

Numerical analysis of a simultaneous wireless information and inductive power transmission system enhanced by nonlinear metamaterial with Duffing-resonator based unit cells

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This work aims to model a wireless power transfer (WPT) system to analyze the effectiveness of nonlinear (NL) metamaterials (MMs) with Duffing-resonator (DR) based unit cells. Its purpose is to boost the inductive power transfer (IPT) in near-field (NF) simultaneous wireless information and power transmission (SWIPT) systems applied to biomedical implanted devices. Firstly, a simplified model is presented, and then numerical simulations are carried out to validate the adopted approaches. The performance of the IPT systems with both MM configurations, DR and linear, are finally analyzed with the aid of 3D numerical simulations in a biomedical application.

Index Terms—Nonlinear metamaterial, wireless power transfer, Duffing resonator, Simultaneous Wireless Information and Power Transmission

I. INTRODUCTION

IN RECENT years, the use of Metamaterials (MMs) composed of 2D-periodic arrays of resonant coils has been considered to enhance the inductive wireless power transmission (WPT) in several applications, e.g. implanted biomedical devices, which is the concern of the present work. Due to the need for high Q values to obtain the effect of a near-zero (or negative) magnetic permeability, μ , in linear-resonator (LR) MMs, with consequent limitations in bandwidth, its use in near field (NF) Simultaneous Wireless Information and Power Transmission (SWIPT) applications becomes restricted. To overcome these constraints, [1] proposes the use of MMs with nonlinear (NL), Duffing resonator (DR) based unit cells to improve the amplitude-bandwidth performance of NF-SWIPT systems, by introducing an analytical criterium for evaluating the amplitude-bandwidth enhancement, with further numerical verifications, as well as experimental validation in [2]. We try to use the proposed approach in a transcutaneous energy transfer (TET) system with a DR-MM and further evaluate both its effectiveness and side effects in humans through numerical simulations in 3D.

II. MATERIALS AND METHODS

The MM-WPT system to be studied is presented in [1], composed of a transmitter (TX), receiver (RX) and a 4×4-lattice MM, as shown in Fig. 1. It can be represented in low to medium frequencies as a set of mutually coupled RLC circuits [3].

A. Parameter calculations

Lumped parameters can be obtained as follows. Resistance: as $R = l/(\sigma A)$. Parasitic capacitances between consecutive copper traces: from conformal mapping. Mutual inductances: by simplifying copper traces as thin wires and evaluating Neumann's integral. Copper loops self-inductances: from well-established formulas for the partial inductance of a straight wire

of finite length. Thus, we can obtain the system's impedance matrix Z and solve the underlying system of equations for the currents as in [3] for the linear case.

B. Non-linear MM (DR)

A DR response is obtained with the use of two varactors connected in anti-series with each unit cell of the MM [1], as illustrated in the bottom view of Fig. 1.

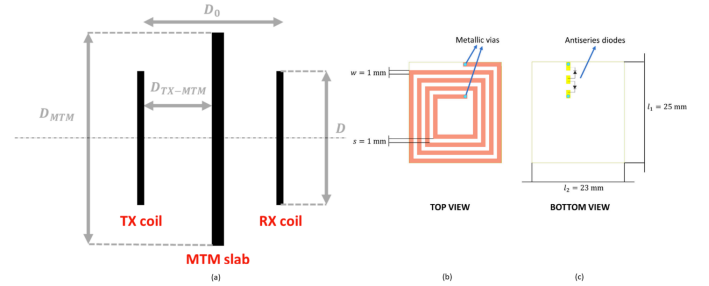


Fig. 1. (a) WPT System with NL-MM. (b) MM unit cell top view. (c) MM unit cell bottom view, showing connection of DR varactors. Adapted from [1].

The study of the NL-MM is done by means of time integration of the NL system of equations until steady state. Then, the amplitude of the response can be compared to that obtained from the linear MM transfer function (TF) to verify the increase in bandwidth gain. All tests with the simplified thin wire model are implemented in Matlab and the results are compared to a simulation by the Method of Moments (MoM) performed in the Keysight Advanced Design System (ADS) package. The enhancement in the amplitude-bandwidth limit is defined [1] as (1),

$$\delta = \frac{A_{nl}\Delta\omega_{nl}}{A_l\Delta\omega_l}, \quad (1)$$

where δ is the amplitude-bandwidth enhancement; A_{nl} , A_l are the amplitudes of the resonance peaks; $\Delta\omega_{nl}$ and $\Delta\omega_l$ are the half-power bandwidths; subscripts nl and l mean NL and linear cases, respectively.

III. RESULTS

The TF curves in Fig. 2 show the resonance hardening effect of the DF-MM, as the shift of the resonance peak to higher frequencies and resulting increase in bandwidth. The simplified model was able to describe the DR-MM behavior. The deviations in resonance frequency, when compared to the results from ADS, can be explained by the approximations in the mutual and self-inductances, since ADS considers the volumetric current distribution, rather than a simplified thin wire model. However, the increase in amplitude-bandwidth limit is approximately characterized by the simplified model, comparing it to the MoM simulations, as shown in Fig. 3.

