Electromagnetic Interactions between Biological Tissues and Implantable Biotelemetry Systems

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***Abstract* — Biotelemetry which provides wireless communication links between internal devices and outside equipment is a promising function for future implantable biomedical devices. In order to build reliable wireless links, detailed characterization and performance evaluation of the telemetry links are required. In this work, the finite difference time domain (FDTD) simulations are performed to analyze the radiation performances of small dipole and loop antennas in biological tissues for various biotelemetry links. By comparing the electrical characteristics of vertical and horizontal loop antennas above a perfect electric conductors (PEC) plane, the effects of biomedical devices on biotelemetry links are estimated in terms of radiation efficiency and specific absorption rate (SAR). Finally, it is observed that electromagnetic band-gap (EBG) structures are useful candidates for biotelemetry link design.**

***Index Terms* — Biotelemetry link, biological tissues, electromagnetic band-gap (EBG), small dipole, small loop.**

I. Introduction

Nowadays, the role of such telecommunication links as radio and optical communications is very critical in biomedicine. Specifically, wireless communication links are promising biomedical functionality for implantable devices. For example, telemetry links of pacemakers, implantable defibrillators, and other implantable therapies are required to interchange physiological data and control implantable devices remotely [1]. To build a reliable telemetry link between the interior device and the exterior equipment, it is needed to understand the interactions between the implanted antenna and the human body and to study electromagnetic characteristics of the implanted antennas and their radiation performance.

Since this study is related to biomedical applications, biotelemetry links are assumed to operate in the available frequency band. One frequency is 402 - 405 MHz which is recommended by the European radiocommunications committee (ERC) for ultra low power active medical implants [2] and another frequency is 1.5 GHz. For the evaluation of performances and safety issues related to implantable biotelemetry, the radiation characteristics and 1-g averaged specific absorption rate (SAR) distributions of implanted antennas are simulated and compared with ANSI/IEEE limitations for SAR [3].

According to the locations of pacemakers and implantable cardioverter defibrillators [4], biotelemetry systems which consist of implanted antennas are placed in the upper human chest as shown in Fig. 1. The difference between Fig. 1(a) and Fig. 1(b) is whether the antenna directly contacts biological tissues or not. The system of Fig. 1(a) requires smaller space in a human body than that of Fig. 1(b) but generates higher SAR value because of the direct contact. The advantage of Fig. 1(b) structure is that there exist many possible methods to improve the performance of the biotelemetry link through the diverse electrical characterization (for example: the effect of the air-box on an implanted antenna). Therefore, in this paper, all studies focus on the electromagnetic interactions between the biotelemetry system of Fig. 1(b) and biological tissues using FDTD simulation results.

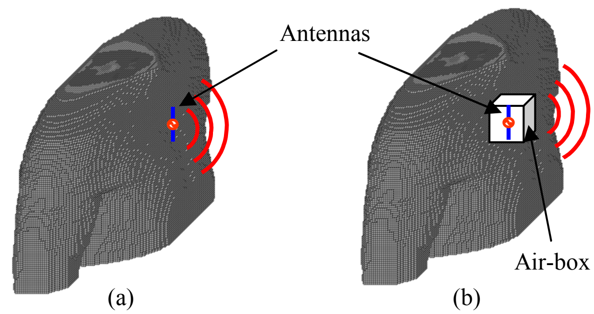


Fig. 1. (a) Biotelemetry system which consists of an antenna in a human body and (b) biotelemetry system which consists of an antenna and an air-box in a human body

First, the electric performances of small antennas such as dipole and loop antennas in biological tissues are compared in terms of the radiation efficiency and maximum 1-g SAR. The effects of perfect electric conductor (PEC) plane on small loop antennas are analyzed to estimate the characteristics of antennas installed on the case of medical devices. Finally, an electromagnetic band-gap (EBG) structure is tuned to work as a perfect magnetic conductor (PMC) for biotelemetry systems. Based on the comparison of the radiation performances between a horizontal loop antenna above a PEC plane and a horizontal loop antenna above a EBG plane inside biological tissues, the usefulness of an EBG structure for biotelemetry systems is evaluated.

II. Characterization of Diverse Biotelemetry Links in Biological Tissues at 402 MHz

A. Comparisons of Diverse Biotelemetry Link Performances

To analyze the performances of diverse biotelemetry links using the FDTD simulations, the human body model, shown in Fig. 1, is simplified as cubic biological tissues whose dimensions are 16x 16x 16 cm^3 as shown in Fig. 2. The simplified body is filled with a skin tissue [5] whose relative permittivity (ε_r) is 49, relative permeability (μ_r) 1, and conductivity (σ) 0.6 S/m at 402 MHz [6]. A small antenna implanted in the simplified body is centered at the cubic air-box whose dimension are 5x 5x 5 cm^3. The gap between the air-box and free space is similar to the skin tissue's thickness (4 mm) in order to consider the locations of implantable medical devices [4]. The center of the air-box is at 8 cm from the upper surface of the simplified body and also from the left side.

