A Method of Focusing for Wireless Powering to In-Body Medical Device by Using Fresnel Zone Plate

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Abstract In this report, we proposed a Wireless Power Transfer (WPT) method for human body with Fresnel Zone Plate (FZP) and a quarter-wavelength matching layer (ML). The quarter-wavelength matching layer (ML) is placed in front of HBEL tank to reduce the surface reflection of Human Body Equivalent Liquid (HBEL). The FZP, placed between matching layer and HBEL, operating at 500 MHz. The focus point is designed as 50 mm far from the surface of HBEL, which simulate the implant situation of biomedical devices such as heart pacemaker. It can be seen that the electric field gets a high density region at about 50 mm by using the proposed WPT method, and the electric field has 11.6 dB improvement compared with transfer power directly case. S parameter and transmission factor τ have also been calculated. The results show that the proposed method can significantly increase the power at designing point, which means this method is a good candidate for human body WPT application.

Keyword Fresnel Zone Plate (FZP), Matching Layer (ML), Wireless Power Transfer (WPT)

1. Introduction

In recent years, various types of electronic apparatus have been implanted in human body for medical sensing, medicine delivery, and local stimulation. These devices help manage a broad range of medical disorders through preventive and post surgery monitoring. In order to avoid the risks associated with the battery exhausting and replacing, and to reduce the size of the medical device, the wireless delivery of energy has been proposed as a key technology for application of those devices [1].The traditional way for wireless power transfer (WPT), including electromagnetic (EM) coupling [2]-[5] and magnetic resonance coupling [6]-[9], is based on the EM near-field coupling with relatively low operation frequencies (several megahertz, for example) and share of the magnetic flux between the transmitting and receiving terminals. Konno et al. [10] improved the coupling coefficient by redesigning and adjusting the inner radius of the spiral coil. Miwa et al. [11] improved the transmission efficiency by using the coil array. However, the large size of the implanted coil and the rigid requirement of the alignment may still pose severe challenges to the technology of the near-field coupling.

The technique of WPT to human body is facing a lot of challenges. Firstly, with high wave impedance of human body, a large proportion of the EM power will be reflected at the surface between air and human body at the moment when EM wave connect to human body. Secondly, as the wireless propagation media, the human body can be regarded as a lossy material with very high conductivity, which means EM power will attenuate rapidly inside human body. Thus the WPT efficiency is low when transfer power into human body directly.

Recently, the WPT techniques with operation frequency from several MHz to sub- GHz have been drawing attention due to their much higher transfer efficiency than that of conventional near-field coupling [12]-[14]. This kind of WPT techniques, including EM radiation, multipath propagation, and receiving, may be interpreted as an interference-based WPT.

In this paper, we proposed a WPT method for human body with Fresnel Zone Plate (FZP) and a quarter-wavelength matching layer (ML). The proposed model along with two contrast models are designed and analyzed in commercial software. The simulation results show that the proposed method can significantly increase the received power, validating the feasibility and validity of our design.

2. Design Progress

2.1. Fresnel Zone Plate (FZP)

Fresnel Zone Plate (FZP) consists of a set of radially symmetric rings, known as Fresnel zones, which alternate between opaque and transparent [15]. The wave hitting the zone plate will diffract around the opaque zones. The zones can be spaced so that the diffracted wave constructively interferes at the desired focus, creating high field density there.

The fundamental structure of FZP is shown in Fig. 1, and r_m can be calculated using equation:

