3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

Analytical Approach to Matching Layer Design for Electric Field Maximization in Biological Tissues

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Abstract

The electromagnetic waves transmission inside biological tissues can be useful in several biomedical applications, such as rehabilitation and microwave imaging. In this context, an important point is to design a matching layer to enhance the penetration of the electric field into a target tissue. Here we present an analytical method to design a matching layer under the near-field regime, i.e. when the electromagnetic source, as for instance a short dipole antenna, lies in the proximity of the body. In particular, two cases are examined: when the matching layer only consists of a dielectric slab, and when it is composed by a metasurface printed on a dielectric substrate. The proposed approach is based on the wave-transmission chain matrix and on the Schelkunoff's definition of wave impedance to consider the source. The body is modeled as a multilayered planar medium. An optimization procedure based on a stochastic algorithm is applied to determine the parameters of the matching layer which could realize the maximum electric field transmission inside the muscle. These parameters are then used to simulate the overall system with a numerical software. The results show that the matching layer comprising the metasurface is the most effective solution in terms of electric field maximization and dimensions of the substrate.

1 Introduction

In recent years, the employment of electromagnetic (EM) fields in the biomedical area has been fundamental in several scenarios and innovative devices; for example, in rehabilitation [1], in microwave imaging [2], and in medical implants design, where the maximum power transfer [3, 4] is required. In those applications, the signal emitted by an EM source, such as an antenna, has to be maximized. In this context, the impedance mismatching should be taken into account. Indeed, the unwanted reflections caused by changes in the impedance of a medium can lead to a signal degradation. Therefore, designing a proper matching layer that could reduce reflections and, at the same time, maximize the transmitted field into the target tissue is a relevant problem.

There are two regimes under which the interaction between the human body and EM fields can be studied: the *far field*, and the *near field*. The wave impedance Z_w, which is the ratio between the electric (**E**) and the magnetic (**H**) field, assumes different expressions in the two cases. In the far-field, Z_w is constant and equals to $Z_0 = 120\pi\Omega$.

On the other hand, the wave impedance in the near-field region has a more complicated expression, which includes the distance between the radiating source and the illuminated object. The interaction between humans and EM fields is often investigated under the far-field regime. One of the most remarkable work is presented in [5], where the increase of the Specific Absorption Rate (SAR) is investigated as a function of tissue composition, when the EM source is in the far-field.

The interaction of EM fields and tissues under the near-field regime is often investigated using numerical methods [6], whereas there's a lack of analytical approaches. The plane-wave spectrum (PWS) method is perhaps the most common approach to quantify the EM energy delivered to the human body under the near field regime. In [7], the PWS is exploited to measure the penetration of the EM field in a multilayered model of the body, under near-field illumination.

Design a proper matching layer able to maximize the EM signal is a relevant problem both in the far and in the near field. In [8], the EM source is placed in the far field and the performance of a matching layer consisting of a periodic surface printed on a lossless dielectric substrate are investigated.

Here, we will consider the electric component of the EM field and we will discuss an analytical approach to design a matching layer able to maximize the electric field inside the muscle. Indeed, the feasible scenario is the application of the field in the abdominal region [9]. Two different designs are examined: when the matching layer is composed of the only dielectric, and when a metasurface is printed on the dielectric substrate. The analytical method we propose requires lower computational resources and less computational time with respect to numerical methods. The results we obtained analytically are validated through comparisons with data provided by the numerical software CST Studio.

2 Formulation of the problem

In this work, the body is modelled as a multilayered planar medium consisting of three homogeneous layers: skin, fat and muscle. The interaction of EM waves with this system can be analyzed with its equivalent transmission line

[10], shown in Figure 1 in the case of a matching layer composed of a dielectric-only substrate. The thickness of the tissues are: $d_{skin} = 0.5$ mm for the skin and $d_{fat} = 26$ mm for the fat. The muscle layer is semi-infinite due the to its high losses. The matching layer is considered as another transmission line section. $Z_{ML}, Z_{skin}, Z_{fat}$ and Z_{muscle} are the impedances of the different line sections, and they can be calculated as: $Z_i = \frac{Z_0}{\sqrt{\varepsilon_{r_i}}}$, where the index i denotes the current section of the line and ε_{r_i} is the permittivity of the corresponding section. The electric field values in every layer of the model are retrieved using the wave transmission chain matrix formalism [11].

