

A Novel Numerical Method for Benchmarking Planar Magnetics Having Thin Solid Conductors Using Layered Mesh

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Planar magnetics such as wireless power transfer (WPT) devices are being developed and applied to various kinds of applications. Thanks to the advantages such as high-quality factor and transmission efficiency, various printed-circuit-board (PCB) resonators are designed for different practical needs. Usually, these planar PCB devices are composed of thin dielectric layers and even thinner copper traces printed on the planar dielectric board. Furthermore, since the WPT devices can work at frequencies as high as several MHz, there is strong skin, proximity and distributed capacitive coupling effects between conductors. For planar magnetic having thin solid foil conductors, the stray capacitance between conductor segments has to be taken also to address the resonant phenomena. In the design of such kind of WPT structures, for example to design the spiral pattern of the winding copper traces, there is a strong need to resort to numerical methods without introducing simplification or equivalent methods. In this work, the layered mesh technique is proposed to remedy the tough meshing process for thin conductors. A numerical example will be given to showcase the efficiency of the method.

Index Terms—Finite element method, layered mesh, planar magnetics, scaling technique, thin conductor.

I. INTRODUCTION

Planar magnetic structures including wireless power transfer (WPT) devices, are widely used for different kinds of applications [1, 2]. Because the merits like high quality factor and transmission efficiency, the printed-circuit-board (PCB) resonators has been designed for practical needs [3]. Usually, these planar PCB devices are composed of thin dielectric layers and even thinner copper traces printed on the planar dielectric board. Furthermore, since the WPT devices can work at frequencies as high as several MHz, there is strong skin, proximity and distributed capacitive coupling effects between conductors [3].

For planar magnetic having thin foil solid conductors, there is a strong need to develop efficient numerical methods without introducing simplification or equivalent methods [3]. Based on our experience, the meshing process for the very thin copper layers is really time-consuming and easy to fail to meet the mesh quality requirement for finite element computation. Although the boundary layer mesh method can be used, but the meshing process is really long due to the highly anisotropic mesh nature near the conductor surfaces. Although at high frequencies, the conductor outer surfaces can be treated as impedance boundaries, but there is unavoidable error introduced since the assumption of the impedance boundaries may not be satisfied for general conductors and hence the solid loss can't be obtained accurately either. In this work, a layered mesh generation technique is proposed to remedy the difficulties in the meshing process for thin conductors with any shape. Numerical examples will be given to showcase the efficiency of the method.

II. PLANAR MAGNETIC WPT DEVICES WITH THIN CONDUCTORS

Planar magnetic WPT device usually has thin conductors, placed on the dielectric layer, as shown in Fig. 1, where the searchers have also eliminated the use of magnetic cores in the

design and production of self-resonant coils, opting instead to design the coils in a spiral shape. This minimizes resistance through geometric design methods and constraints, as shown in Fig. 1 below [2].

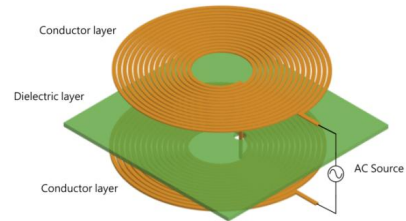


Fig. 1. Structural diagram of self-resonant coil without magnetic core [2].

Their lightweight and compact design enables efficient energy transfer using only two self-resonant coils. By adjusting the pitch size and the distance between the coils, the resonant frequency of the system can be correspondingly modified. This coil structure design significantly reduces material usage and decreases the overall volume of the system [4]. This type of coil is widely used in mid-range high-frequency (HF) Wireless Power Transfer (WPT) systems.

For the structural design of the self-resonant coil, the geometry objects are primarily concentrated on the PCB board, resulting in layers having very small thicknesses. As shown in Fig. 2, the width of the given spiral coil trace is about $w=4.6$ mm, the outer diameter is approximately 70 mm, and its thickness is only about $t_c=0.035$ mm. These parameters can make the volume meshing really difficult, resulting in big error in the finite element computation.

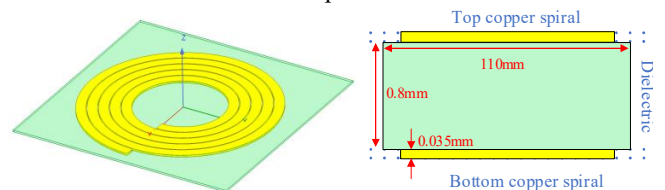


Fig. 2. Self-resonant coil and the dimension parameters.

III. PROPOSED LAYERED MESHING TECHNIQUE

A. Proposed Geometric Scaling Technique and Layered Mesh Generation

Due to extremely high aspect ratio of the thin foil conductor objects in planar magnetics or planar WPT applications, the mesh generator to generate unacceptable poor-quality mesh elements and the mesh generation is really time-consuming.

