Design and Analysis of Resonator for Wireless Power Transmission System Based on Resonant Coupling

Zhuo Yan[1], Chao Zhang[1], Haiyan Chen[1] , Yongjian Li[1],Qingxin Yang[2], Yang Li[2]
1 Hebei University of Technology, Tianjin, 300130
2 Tianjin Polytechnic University, Tianjin, 300160

Abstract—This paper mainly studies on the resonant frequency and its influence factor on the resonator for wireless power transmission based on resonant coupling（WPTRC）. Using coupling mode theory, the mode conversion and work efficiency, loss efficiency are analyzed. A cubic film resonator is designed and the influence of thickness, length, strip width, gap between strips of outer conductor layer and length of inner conductor layer on resonant frequency are analyzed by simulation. The influence of inner conductor layer on resonant frequency is verified through experiment. The average difference between simulation and experiment is within 5%. The system efficiency is measured with different length of inner copper sheet and can reach 40% at a distance of 15 cm.

I. INTRODUCTION

Wireless power transmission has always been a dream of human beings. After Nikola Tesla proposed the theory and conducted a preliminary experiment as early as 1897, serious interest and effort was devoted to this field [1-2]. WPTRC is based on the well known principle of resonant coupling that two same-frequency resonant objects tend to exchange energy efficiently, while interacting weakly with other off-resonant environmental objects [3-4].

Though the resonant coupling between transmitter and receiver is decayed following with the increase of distance between the two resonators, theoretically, the energy not been absorbed will return to the transmitter and has little influence on efficiency. As the resonant wavelength is far greater than the resonator size, not only objects in the vicinity have limited impact on it, but also organisms are relatively safe because of interaction between magnetic field and organisms is weak[5-6].The structure of WPTRC system is shown in Fig.1.

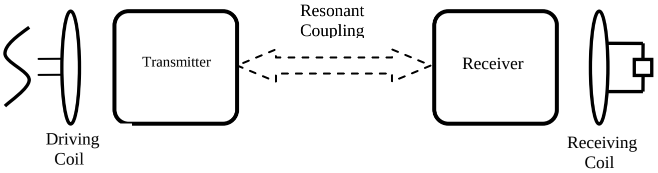

Fig.1 The Structure of WPTRC System

Due to far transmission distance, high efficiency and stability, WPTRC has a variety of possible applications such as cell phones, implantable devices (VNS, DBS) [7], artificial heart, electric vehicles, household robot[8], laptop computers and so on.

II. THERETICAL ANALYSIS OF WPTRC

Based on coupling mode theory, the variable $a_{\mathrm{S}}(t)$ and $a_{\mathrm{D}}(t)$ are defined so that the energy contained in transmitter and receiver is $|a_{\mathrm{S}}(t)|^2$ and $|a_{\mathrm{D}}(t)|^2$ respectively.

$$a_S(t) = A\exp(-i\omega t - \frac{\Gamma_S+\Gamma_D}{2}t)\begin{bmatrix} \cos\left(\frac{t}{2}\sqrt{4k^2 - i(\Gamma_D-\Gamma_S)^2}\right) + \frac{\Gamma_D-\Gamma_S}{\sqrt{4k^2-i(\Gamma_D-\Gamma_S)^2}} \\ \sin\left(\frac{t}{2}\sqrt{4k^2-i(\Gamma_D-\Gamma_S)^2}\right) \end{bmatrix} \quad (1)$$

$$a_D(t) = A\exp(-i\omega t - \frac{\Gamma_S+\Gamma_D}{2}t)\begin{bmatrix} \frac{i2k}{\sqrt{4k^2-i(\Gamma_D-\Gamma_S)^2}} \times \\ \sin\left(\frac{t}{2}\sqrt{4k^2-i(\Gamma_D-\Gamma_S)^2}\right) \end{bmatrix} \quad (2)$$

To define the coupling intensity：

$$\gamma = \frac{k}{\sqrt{\Gamma_s\Gamma_d}} \quad (3)$$

From the three formulas above, the distance-dependent ratio γ is the key to efficient power transmission for mid-range distance. The desired regime of strong coupling is satisfied when $\gamma >> 1$, in other words, the coupling rate k is much higher than the loss rate $\Gamma_{s,d}$.