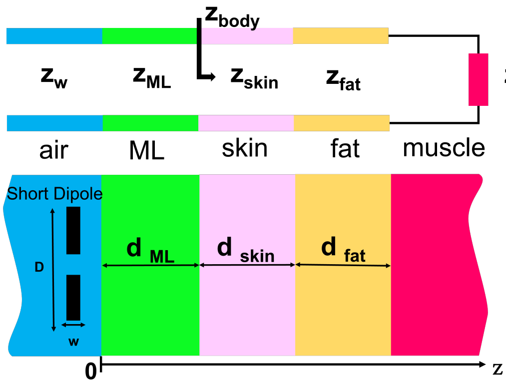

Figure 1. Representation of the system and its equivalent transmission-line model.

The frequency chosen for this study is $f = 2.5$ GHz. Indeed, according to [12], a good trade off between received power and tissue absorption can be obtained in the GHz-range, if the radiating antenna is shorter than a wavelength. The permittivity ε_r and the conductivity σ of the tissues at 2.5 GHz are reported in Table 1.

Table 1. Dielectric parameters of tissues at 2.5 GHz.

Tissue	ε_r	σ (S/m)
skin	38	1.46
fat	5.5	0.155
muscle	47	2.21

The impedance offered by the body is indicated in Figure 1 with Z_{body} and it should be taken into account when the metasurface is inserted in the model. Z_{body} can be obtained using recursively the lossy transmission line formula in Eq.1. In the expression, l_i is the distance at which the impedance is calculated, γ_i is the propagation constant $(-j|\gamma_i| = k_i)$ in the considered section of the line, $Z(-l_i)$ is the impedance seen at that distance, Z_{L_i} is the impedance in the current section, and Z_{0_i} is the characteristic impedance of the line:

$$Z(-l_i) = Z_{0_i} \frac{Z_{L_i} + Z_{0_i} \tanh(\gamma_i l_i)}{Z_{0_i} + Z_{L_i} \tanh(\gamma_i l_i)} \tag{1}$$

The impedance offered by the body is represented in Figure 2, by using Eq. 1 for a frequency range between 2 and 3 GHz. In the following, the wave impedance definition

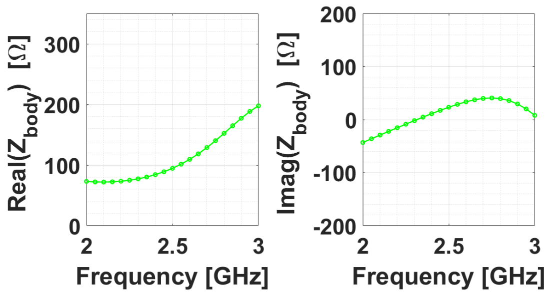

Figure 2. Real and imaginary part of the impedance offered by the body in the bandwidth 2-3 GHz.

as provided by Schelkunoff [13] for an Hertizan dipole is applied in order to design a proper matching layer in the near field regime. The wave impedance expression is the following:

$$Z_w = Z_0 \frac{\frac{j}{k_0 r} + \frac{1}{(k_0 r)^2} - \frac{j}{(k_0 r)^3}}{\frac{j}{k_0 r} + \frac{1}{(k_0 r)^2}} \tag{2}$$

Indicating the speed of light with $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$, where ε_0 and μ_0 are the electric permittivity and the magnetic permeability of vacuum, $k_0 = \frac{2\pi f}{c}$ in Eq. 2 is the free space wave number, r is the distance between the source and the illuminated object, and Z_0 is the free space impedance. We simulated a short dipole because, unlike the hertzian one, it has finite dimensions. If we indicate with λ the free-space wavelength, the length of the dipole can be expressed as $D = \frac{\lambda}{10}$, whereas its width w is equal to $\frac{D}{20}$ (Figure 1). The near field region for the considered short dipole extends approximately from $r = \lambda/2\pi = 2$ cm to $3\lambda = 36$ cm. The value of Z_w for a specific distance between the source and the body is included in the optimization procedure to find the thickness and the material of the matching layer that could maximize the transmitted field at the interface between fat and muscle. In a real scenario, not all possible combinations of dielectric properties of a material can be realized, therefore the search domain of the stochastic algorithm used in the optimization procedure is constrained. This means that the dielectric matching layer has to be chosen from a database, whereas its thickness can span between 0.5 and 2 cm. In the case in which the metasurface is inserted in the model, the optimization procedure has to find an additional parameter: the value of the inductance or the capacitance offered by the metasurface itself. A metasurface, represented in the following by the lumped impedance Z_S, is a sub-wavelength periodic two-dimensional structure [14] able to shape the EM field which impinges on it. The behaviour of the metasurface should be chosen taking into account the impedance offered by the body. The equivalent transmission line of the system with an inductive metasurface (a *wire grid*) is shown in Figure 3. The periodicity of the structure is indicated with p, whereas the width of the wire is w.