To address this problem, this work proposes to first extrude the foil conductors and thin dielectric layer in z -direction, resulting in a scaled geometry where the copper thickness is set to 3.5 mm and the thickness of the middle dielectric layer is set to 3.2 mm, as shown in Fig. 3(a). This modification allows the new geometry to be conveniently and effectively triangulated into traditional tetrahedrons as shown in Fig. 3(b) since there are no more extreme aspect ratios. After the scaled mesh is obtained, one can easily scale the mesh nodes back to the real dimensions.

Taking into account of the layered structure of the WPT system, we can further generate a layered mesh for each of the sub-domain layers along z -axis, where the 2D triangular cross section mesh for each layer is extruded to generate the final 3D tetrahedral mesh [5]. In this way, the tedious mesh generation process for the original geometry having extremely high aspect ratio is overcome, and the layered mesh can be further made nonconforming in cases where generating a 2D mesh for all the stitched planar cuts from each layer is difficult.

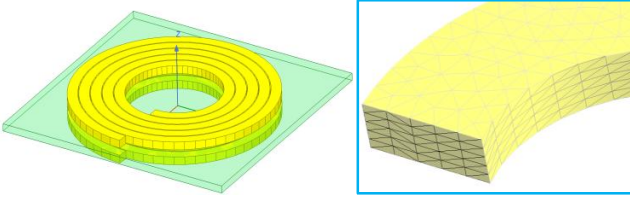


Fig. 3. (a) Scaled geometry; (b) Extruded coil and coil layer mesh.

B. Numerical Formulation

For the coupled inductive-capacitive problems such as the simulation of self-resonant WPT devices where all the material properties are linear, the frequency domain formulation proposed in [6] can be used, where the magnetic vector potential and the electric scalar potential are solved together to address the coupled inductive-capacitive effects. Note that this finite element formulation can also take into account the effect of the lossy dielectric (the loss tangent can also change with different frequencies or there can be tangent dispersion), which is necessary for high excitation frequencies of several MHz.

$$\begin{cases} \nabla \times (\nabla \times \vec{A}) + \sigma(j\omega\vec{A} + \nabla\phi) + j\omega\epsilon\nabla\phi - j\omega\epsilon\nabla\chi = \vec{J}_s \\ \frac{1}{j\omega} \nabla \cdot (-\sigma(j\omega\vec{A} + \nabla\phi) - j\omega\epsilon\nabla\phi) - j\omega\nabla \cdot (\epsilon\vec{A}) = 0 \\ j\omega\nabla \cdot (\epsilon\vec{A}) = 0 \end{cases} \quad (1)$$

C. Numerical Result

The self-resonant WPT having planar structure is solved using the proposed meshing technique and the above formulation. The coil has 5 turns and the mean radius of the inner most turn is $d_i=19.25$ mm and the radius of the

outermost turn is $d_o=47.75$ mm, the width of the copper trace is $w=4.5$ mm. The dielectric layer has a thickness of $h_c=0.7$ mm and the length and width dimensions are all 110mm. The complex relative permittivity of the middle dielectric layer is $\epsilon_r = 4.4 - j \cdot 0.08$. That means the loss tangent is 0.02 for all given frequencies. After performing the frequency sweeping analysis in the range of [6MHz, 7MHz], the impedance values are obtained and given in Fig. 4, where the minimal impedance value is achieved at about 6.65MHz. A prototype of the planar WPT is fabricated and the experiment is also carried out by the analyzer, where the resonant frequency is found to be 6.53MHz, which is close to the numerical one. And more numerical examples, more physical prototypes and relevant measurements will be made.

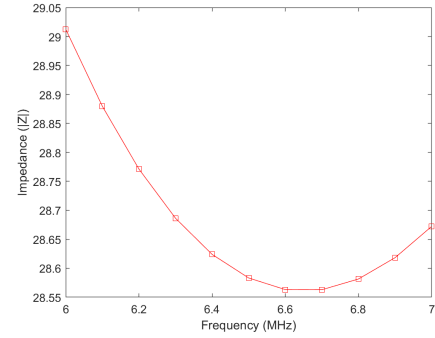


Fig. 4. Frequency sweeping analysis results for lossy dielectric material.

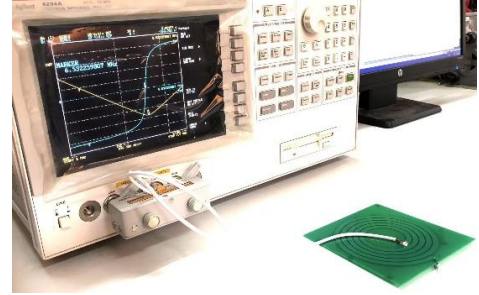


Fig. 5. The experiment for finding the resonant frequency.

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