The work efficiency and the loss efficiency of WPTRC system can be calculated by equation (4) and (5). The variation curves are shown in Fig.2 and Fig.3.

$$\eta_w(x,\gamma) = \frac{\gamma^2 x}{\gamma^2(1+x)+(1+x)^2} \quad (4)$$

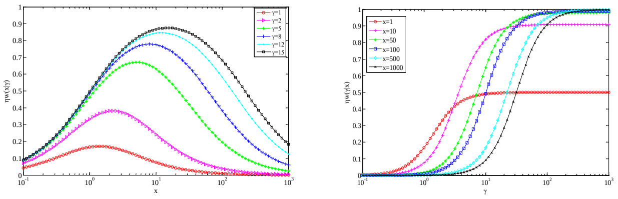

Fig.2 Work efficiency as the function of x and γ

$$\eta_l(x,\gamma) = \frac{P_l}{P_{total}} = \frac{\gamma^2+(1+x)^2}{\gamma^2(1+x)+(1+x)^2} = \frac{\gamma^2+(1+x)^2}{\gamma^2(1+x)+(1+x)^2} \quad (5)$$

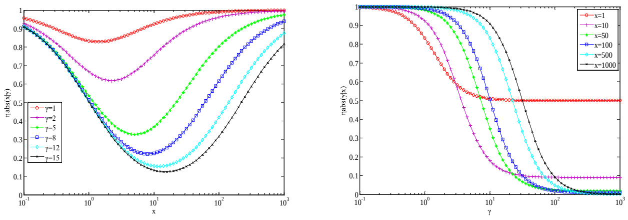

Fig.3 Loss efficiency as the function of x and γ

III. SIMULATION AND EXPERIMENT ANALYSIS OF WPTRC

As shown in Fig.4, a novel Cubic film resonator for WPTRC is designed and simulated, and the experimental prototype is built in the laboratory. The resonator is consisted with three layers, which from outside to inside are outer conductor layer (copper), medium layer (Polyethylene) and inner conductor layer (copper).

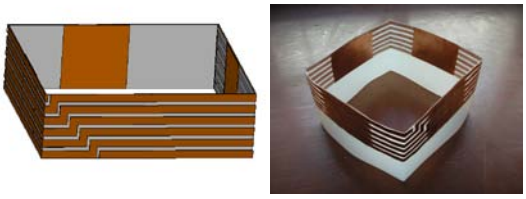

Fig. 4 Simulation and experiment model of cubic film resonator

The influence of the thickness, length, strip width, gap between strips of outer conductor layer on resonant frequency is analyzed using finite element simulation. As shown in Fig.5, Fig. 6, Fig.7 and Fig.8. The length and the strip width have obvious influence on resonant frequency, while the thickness and the gap between strips of outer conductor layer have little influence on resonant frequency due to skin effect.

