Midfield Wireless Powering: A Brief Computational Tutorial

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March 27, 2015

1 Introduction

Midfield powering is a method for wirelessly transferring power to highly miniaturized electronic devices implanted deep in the body. It relies on the controlled interaction between biological tissue and the evanescent field of a nearby electromagnetic structure to produce a focused spot deep in tissue. The method is suitable for powering millimeter-scale structures across several centimeters of tissue and can in some applications enable miniaturization to scales not possible with conventional powering methods. In typical configurations (e.g. a 2-mm device implanted 5 cm from the surface), the transfer efficiencies obtained by midfield powering are of the order 10^{-3} to 10^{-4}, making the method best suited for tiny, low-power devices with power consumption in the milliwatt to microwatt range for which the output power can be less than 1 W (a cell phone, by comparison, radiates ∼500 mW).

The basics of the method can be illustrated through computational electromagnetics software. This tutorial illustrates midfield powering with the patterned metal plate described in Ref. [1] and [2] in a simplified tissue half-space. The software package used in this tutorial is *CST Microwave Studio.* All necessary design files are provided online:

- `Structure.sat`: 3D model file of the metal plate, including the substrate and input coaxial cables.
- `TissueProperties`: Folder containing data files of the dielectric permittivity in the frequency range 100 MHz to 3 GHz. The columns in each data file

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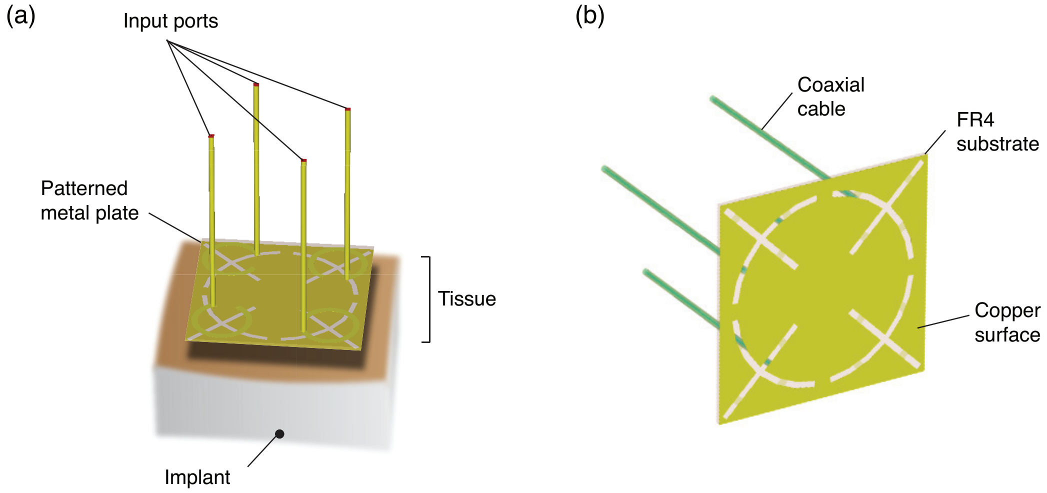

Figure 1: Source structure. (a) Wireless power source consisting of a patterned metal plate (dimensions 6 cm× 6 cm) excited by four coaxial cables. (b) Slot patterns in the metal plot. The substrate appears transparent in this illustration.

are frequency (in gigahertz), real part of the relative dielectric permittivity ϵ_r', and imaginary part of the relative dielectric permittivity ϵ_r''.

2 Patterned Metal Plate

This tutorial considers the patterned metal plate structure in Fig. 1. The plate is designed to generate surface currents along circular paths whose relative phases can be configured based on the phase of the excitation signal at four locations on the plate. In the computational model, the input signal is fed along four coaxial cables at a height sufficiently removed from the surface to suppress potential excitation artifacts. The structure can be imported directly into the computational solver through the file `Structure.sat`. The metal is then assigned the conductivity of copper ($\sigma = 5.8 \times 10^7$ S/m) and the substrate the properties of FR4 ($\epsilon_r = 4.3$).

Below the structure, we consider a half-space with the dielectric properties of muscle tissue 1 cm below the surface of the plate. The rectangular slab is assigned material properties using the real and imaginary parts of the relative dielectric permittivity ϵ_r in the folder `TissueProperties`. The simulation software interpolates the values as needed. The values are based on the ColeCole model of dispersion in Ref. [3]. Fig. 2 shows an example where the plate is used to focus the field at a distance of 5 cm from the surface of the plate (1 cm air gap and 4 cm tissue).

