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Citation: AIP Advances **7**, 115316 (2017);
View online: https://doi.org/10.1063/1.5010218
View Table of Contents: http://aip.scitation.org/toc/adv/7/11
Published by the American Institute of Physics

AIP ADVANCES **7**, 115316 (2017)

Investigation of negative permeability metamaterials for wireless power transfer

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(Received 24 October 2017; accepted 21 November 2017; published online 30 November 2017)

In order to enhance the transmission efficiency of wireless power transfer (WPT), a negative permeability metamaterials (NPM) with a structure of honeycomb composed by units of hexagon-shaped spirals copper is proposed in this paper. The unit parameters of the NPM are optimized, to make sure the negative permeability at the special frequency. The S-parameters of the designed NPM are measured by a network analyzer and the permeability is extracted, it shows the honeycomb NPM has a negative permeability at 6.43 MHz. A two-coil WPT is setup and the transmission efficiency of WPT embedded with NPM at the different position and with different structure are investigated. The measured results show that the 2-slab honeycomb NPM have a good perform compared with the 1-slab NPM, and the efficiency can be increased up to 51%. The results show that honeycomb NPM embedded in the WPT help to improve the transmission efficiency remarkable.
https://doi.org/10.1063/1.5010218

I. INTRODUCTION

In recent years, Wireless power transfer (WPT) is widely used in many application, such as electric vehicles, portable electronics and implanted medical devices. Inductive coupling and magnetic resonance are the two major WPT technologies, they are suitable for short-range and mid-range, respectively. For these types of WPT, the transfer efficiency will drop dramatically as the distances between the transfer and receiver are larger than the coil diameters. To improve the efficiency, the coupling coefficient between the transfer coil and receiver coil, the quality factor of coils and the compensation network are the main aspects.[1] Metamaterials are new artificial material with unusual properties that are not found in nature, they have both/either negative electrical permittivity and/or negative magnetic permeability, which make them have an amazing physical property that go beyond what is possible with conventional materials.[2] NPM(negative permeability metamaterial) is one kind of metamaterials with negative permeability, it could manipulate the magnetic field so as to enhance coupling coefficient thereby.[3]

There are some researches about NPM using in WPT. B. Wang proposes a NPM unit of three-turn square spiral coil printed on double sides of Rogers RO4003C substrate. Compared to the WPT without NPM, the transmission efficiency is improved from 17% to 47% when using the NPM planes composed by 6×6 units.[4] As the operation frequency of Wang's NPM is high to 27.12 MHz, not easy to implement in a practical application; A. L. Ranaweera investigates a compact NPM which can operate around 6.5 MHz, the proposed NPM is realized on a thin slab using an array of three-turn circle spiral coil. With the structure of 2-slab of 5×5 units, they also achieve a remarkable efficiency improvement.[5] For the future application, the operation frequency of the WPT with NPM should be

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6.78 MHz, which is the industrial, scientific and medical (ISM) radio band. Based on this frequency, L. Wenwen and Y. Dong put forward a 4-coils WTP with 6×6 units NPM, they invested the planar array NPM with 1-slab, 2-slab, 2-dimentional and 3-dimentional structure, their results shown that the efficiency can be improved to 24%.[6,7] Joungho Kim suggest using the NPM to concentrate the magnetic fields between the transfer and receive coils, in the research, they designed and fabricated a thin NPM using a 1.6mm dual layer printed circuit board with a high dielectric constant substrate to achieve a negative relative permeability, their experiments demonstrated a 44.2% efficiency improvement.[8]

In this paper, an innovative honeycomb-like NPM is proposed. The honeycomb NPM is composed by the unit of hexagon-shaped spirals copper manufactured on FR-4 substrate. Difference from the researches above in which the unit are square-shaped or circle-shaped, the hexagon-shaped unit has a good geometry structure, it can be easily united to form a large hexagon-shaped negative permeability space, which is more suitably for the WPT application. As for the practical application, the NPM embedded in WPT should have negative permeability around 6.78 MHz, to realize it, the strip of copper is optimized and verified. Based on the NPM, a corresponding WPT is established and efficiency performance of WPT with 1-slab and 2-slab NPM are investigated.