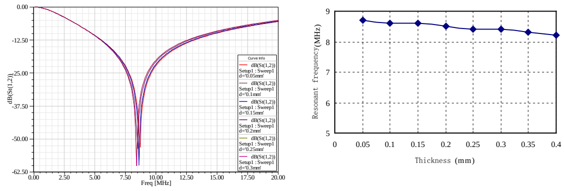

Fig. 5 Resonant frequency as a function of thickness of outer cooper sheet

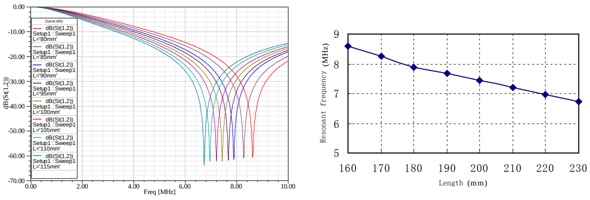

Fig. 6 Resonant frequency as a function of the length of outer cooper sheet

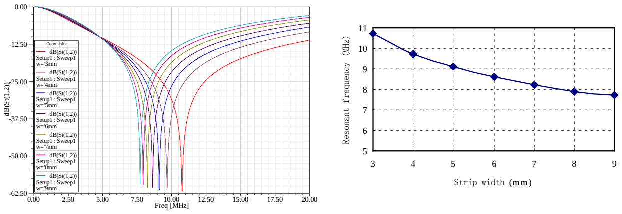

Fig. 7 Resonant frequency as a function of the strip width of outer cooper sheet

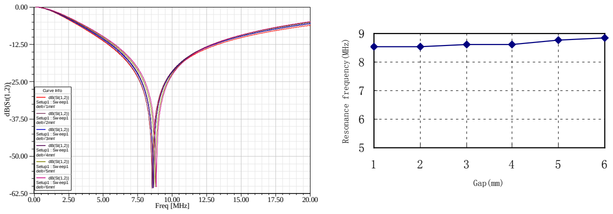

Fig. 8 Resonant frequency as a function of gap between strips of outer layer

The influence of the length of inner copper sheet on resonant frequency is analyzed by both simulation and experiment. The average difference between simulation and experiment result is within 5%, as shown in Fig.9.

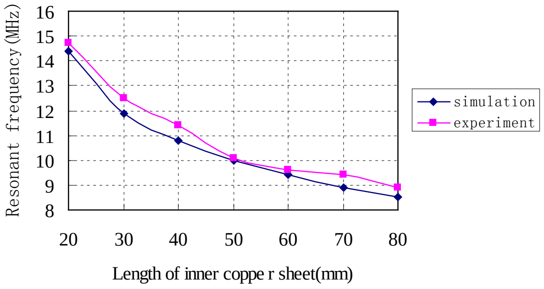

Fig. 9 Resonant frequency as a function of different length of inner copper sheet

In the experiment, the source is a function generator, and a power amplifier that outputs sine wave to the driving coil. A 250Ω resistor is used as a load and the power it consumed is calculated based on the measured voltage across the resistor. A second 20 Ω resistor is connected in series with the source to measure the power supplied. By measuring the voltage across the 20 Ω resistor, the source current and therefore the power supplied are obtained. The work efficiency of different length of inner copper sheet (20mm, 50mm, 80mm) is measured. The efficiency at a distance of 15cm between the two resonators can reach 40% using WPTRC.

IV. REFERENCES

[1] Ma Guanying , Yan Guozheng . Research on wireless power transmission for gastrointestinal microsystems based on inductive coupling[J]. Journal of Biomedical Engineering, 2008, 25(1) : 61-64

[2] Fredy S Q, Jesús G C, Jordi S, et al. Wireless power of single-chip systems with integrated coil and external wire-loop resonator[J]. Applied Physics Letters, 2008, 92(7) : 074102 (1-3).

[3] Soljačić M, Kurs A, Karalis A, et al. Wireless power transfer via strongly coupled magnetic resonances[J]. Sciencexpress, 2007, 112(6) : 1-10.

[4] Aristeidis Karalis, J. D. Joannopoulos, and Marin Soljacic. Wireless Non-Radiative Energy Transfer. The AIP Industrial Physics Forum, 2006.11.

[5] Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless power transfer via strongly coupled magnetic resonances," Science, July 2007, 317:83-86.

[6] Karalis; J. D. Joannopoulos, and M. Soljacic, "Efficient wireless non-radiative mid-range energy transfer," Annals of Physics, Jan. 2008, 323:34-48.

[7] Fei Zhang, Xiaoyu Liu, Steve Hackworth,Robert Sclabassi, Mingui Sun, "InVitro and In Vivo Studies on Wireless Powering of Medical Sensor and Implantable Devices", IEEE/NIH 2009 Life Science Systems and Applications Workshop.

[8] W. Stewart, "The Power to Set You Free ", Science, Vol.317, No. 5834, pp. 55-56, Jul. 2007.