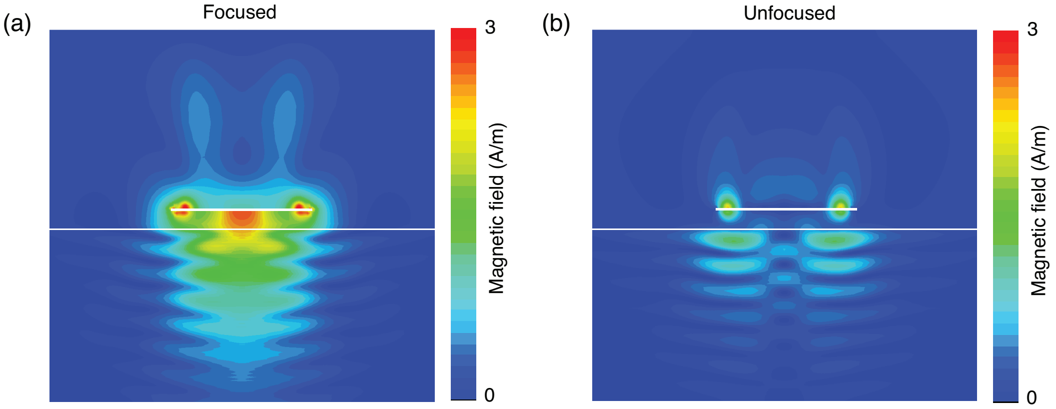

Figure 2: Focusing with the patterned metal plate. (a) Time snapshot of the magnetic field amplitude for phase assignment $\phi_1 = 0°, \phi_2 = 80°, \phi_3 = -100°$, and $\phi_4 = 180°$. The field is focused at a distance of 5 cm from the plate. (b) Time snapshot of the magnetic field amplitude for phase assignment $\phi_1 = \phi_2 = \phi_3 = \phi_4$. The field is not focused for this phase assignment.

In the simulation, each input port is independently excited with a time harmonic signal at frequency 1.6 GHz. In this particular example, the coaxial cables are excited by defining a cylindrical waveguide port over the outer conductive shell. The electric and magnetic fields generated from each excitation can then be superimposed with the specified amplitude and phase at each port in order to compute the total field.

3 Focusing

The phase conjugate method is the simplest way to focus the field. In this method, the phases of the field $\phi_1, \ldots, \phi_4$ at the focal point are recorded for each excitation signal. The phase assignment $-\phi_1, \ldots, -\phi_4$ is then made at the respective ports to force the fields to add coherently at the recorded point. For a time-harmonic field, this is equivalent to time-reversal of the input signal. Although this method does not account for coupling with the receive structure, the method is nearly optimal in the weak coupling regime considered here. In practice, focusing can be implemented either by receiving feedback from the implant (e.g. received power measurement) or by using the phase assignments obtained from simulation.

Because the field is propagating in tissue, the focused field component is generally transverse to normal of the surface. If the plate is taken to be on the $z = 0$ plane, one would record the field component H_x^n, for example, at a focal point on the plane $z = 5$ cm for each input $n = 1, \ldots 4$. Focusing would then maximize power transfer to a coil that generates a magnetic dipole moment in the x direction. This orientation is notably different from near-field power transfer, which occurs through the longitudinal component (z direction) of the field.

Fig. 3 shows the fields emanated by the structure in absence of tissue. Unlike an antenna, the plate does not radiate significantly. The surrounding field is evanescent and is non-stationary – the lobes appear to propagate along the surface over a time span of a period.

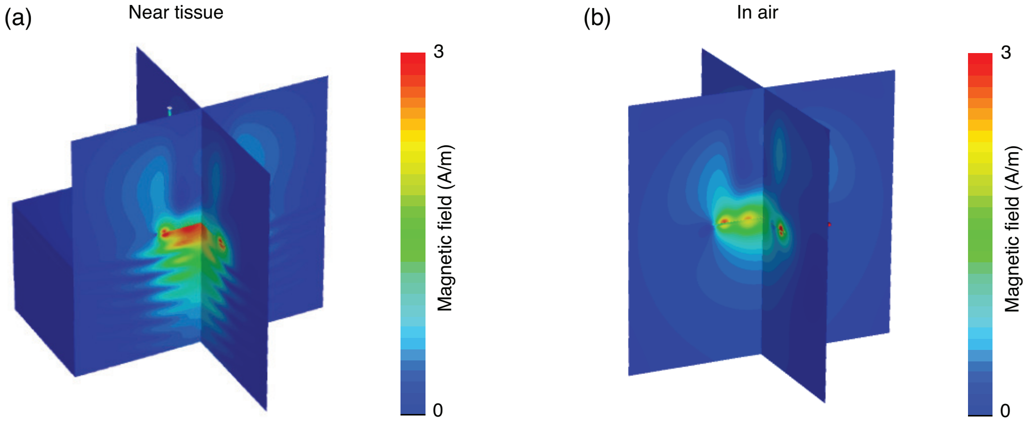

Figure 3: Source interaction with tissue. (a) Time snapshot of the focused field pattern in close proximity to tissue. (b) Time snapshot of the field pattern in air (in absence of tissue).