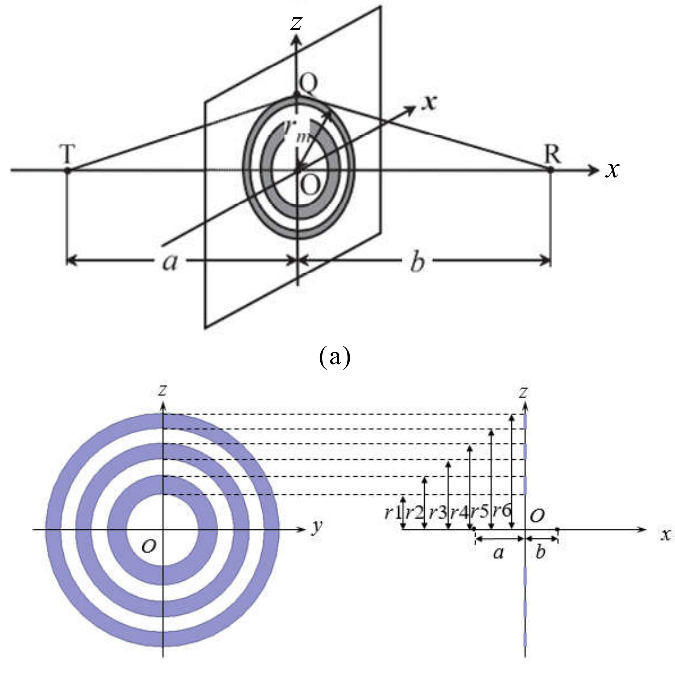

Fig. 1 Structure of FZP. (a) Fundamental structure, (b) Structure of proposed FZP

TABLE I

PARAMETER OF PROPOSED FRESNEL ZONE PLATE

Parameter	Value	Parameter	Value
a	100 mm	*r2*	112 mm
b	50 mm	*r3*	150 mm
ε_{r1}	1	*r4*	187 mm
ε_{r2}	57.15	*r5*	223 mm
r1	70.8 mm	*r6*	259 mm

$$\sqrt{a^2+r_m{}^2}+\sqrt{b^2+r_m{}^2}-(a+b)=\frac{m\lambda_0}{2} \qquad (1)$$

In this study, the permittivity of left half region is ε_{r1} and right half region is filled with HBEL which permittivity is ε_{r2}, so the equation to calculate r_m is amended to:

$$\frac{\sqrt{a^2+r_m{}^2}}{\sqrt{\varepsilon_{r1}}}+\frac{\sqrt{b^2+r_m{}^2}}{\sqrt{\varepsilon_{r2}}}-\left(\frac{a}{\sqrt{\varepsilon_{r1}}}+\frac{b}{\sqrt{\varepsilon_{r2}}}\right)=\frac{m\lambda_0}{2} \qquad (2)$$

Fig. 1(b) shows the proposed structure of FZP, and detailed information of FZP is given in Table I as below.

2.2. MATCHING LAYER (ML)

Matching layer is a basic concept in electromagnetics [16]. When an electromagnetic wave propagates from one medium into another medium, reflection occurs when the characteristic impedances of the two media do not match. To suppress the reflection, a matching layer is designed and inserted in. between. A conventional matching layer is known as the quarter-wavelength impedance transformer, and for non-magnetic media its permittivity must satisfy the follow relation:

$$\varepsilon_{r3}=\sqrt{\varepsilon_{r1}\varepsilon_{r2}} \qquad (3)$$

where ε_{r1} and ε_{r2} are permittivities of the original two media. It is noted that ε_{r3} of 7.56 is calculated from this equation.

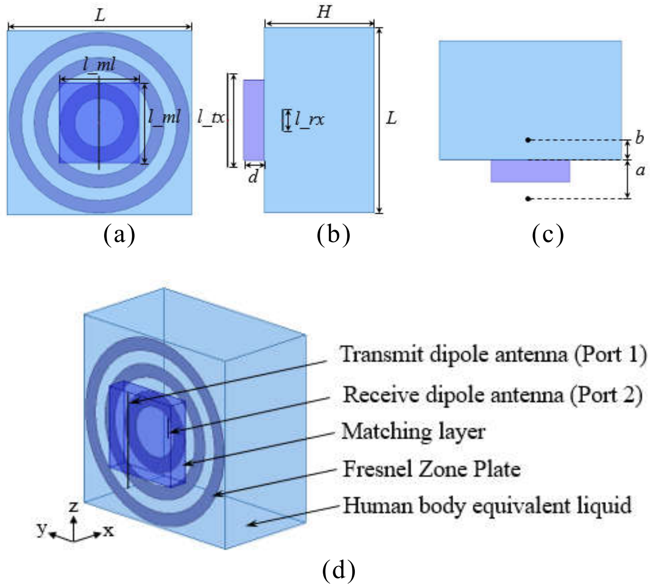

Fig. 2 Structure of proposed model. (a) Front view, (b) Side view, (c) Top view and (d) Diametric view

TABLE II

PARAMETER OF PROPOSED MODEL

Parameter	Value[mm]	Parameter	Value[mm]
L	530	*d*	55.45
H	300	*l_ml*	230
a	100	*l_tx*	265
b	50	*l_rx*	57

3. MODEL STRUCTURE

Fig. 2 shows the structure of the proposed WPT model which contains six parts: transmit dipole antenna (Port 1), receive dipole antenna (Port 2), matching layer (ML), Fresnel Zone Plate (FZP) and Human Body Equivalent Liquid (HBEL). The detailed dimension of proposed model is given in Table II.