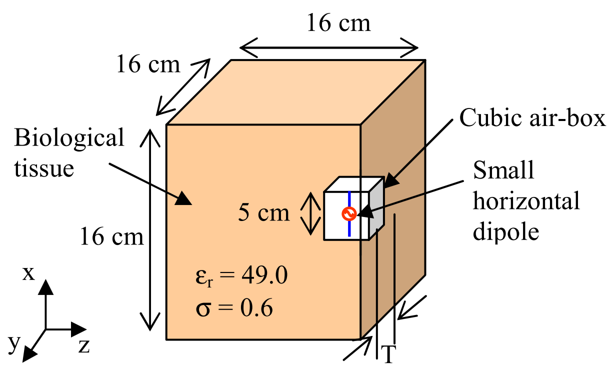


Fig. 2. Simplification of a human body for biotelemetry antenna study. (T, thickness of skin tissue = 4 mm)

By changing the small antenna inside the air-box with four different types of antenna (vertical dipole, horizontal dipole, vertical loop, and horizontal loop), the performances of telemetry links are evaluated as given in TABLE I. Here "vertical" means that antenna geometries (line for dipole and surface of loop) are normal to xy plane of the air-box and "horizontal" means that antenna geometries are parallel to xy plane of the air-box. The antennas are assumed to deliver 1 W and operate at 402 MHz.

TABLE I
Comparisons of Characteristics of Different Antennas in Biological Tissues (Frequency=402 MHz)

Antennas	Vertical Dipole	Horizontal Dipole	Vertical Loop	Horizontal Loop
Length	0.05 λ_0	0.05 λ_0	0.20 λ_0	0.20 λ_0
Rad. Eff.	0.09 %	0.11%	1.05 %	1.41 %
Max. SAR*	1221.9	1214.9	18.9	17.7

(*: Delivered power=1W)

TABLE I includes the physical dimensions as well as electrical characteristic data (radiation efficiency (= radiated power/delivered power) and maximum 1-g SAR) for four antennas. According to the radiation efficiency and 1-g SAR values given in TABLE I, it is found that small loop antennas are more suitable for biotelemetry links than small dipole antennas because loop antennas generate high magnetic fields [5].

B. Effects of PEC Plane on Biotelemetry Links

The same simulation structure as Fig. 2 is used to evaluate the effects of a PEC plane on the performances of biotelemetry links. As shown in Fig. 3, the PEC plane which is parallel to xy plane of the air-box is located behind the small loop antenna. The PEC plane can be considered as the surface of implantable medical devices if antennas for biotelemetry are installed on the case of the devices.

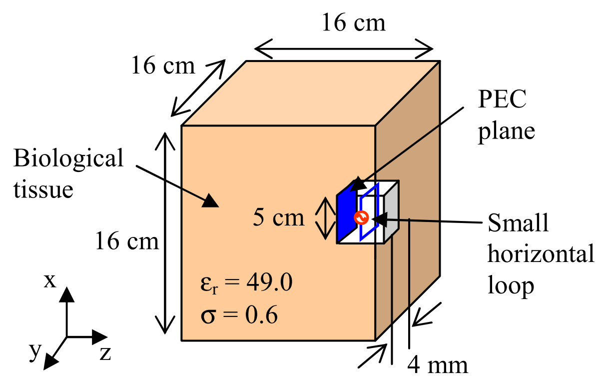


Fig. 3. Horizontal loop antenna with PEC plane inside a biological tissue

If the results of TABLE II are compared with those of TABLE I to see the effects of PEC plane, the radiation efficiency of the vertical loop increases and that of the horizontal loop decrease because of the image effect applied for the radiation performance enhancement of pager antennas above a metallic plane [7]. Also the maximum 1-g SAR of the horizontal loop is larger because of the PEC plane. From the results of TABLE II, it is expected that the radiation performance of the horizontal loop antenna would be degraded if the horizontal loop approaches the PEC plane.

TABLE II
Effects of PEC plane on Loop Antennas in Biological Tissues (Frequency=402 MHz)

Antennas	Vertical loop	Horizontal loop
Length	0.20 λ_0	0.20 λ_0
Rad. Efficiency	1.61 %	0.83 %
Max. SAR*	20.1 W/kg	23.6 W/kg

(*: Delivered power=1W)

III. Interaction between Loop Antennas above EBG Structure and Biological Tissues at 1.5 GHz

As far as the size of biotelemetry systems is concerned, horizontal loop antennas are better candidates for biotelemetry links than vertical loop antennas. Furthermore, it is worthwhile to focus on the radiation characteristics of horizontal loop antennas above the PEC or EBG planes in order to improve the performances of biotelemetry link. For this study, the operating frequency is changed from 402 MHz to 1.5 GHz (another medical frequency). At this frequency, an acceptable size EBG structure can be designed.