II. NPM DESIGN AND OPTIMIZATION

The geometry structure of NPM unit proposed in this paper is shown in FIG. 1. The hexagon-shaped unit in the FIG. 1 (a) is fabricated on a substrate by the method of printed circuit board (PCB). The material of substrate is FR4 with the thickness of 0.5 mm and the outer radius of 38 mm. Two nine-turn, hexagon-shaped spiral copper are printed clockwise on the top and bottom layers, respectively, and they are connected through via in the inner ring. The thickness of the strips is 0.07 mm and the gaps between two adjacent strips are 2 mm. In this mode, the width of the spiral strips are adjustable, which will decided the negative permeability frequency of the NPM. The NPM slab is constructed with 19 unites by periodic arranging like a honeycomb, shown in FIG. 1 (b).

The model of unit shown in FIG. 1 (a) is simulated in HFSS by the waveguide method.[9] FIG. 2 (a) is the acquired s-parameter with the frequency scanning. It shows that for each of unit with different strip width there is a special frequency band where the reflection coefficient S_{11} and transmission coefficient S_{21} vary sharply, which mean that unit possesses a special physical features. FIG. 2 (b) is the retrieved effective permeability based on the S-parameter,[9,10] due to the imaginary part of permeability represents the magnetic loss, only the real part are plotted out. The FIG. 2 (b) shows that all the unit with different strip width process a negative effective permeability and the frequency of negative permeability decreases as the width increases, when the width increase from 0.2 mm to 0.8 mm, the frequency decrease form 6.78 MHz to 5.62 MHz. Thus, the

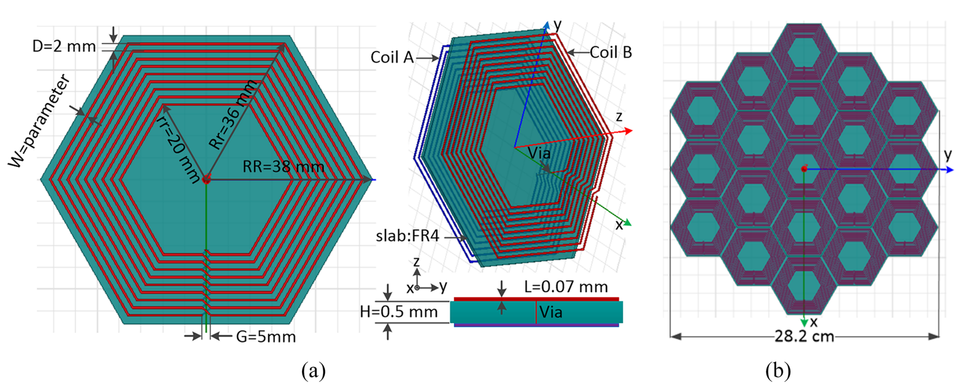

FIG. 1. (a) Geometry structure of metamaterials unit cell. (b) The honeycomb-like NPM slab composed by 19 units.

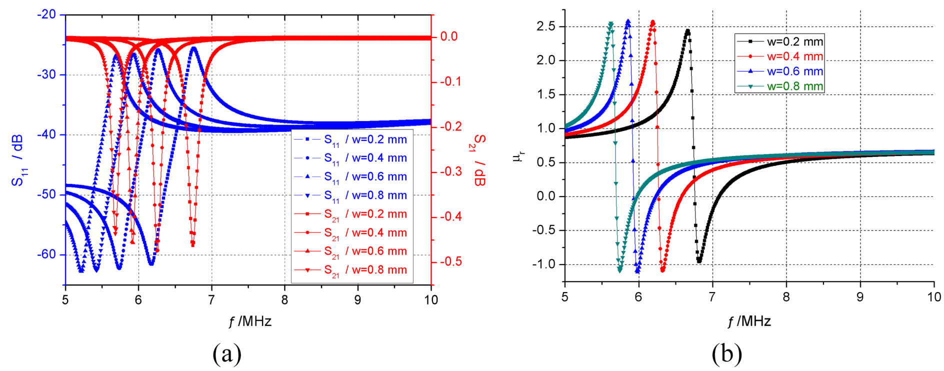

FIG. 2. (a) S-coefficients and (b) the retrieved permeability of proposed NPM cell with the W in FIG. 1 (a) changing.

frequency of negative permeability can be adjusted by the width of the spiral strips, if we want set the frequency of negative permeability at the 6.78 MHz, the width of the spiral strip should be selected to 0.20 mm.