The human body is modelled as a tank filled with Human Body Equivalent Liquid (HBEL), the total volume of tank is 530×530×300 mm^3. The quarter-wavelength matching layer is placed in front of HBEL tank to reduce the surface reflection of HBEL. The FZP, placed between matching layer and HBEL, operating at 500 MHz. The focus point is designed as 50 mm far from the surface of HBEL,

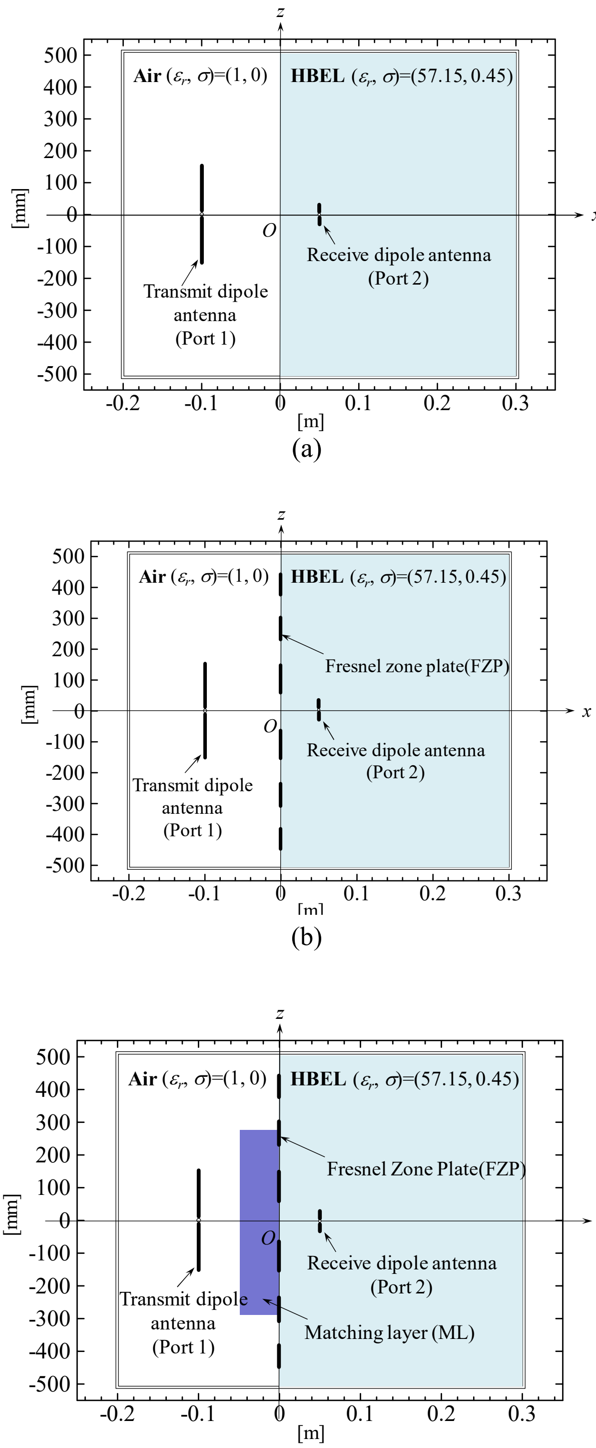

Fig. 3 Analysis model. (a) Model 1, (b) Model 2, (c) Proposed model

which simulates the implant situation of biomedical devices. The transmit antenna is placed 100 mm far from the FZP on left side.

4. Simulation and Discussion

Fig. 3 shows three models analyzed in this study: model 1, model 2 and proposed model. Model 1 is the case when proposed model removes FZP and ML. Model 2 is the case when proposed model removes ML. In other words, model 1 only contains transmit and receive antenna and model 2 contains one more FZP. All models are analyzed by using commercial software Speag SEMCAD X.