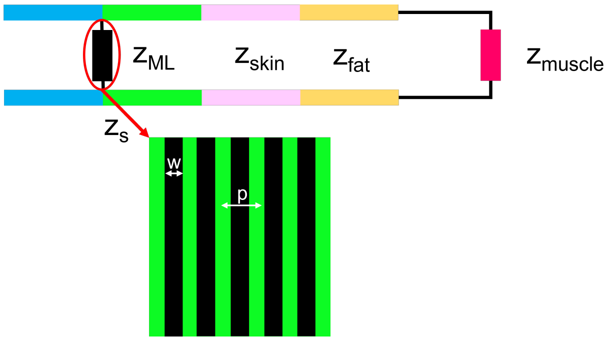

Figure 3. Representation of the model when an inductive metasurface is printed on the dielectric.

3 Preliminary results and discussion

The considered distance between the source and the body is 2.5 cm, which lies in the near-field region. For that distance, the wave impedance is equal to $Z_w = 238 - j106$, so it is capacitive. The behaviour of the body impedance is inductive for the considered thickness of the tissues, as shown in Figure 2. The metasurface thus should emphasize that behaviour and, at the same time, reduce the capacitive reactance of the source. It means that the metasurface should exhibit an inductive behavior, so that it can be defined as:

$$Z_S = j2\pi f L \tag{3}$$

The equivalent inductance L can be realized with a wire grid, and has the following expression [15]:

$$L = \frac{p\mu_0}{2\pi}\log\left(\frac{1}{sin(\frac{\pi w}{2p})}\right) \tag{4}$$

where p is the periodicity of the grid and w is the width of the wire, as stated before. In the dielectric-only case, the optimization procedure outputs are: a substrate thickness of 0.95 cm and a material with $\varepsilon_r = 6.5$ and $\sigma = 0.35$ mS/m. On the other hand, in the case with the metasurface, the optimization procedure indicated a substrate width of 0.8 cm, a material with $\varepsilon_r = 78.4$ and $\sigma = 0.0067$ mS/m, and an inductance of $L = 4.14$ nH. This value of inductance can be obtained using a wire grid with $p = 2$ cm and $w = 4.6$ mm. The parameters obtained with the optimization procedure in the two cases have been used to design the matching with a simulation code, considering a variability of around 10 % of the working frequency f = 2.5 GHz. The results obtained with the numerical software are shown in Figure 4, in which the electric field profiles are represented considering a plane placed at the interface between fat and muscle ($z = 26$ mm). From Figure 4 it is possible to observe that the maximum transmitted field in the muscle is obtained when the metasurface is inserted in the model and when the frequency is 2.6 GHz. However, considering the working frequency of 2.5 GHz, the electric field enhancement when the metasurface is employed is around 44 %, using a dielectric substrate which is 19 % thinner than in the case with the dielectric-only. The trend is confirmed for all the frequencies considered, suggesting that the method is robust for small changes of the working frequency. Moreover, the profile of the electric field in presence of the metasurface seems sharper with respect to the case when no metasurface is used.

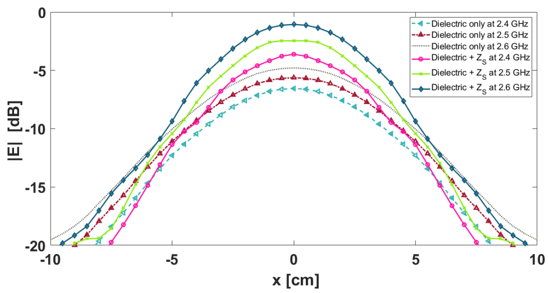

Figure 4. Electric field profiles (in dB) at the fat/muscle interface when the ML is made of a dielectric-only and when a metasurface (Z_S) is used, for frequencies around 2.5 GHz.

4 Conclusion

The maximization of electric field inside biological tissues can be beneficial in several applications, from maximum power transfer to microwave imaging. Therefore, it is important to design a matching layer which can help to achieve the maximum transmission of the electric field. We presented an analytical approach based on wave transmission chain matrix and Schelkunoff's definition of wave impedance to design a matching layer in the near-field regime. Two cases are considered: when the matching layer is a dielectric only, and when a metasurface is printed upon a dielectric substrate. The electric source is a short dipole. We used an optimization procedure based on a stochastic algorithm to find the best dielectric material and its correspondent width and, in the second case, the parameters of the metasurface. For a fixed distance between the source and the body, the results obtained with the analytical approach are validated numerically. The results suggest that, when a metasurface is inserted in the model, the maximum transmitted field is achieved. At the same time, the thickness of the matching layer is reduced, a feature which could increase the user's comfort.