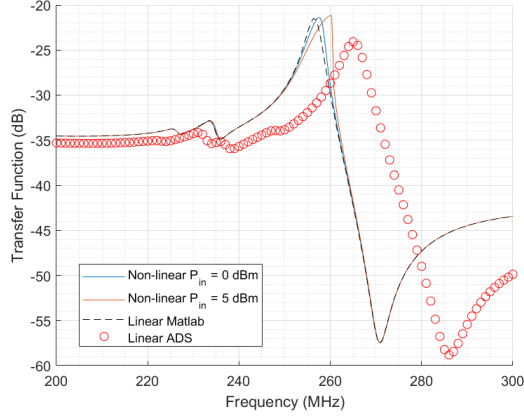


Fig. 2. Transfer function of Wireless Power Transfer system with Metamaterial. Linear MM with thin-wire approximation (dashed black line); NL-MM with thin-wire approximation (blue and red lines); Linear MM solved by MoM in Keysight ADS (red circles). P_{in} is the input power in the TX coil.

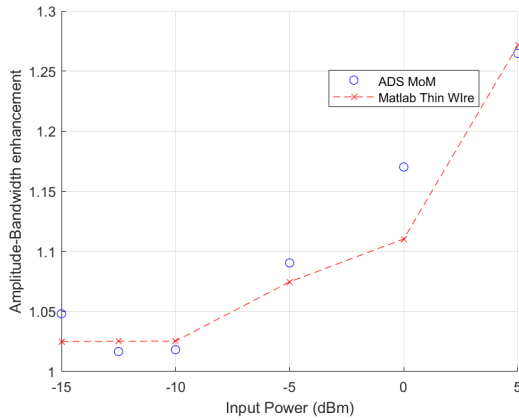


Fig. 3. Power response of amplitude-bandwidth enhancement (δ). Input Power is the power delivered by the source to the TX coil.

Finally, the use of DR-MM will be tested in a 3D finite-element model of a TET system, as shown in Fig. 4 with a linear MM. It is worth mentioning that the MM used in this case was not conceived for that particular application (biomedical device), being instead an at-hand, randomly-chosen prototype. Even though, a gain in magnetic coupling could be observed, which is in accordance with what is expected and reported in the literature, despite the several simplifications adopted in

the model to unburden the 3D-FE computational effort (MM modeled as non-meshed coils). The same modeling is under test for the configuration analyzed in [1], but the results were not yet enough complete to be presented here.

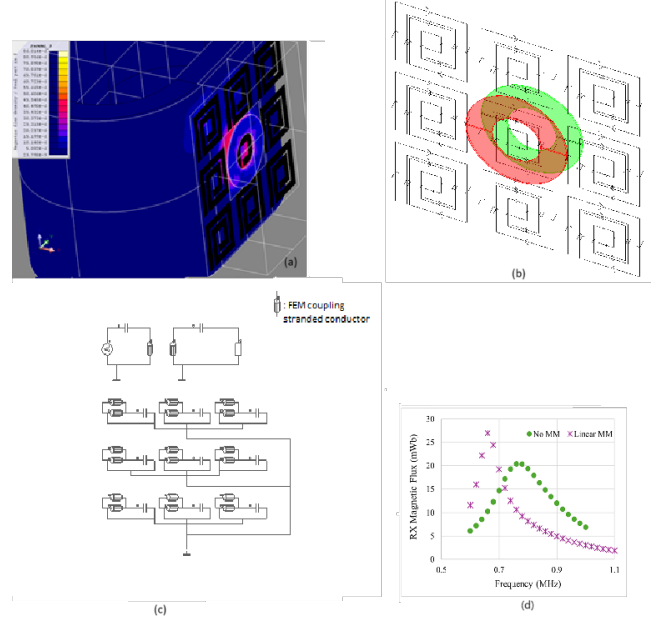


Fig. 4. (a) 3D model of a section of a human torso, a TET system and a metamaterial; color map represents flux density magnitude in the skin (Altair FLUX). (b) Detail of 3D model with TX and RX coils and MM cells. (c) Circuit model of the IPT+linear MM system. (d) Frequency response (RX magnetic flux) with and without MM.

IV. CONCLUSION

This work validated the use of a thin wire approach for studying a nonlinear resonant MM in a TET WPT system. Future objectives are to specialize the Matlab code to work with metamaterials with a great number of unit cells using the methods presented in [1], as well as incorporate a faster nonlinear system solving technique than direct time integration.

Despite its complexity, a full 3D FE model is still a valuable tool, not for being used routinely in the design of MMs, but as a validation resource, while a consolidated design standard is not yet available.

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