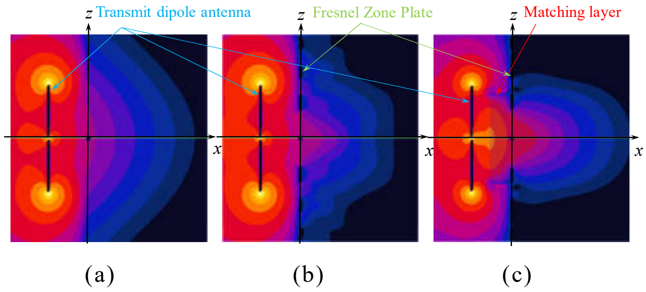

Fig. 4 Simulated electric field $|E_z|$ distribution of xz plane. (a) Model 1, (b) Model 2, (c) Proposed model

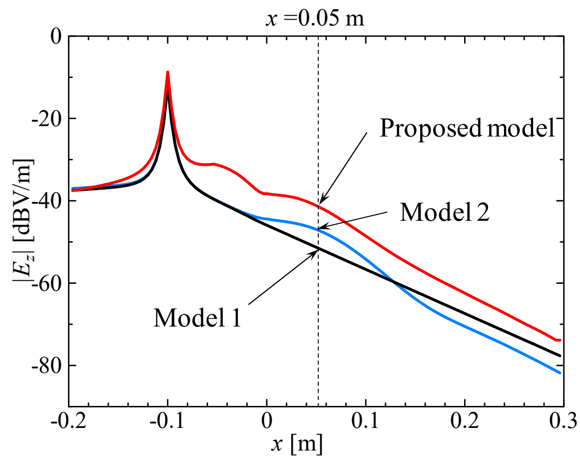

Fig. 5 Simulated electric field |Ez| along optical axis x

4.1. Electric Field Distribution

Fig. 4 shows the simulated electric field $|E_z|$ (z component of total electric field) distribution in xz plane of three models. It's note that the receive antenna is ignored in this simulation. It can be seen that electric field attenuates significantly in all cases due to the loss of HBEL, and the electric field in desirable region can be increased by FZP and ML.

The curve of electric field $|E_z|$ along the x-axis is given in Fig. 5, in this calculation, the input power and $|E_z|$ are normalized by 1W and 3655.85V/m, respectively. It can be seen that the electric field attenuates quickly in model 1. However, there appears a relative strong electric field region around x = 50 mm in model 2, which demonstrate that the FZP can increase the transfer power in HBEL. Moreover, the electric field can be increased further

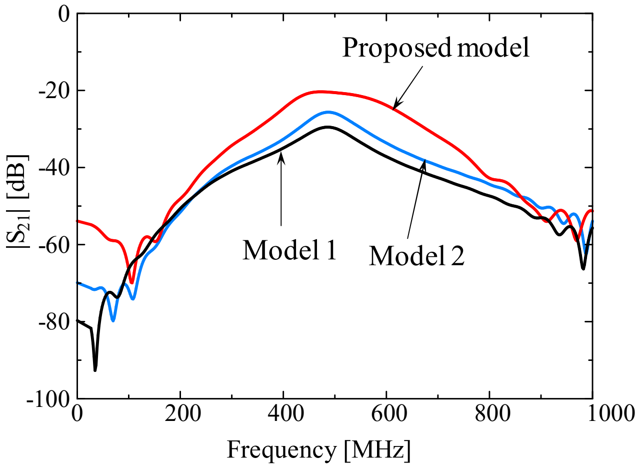

Fig. 6 Comparison of S-parameter of three WPT model

by utilizing FZP and ML simultaneously. Compared with model 1, a great increment (total 11.1 dB) of $|E_z|$ value can be obtained by using designed FZP and ML in proposed model.

4.2. S Parameter

In this part, the receive antenna is placed at designed focus point in HBEL which is 50 mm far from the surface and the S parameter has been calculated.

Fig. 6 shows the curve of S_{21} magnitude versus frequency. It can be seen that the $|S_{21}|$ increases with frequency first and then decreases and the maximum value occurs at about 500 MHz which is designed operating frequency in all three models. The maximum value of three curves are -29.8 dB, -25.9 dB and -20.6dB, respectively. Moreover, it can be found that an increment of 4.1 dB can be obtained by using FZP and an increment of 5.3 dB can be obtained by using ML when comparing the results above. A huge increment of total 9.2 dB can be achieved by utilizing FZP and ML simultaneously, which verifies the designed WPT method.