III. SIMULATIONS

In order to verify the performance of NPM, a model of WPT system with NPM is established and simulated in HFSS. FIG. 3 is the structure of simulation, the WPT system consists a pairs of transfer coil and receiver coil, all the radius of coils are 11.5 cm and the distance between them is 30 cm, To make sure the WPT resonate, both the transfer coil and receiver coil are established with lumped parameter of L=5.51 uH and C=100 pF, they can resonate at the frequency of 6.78 MHz, which is also the negative permeability frequency of NPM. The transfer coil is driven by the lumped port, then, the distribution of magnetic field intensity of the WPT is achieved. As the WPT system with the NPM is axisymmetric, only half of magnetic distribution is displayed, shown in FIG. 4. For the comparison, four cases (without NPM, relay coil, 1-slab NPM and 2-slab NPM) are included, the 2-slab consist of two 1-slab NPM with a distance of 1.5 cm apart, both 1-slab and 2-slab are put in the middle of WPT.

Form the FIG. 4, it shows that the relay coil can enhance the magnetic field nearby the receiver coil a little bit, but to 1-slab and 2-slab NPM, the magnetic field enhancement are remarkable, which mean that NPM can increase coupling coefficient of coils and enhance the transfer efficiency, the result also shows the 2-slabs NPM have a better performance.

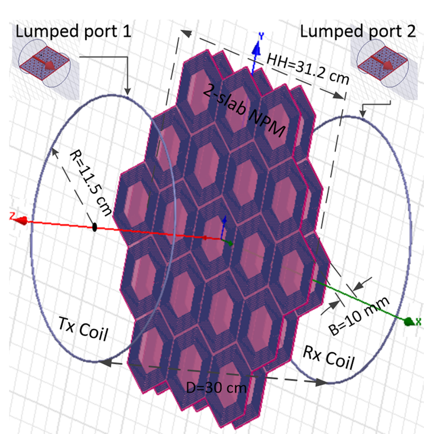

FIG. 3. Simulation structure with proposed metamaterials.

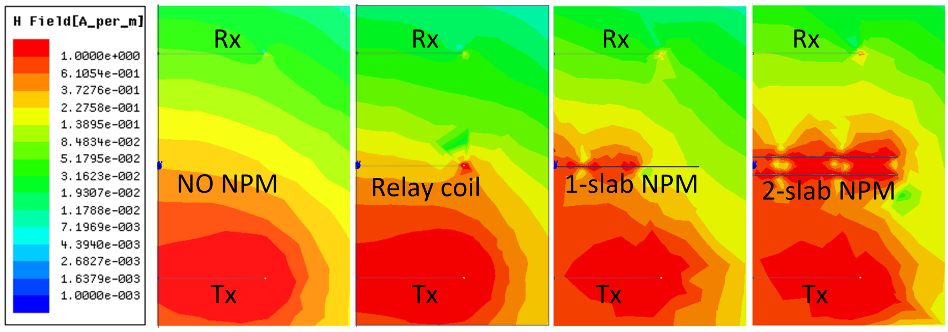

FIG. 4. Magnetic field distribution in the yoz plane of WPT system without NPM and with relay coil, 1-slab, 2-slab in the middle position of WPT system.

IV. EXPERIMENTS

To verify the simulation, a practical WPT system with the NPM is established. The NPM is fabricated absolutely as the description in section II. To the WPT system, two 7-turn coils are used to form the transfer coil and receiver coil, shown in FIG. 5. A network analyzer (KEYSIGHT: 5072A) is used to investigate the performance of the system.

