{FEM})$ calculated using FEM and complex S_{11} signals (not shown in Table I) recorded in real SMM experiments for Devices 2,3,4. Analogously for Device 2, the Devices 1,3,4 are used for calculation. The measurements are realised using a home-made SMM at METAS with a microwave signal at 9.4 GHz under ambient conditions. More details about the SMM setup can be found in [23].

In simulations, the impedance is extracted by near-field integration close to the tip. Due to the locally quasi-TEM character (Fig. 5), E-field (voltage) integration is unambiguous while for H-field (current) a convention needs to be agreed, and circular contours at 30 μm from the tip are used. The arrangement of the columns in Table I is not coincidental: it emphasises that the calibrated measurements are in-between the results obtained from the FEM and FDTD models. This is consistent with the different convergence properties of FDTD and FEM, and illustrates the relevance of invoking different solvers from the same GUI, facilitating solver cross-comparisons and enhanced reliability of the model results.

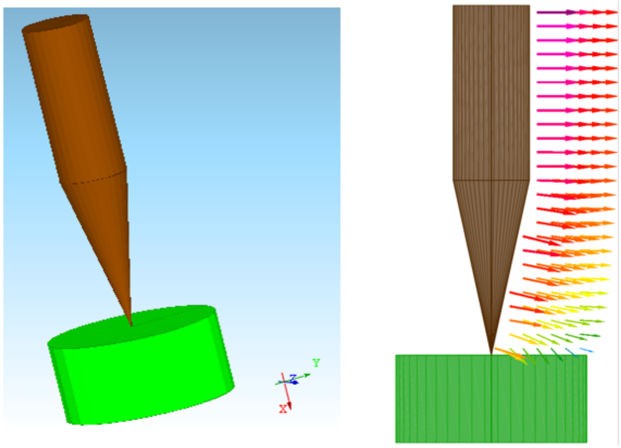

Fig. 5. SMM probe modelling example and EM simulation results (distribution of electric field) from FDTD solver [2].

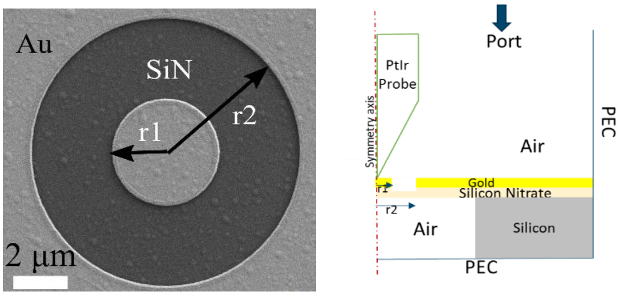

Fig. 6. Scenario for the extraction of capacitance of capacitors fabricated by METAS: a top view (SEM image) of one of the four fabricated devices (left) and simulation setup (right).

TABLE I. VALUES OF IM(ZIN) OBTAINED FROM SIMULATION AND FROM CALIBRATION USING METAS MEASUREMENTS AT 9.4 GHZ

Device	r1/r2 [um]	FEM [Ω]	Calibration [Ω]	FDTD [Ω]
1	20/20.2	1861.6	1731.7	1405.3
2	20/21	3142.8	3035.1	2936.4
3	10/11	5745.8	5375.5	4949.0
4	2/5	16447.0	16387.1	16383.2

IV. CONCLUSIONS

We have presented an open access platform, which combines a FreeCAD-based unlicensed GUI with an expandable set of solvers relevant to microwave technology, and available upon multi-level access rights, including open tools for teaching and dissemination. The platform incorporates the background knowledge of the H2020 MMAMA consortium [7] and within the project, is being specifically expanded for the modelling of microwave microscopy of materials. To promote and represent other physical sciences and technologies areas, new collaborations have been initiated and are further sought. Modelling examples and results are accumulated in standardised formats, MODA and Gwyddion, for easy re-use in accordance with the open science European strategy.

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