4.3. Transmission Factor τ

Two-port network equivalent circuit is shown in Figure 7 [17]. Transmitting antenna is connected to a source with an internal impedance of Z_S, while receiving antenna is loaded with an internal impedance of Z_L. P_L is the power delivered to the load Z_L, P_{in} is the input power, P_{inc} is the incident power, Γ_S and Γ_L are the reflection coefficients looking toward the source Z_S and the load Z_L, respectively, and Γ_{in} and Γ_{out} are the reflection

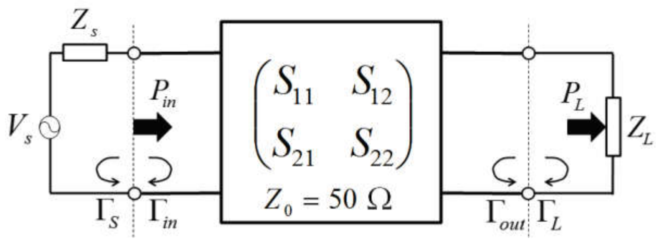

Fig. 7 Two-port equivalent circuit

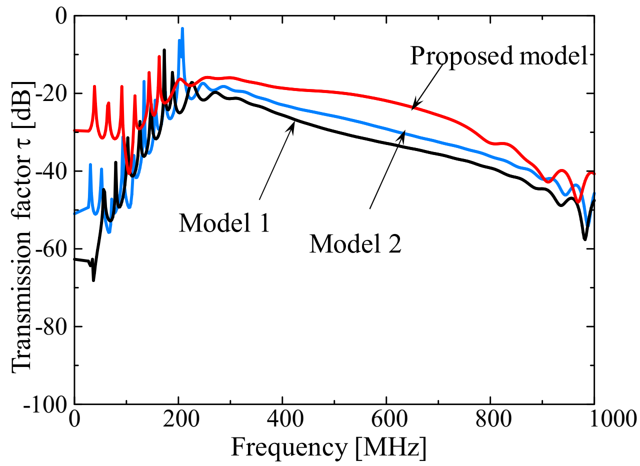

Fig. 8 Calculated τ curve vs frequency of three WPT mode

coefficients looking toward Port 1 and Port 2. In this equivalent circuit, there is a relation as

$$\frac{P_L}{P_{inc}} = \frac{1-|\Gamma_S|^2}{|1-\Gamma_S\Gamma_{in}|^2}|S_{21}|^2\frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_{in}|^2} \tag{4}$$

Where

$$\Gamma_S = \frac{Z_S - Z_0}{Z_S + Z_0}, \Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{5}$$

$$\Gamma_{in} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L}$$
$$\Gamma_{out} = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1-S_{11}\Gamma_S} \tag{6}$$

If antennas are perfectly matched to the loads with the complex- conjugate impedances at both Port 1 and Port 2 as

$$Z_S = Z_{in}^*, Z_L = Z_{out}^* \tag{7}$$

and the transmission factor τ is defined by using S parameters of the circuit as

$$\tau = \left.\frac{P_L}{P_{inc}}\right|_{Z_S=Z_{in}^*, Z_L=Z_{out}^*} = \frac{P_L}{P_{in}} = \frac{1^2}{|1-\Gamma_S|^2}|S_{21}|^2 \frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_{in}|^2} \quad (8)$$

The calculation of transmission factor τ of three models are shown Fig. 8. It can be seen that the τ increases with frequency first and then decreases and the maximum value occurs at about 200 MHz. The τ value at 500 MHz of three curves are -29.8 dB, -25.9 dB and -19.7dB, respectively. Just like the discussion of S parameter, it can be found that an increment of 4.1 dB can be obtained by using FZP and an increment of 6.2 dB can be obtained by using ML when comparing the results above. A great improvement of total 10.3 dB can be obtained by utilizing FZP and ML simultaneously.

5. Conclusion

In this paper, we proposed a new WPT method to enhance the transfer power by using Fresnel Zone Plate (FZP) and quarter-wavelength matching layer (ML). Three models (model 1,2 and proposed) has been calculated by simulation software, and the results shows that the proposed model gets an excellent performance. The electric field distribution shows that electric field gets a high density region which is about 50 mm far from surface of HBEL which is designed focus point. The S parameter results shows that a huge increment of total 9.2 dB can be achieved by using proposed WPT method compared with transfer power directly. The transmission factor τ has also been introduced to evaluate the relative maximum received power under complex-conjugate matching conditions. The calculation results show that proposed WPT method can increase transmission factor τ by 10.3 dB, which means 50% increment compared with transfer power directly. The simulation results and comparison with other 2 models demonstrate that the proposed model is a good candidate for human body WPT application.

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