First, the negative permeability frequency of the NPM is measured. To do this, the transfer coil and receiver coil are connected with exciting port and loading port of network analyzer, and the S-parameter are recorded as an incident wave with frequency sweeping from 5 MHz to 10 MHz is poured into the exciting port. Since the purpose of this step is to find the negative permeability frequency of NPM, the coils of WPT system don't need to tune by resonance capacitor. For the contradistinction, the measured S-parameter of WPT in two cases, with and without NPM in the center, are plotted out in the FIG. 6.

As the WPT system with or without NPM can all be simplified as 2-port system, the theory of 2-port system can be used to analyze its feature. For the 2-port system, S_{11} represents the reflection coefficient of the exciting port and S_{21} represents the transmission coefficient from exciting port to loading port. In FIG. 6, for the WPT without NPM, the S_{11} is smooth and the S_{21} decrease a little as the frequency increase, while for the WPT with 1-slab NPM, S_{11} and S_{21} vary dramatically at 6.43 MHz: S_{11} decreases form 0.025 dB to -0.077 dB and the S_{21} increases form -57 dB to -42 dB. This means the WPT with NPM transfers more power from source to load. These results also indicate the negative permeability frequency of 1-slab NPM is 6.43 MHz. The same experiments also carry out on 2-slabs NPM, the result shows its negative permeability frequency is 6.36 MHz. Even there are some disparity compared with the simulation, the experiments are basically

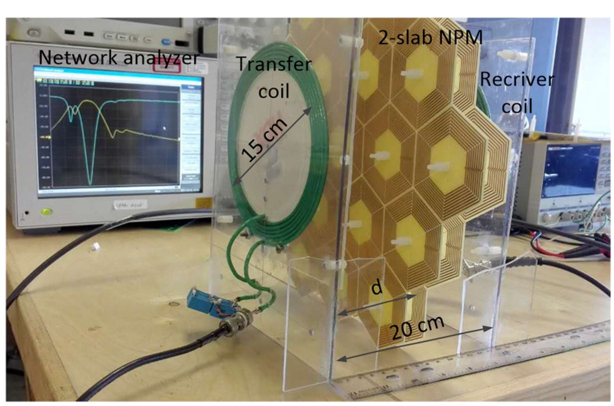

FIG. 5. Experimental setup for WPT system.

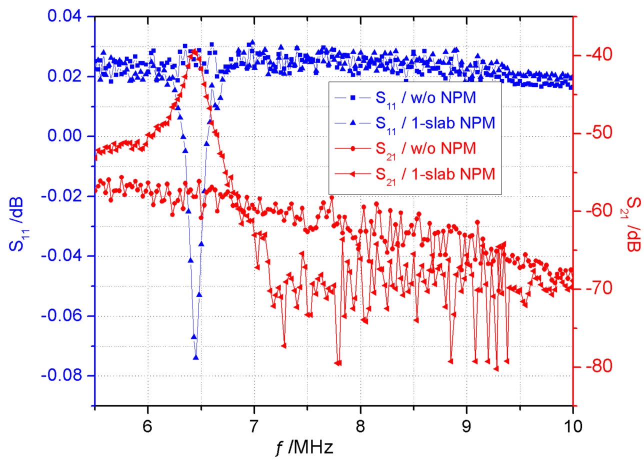

FIG. 6. Measured S-Coefficients of WPT system without NPM and with 1-slab NPM.

consistent with date in FIG. 4, The NPM presentation negative permeability at the assignation frequency.

Second, power transfer experiments with NPM in a resonant WPT system are carried out. In order to tune the WTP system, the transfer and receive coils are connected with capacitors in series and the capacitors are selected carefully to make two coils resonate at 6.4 MHz, which is also the NPM working frequency.