4 Safety

Although no established safety guidelines exist for medical applications of wireless powering, a useful reference for safety is the IEEE C95.1-2005 guidelines for human exposure to electromagnetic fields in the frequency range 3 kHz to 300 GHz [4]. We emphasize that these standards are explicitly not intended for medical use, and that the most rigorous method to assess safety is to test the device in a compliance laboratory. Nevertheless, these guidelines provide a useful reference, and enable a basic safety assessment to be obtained from numerical simulations.

The primary metric for safety measurements is the specific absorption rate (SAR), defined as the power dissipated over a specified volume of tissue (measured in W/kg). Because the density of many tissue types is close to 1000 kg/m^3, SAR is also often reported in units mW/cm^3. The standard states that the following thresholds are protective against all established adverse health effects:

- Whole-body average SAR less than 0.4 W/kg

- Maximum local SAR, averaged over 10 g of tissue, less than 10 W/kg

For general public exposure, these thresholds are reduced by a factor of 5; however, these reduced thresholds are not applicable to medical wireless power transfer since the users are aware of the risk of exposure. For far-field exposure, the alternative maximum permissible exposure (MPE) metric can be used. These thresholds require only a point measurement of the electric field (in units V/m) in free-space, which is significantly easier to measure, but cannot be used here due to the key role wave interactions with tissue play in the powering mechanism.

For a total input power (averaged across all ports) of 500 mW, the whole-body average is 0.007 W/kg (assuming body weight of 70 kg) and is compliant with the standard. Fig. 4 shows the local SAR distribution, averaged over 10-g cubes of tissue. The peak SAR is 0.45 W/kg, which is also far below the threshold. In a safety compliance laboratory, the measured SAR for this device was higher (0.89 W/kg) [2] due to the differences in experimental conditions, but remained far below the safety threshold.

We note that a safety threshold often quoted in literature is 1.6 mW/cm^3, averaged over 1 g of tissue. This value, based on the older C95.1-1998 standard (in which the maximum local SAR threshold is 8 W/kg averaged over 1-g of tissue, with an additional factor of 5 margin for general public exposure), remains in active use by the FCC for telecommunications applications. However, for medical applications of wireless powering, we believe that the C95.1-2005 standard to be more appropriate and advocate its use in future studies.

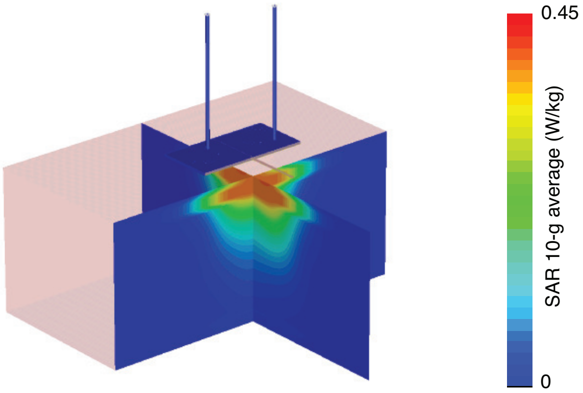

Figure 4: Safety assessment. (a) Specific absorption rate (SAR) averaged over 10-g cubes of tissue.

References

[1] S. Kim, J. S. Ho, and A. S. Y. Poon, “Midfield wireless powering of subwavelength autonomous devices,” *Phys. Rev. Lett.*, vol. 110, p. 203905, May 2013.

[2] J. S. Ho, A. J. Yeh, E. Neofytou, S. Kim, Y. Tanabe, B. Patlolla, R. E. Beygui, and A. S. Y. Poon, “Wireless power transfer to deep-tissue microimplants,” *Proc. Natl. Acad. Sci. U.S.A.*, vol. 111, no. 22, pp. 7974–7979, 2014.

[3] S. Gabriel, R. W. Lau, and C. Gabriel, “The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues,” *Phys. Med. Biol.*, vol. 41, pp. 2271–2293, Oct. 1996.

[4] IEEE Standard C95.1, *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*, 2005.