5 Acknowledgements

Work partially supported by the Italian Ministry of Education and Research (MIUR) in the framework of the CrossLab project (Departments of Excellence) and of the PRIN2017 GREEN TAGS "Chipless radio frequency identification (RFID) for GREEN TAGging and Sensing" (2017NT5W7Z).

References

[1] R. M. Enoka, I. G. Amiridis, and J. Duchateau, "Electrical Stimulation of Muscle: Electrophysiology and

Rehabilitation", *Physiology*, **35**, 1, 2020, pp. 40–56, doi: 10.1152/physiol.00015.2019.

[2] B. Sohani, G. Tiberi, N. Ghavami, M. Ghavami, S. Dudley and A. Rahmani, "Microwave Imaging for Stroke Detection: Validation on Head-mimicking Phantom," *2019 PhotonIcs & Electromagnetics Research Symposium - Spring (PIERS-Spring)*, 2019, pp. 940–948, doi: 10.1109/PIERS-Spring46901.2019.9017851.

[3] D. B. Ahire and V. J. Gond, "Wireless power transfer system for biomedical application: A review," *2017 International Conference on Trends in Electronics and Informatics (ICEI)*, 2017, pp. 135–140, doi: 10.1109/ICOEI.2017.8300903.

[4] Y. Zhou, C. Liu, Y. Huang, "Wireless Power Transfer for Implanted Medical Application: A Review", *Energies* **13**, 2020, p. 2837, doi: 10.3390/en13112837.

[5] A. Christ, A. Klingenbock, T. Samaras, C. Goiceanu and N. Kuster, "The dependence of electromagnetic far-field absorption on body tissue composition in the frequency range from 300 MHz to 6 GHz," *IEEE Transactions on Microwave Theory and Techniques*, **54**, 5, May 2006, pp. 2188–2195, doi: 10.1109/TMTT.2006.872789.

[6] K. Agarwal and Y. Guo, "Interaction of electromagnetic waves with humans in wearable and biomedical implant antennas," *2015 Asia-Pacific Symposium on Electromagnetic Compatibility (APEMC)*, 2015, pp. 154–157, doi: 10.1109/APEMC.2015.7175377.

[7] I. Chatterjee , M.J. Hagmann, O. P. Gandhi. "Electromagnetic absorption in a multilayered slab model of tissue under near-field exposure conditions", *Bioelectromagnetics*, 1980, **1**, 4, pp. 379–88. doi: 10.1002/bem.2250010404.

[8] S. Genovesi, I. R. Butterworth, J. E. C. Serrallés and L. Daniel, "Metasurface Matching Layers for Enhanced Electric Field Penetration Into the Human Body," *IEEE Access*, **8**, 2020, pp. 197745–197756, doi: 10.1109/ACCESS.2020.3034833.

[9] J. Lee, A. J. Park, Y. Tanabe, A. S. Y. Poon, and S. Kim , "A microwave method to remotely assess the abdominal fat thickness", *AIP Advances*, **11**, 2021, p. 035111, doi: 10.1063/5.0025865.

[10] H. Oraizi, M. Afsahi, "Analysis of planar dielectric multilayers as fss by Transmission Line Transfer Matrix Method (TLTMM)", *Progress in Electromagnetics Research*, **74**, 2007, pp. 217–240, doi:10.2528/PIER07042401.

[11] R. E. Collin, *Field theory of guided waves*, vol. 5. John Wiley & Sons, 1990.

[12] A. S. Y. Poon, S. O'Driscoll and T. H. Meng, "Optimal Frequency for Wireless Power Transmission Into Dispersive Tissue," *IEEE Transactions on Antennas and Propagation*, **58**, 5, May 2010, pp. 1739–1750, doi: 10.1109/TAP.2010.2044310.

[13] S. A. Schelkunoff, "The impedance concept and its application to problems of reflection, refraction, shielding and power absorption" *Bell System Technical Journal* **17**, 1, 1938, pp. 17–48.

[14] C. L. Holloway, E. F. Kuester, J. A. Gordon, J. O'Hara, J. Booth and D. R. Smith, "An Overview of the Theory and Applications of Metasurfaces: The Two-Dimensional Equivalents of Metamaterials," *IEEE Antennas and Propagation Magazine*, **54**, 2, April 2012, pp. 10–35, doi: 10.1109/MAP.2012.6230714.

[15] O. Luukkonen et al., "Simple and Accurate Analytical Model of Planar Grids and High-Impedance Surfaces Comprising Metal Strips or Patches," *IEEE Transactions on Antennas and Propagation*, **56**, 6, June 2008, pp. 1624–1632, doi: 10.1109/TAP.2008.923327.