FIG. 7 is S-parameter curve with the frequency scanning on three cases: without NPM, with 1-slab NPM and 2-slab NPM. For the cases with NPM, they are place in the center position of transfer coil and receiver coil. Due to the S_{21} reflects the transmission power, form FIG. 7, it shows that both 1-slab and 2-slab can increase the power remarkable. For the 1-slab NPM, S_{21} increase from -4.56 dB to -2.10 dB, and for the 2-slab NPM, S_{21} increase to -1.39 dB.

FIG. 8 is transfer efficiency of WPT system when 1-slab and 2-slab NPM are placed at different position. Based on the 2-port system theory, transfer efficiency can be calculated by the formula (1):[11]

$$\eta = \frac{|s_{21}|^2}{1 - |s_{11}|^2} \tag{1}$$

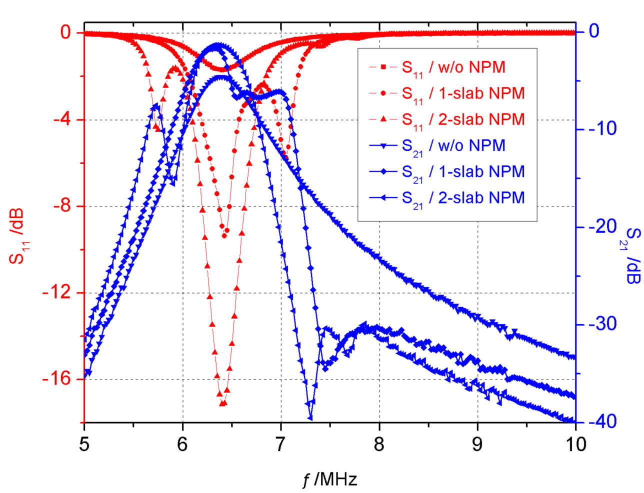

FIG. 7. Measured S-Coefficients of WPT system without NPM and with 1-slab, 2-slab NPM as the WPT system resonate at 6.4 MHz.

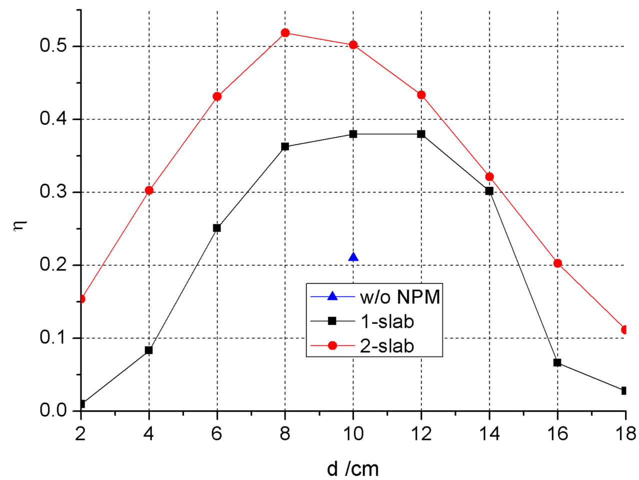

FIG. 8. Measured efficiency as a function of the NPM position in the WPT system.

FIG. 8 shows that both the 1-slab and 2-slab can increase the transfer efficiency at most position and the center position is the optimal position, when they are put in the center, they can increase the efficiency form 21% to 38% and 51%, respectively. But when they are put too close to the transfer or receiver coil, the transmission efficiency will decrease, this may be the too close position detune the system.

V. CONCLUSIONS

In this paper, a honeycomb-like NPM are designed and investigated. The NPM is composed by multiple units of hexagon-shaped spirals copper, through the unit parameter tuning, the NPM have the negative permeability at the specified frequency. The transfer efficiency of two kinds of NPM at the different position of WPT are investigated and compared. The result show the 2-slab NPM have a good performance and the efficiency can be increased to 51% when they are placed at the center of WPT. As the fabricated NPM slab in this work have the negative permeability at 6.4 MHz, the comprehensive parameter need further investigation, a WPT system with the NPM having the negative permeability at 6.78 MHz is expected to be presented in the future.

ACKNOWLEDGMENTS

The authors would like to acknowledge the funding support from the China Scholarship Council (CSC), the Doctoral Scientific Research Foundation of Xi'an University of Technology.

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