A. Horizontal Loop Antenna above EBG structure

Fig. 4 shows the geometry of mushroom-like EBG structure [8] which is composed of 6 by 6 square patches, a dielectric layer, and a square ground plane. At 1.5 GHz frequency, each patch of 0.09 λ_0x 0.09 λ_0 is located 0.03 λ_0 above the ground plane whose dimension is 0.62 λ_0x 0.62 λ_0 and the gap between neighboring patches is 0.015 λ_0. Each EBG patch is printed on a dielectric layer whose thickness is 0.04 λ_0 and dielectric constant (ε_r) is 10.2. A square horizontal loop antenna is located 0.015 λ_0 from the EBG surface and the length of the antenna is 0.9 λ_0.

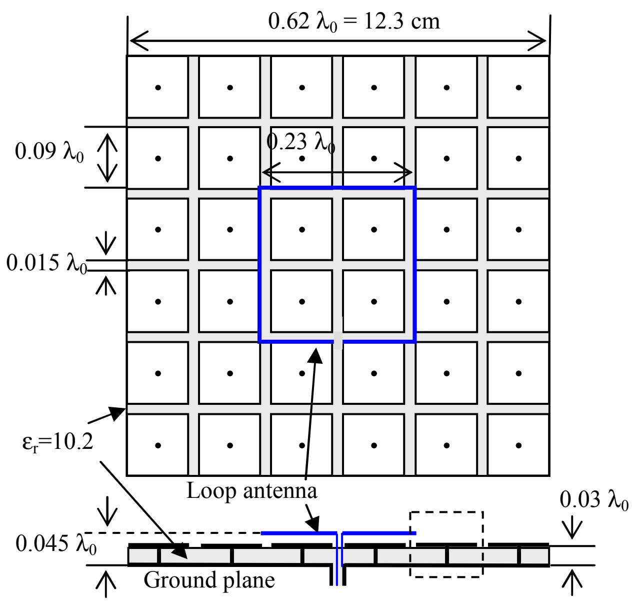
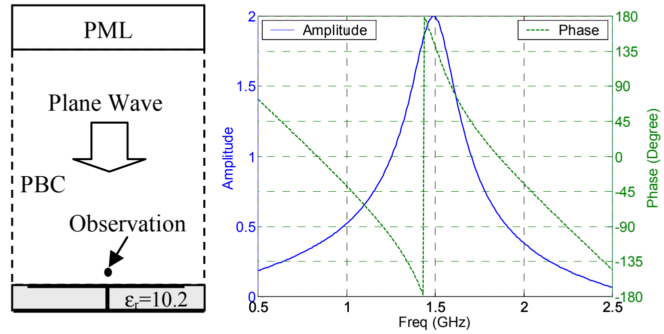


Fig. 4. Horizontal loop antenna above EBG structure.

To estimate the electrical behavior of the mushroom-like EBG structure, FDTD simulations are performed by utilizing the simulation model given in Fig. 5. The simulation model is constructed using the perfectly matched layers (PML), periodic boundary conditions (PBC), one element of the EBG structure given in Fig. 4, and an incident plane wave. PML simulates the free space, and PBC represents the periodic EBG structure. The observation point is at the location of the horizontal loop antenna above the EBG structure in order to calculate the amplitude and phase of total electric fields (incident plane wave + reflected plane wave). According to Fig. 5(b), the maximum amplitude (=2) of the total electric field is observed at 1.5 GHz which is used to operate the loop antenna because the EBG structure works as a PMC-like plane at 1.5 GHz.

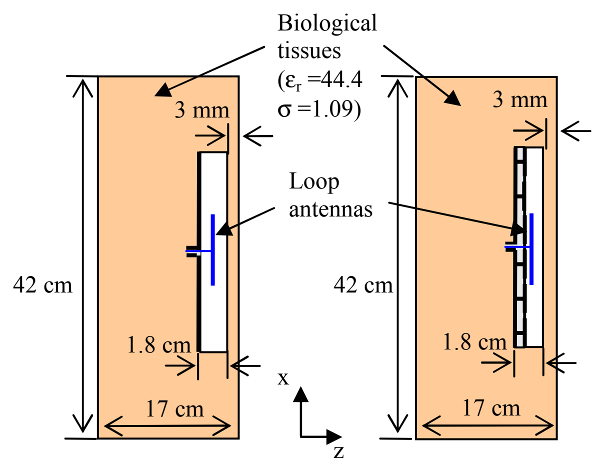


(a) (b)

Fig. 5. Electrical behavior of the EBG structure used for the horizontal loop antenna. (a) Simulation method. (b) Amplitude and phase of total electric fields at the observation point.

B. Performances of the Biotelemetry Link with Horizontal Loop Antenna above PEC and EBG planes

In order to study the effect of PEC and EBG planes on the performance of biotelemetry links, horizontal loop antennas are placed in biological tissues as shown in Fig. 6. The dimensions of the biological tissues (ε_r=44.4, μ_r=1, and σ=1.09 S/m [6]) are 42x 42x 17 cm^3. The biotelemetry systems which consist the loop antennas are located 3 mm from the free space.



(a) (b)

Fig. 6. Horizontal loop antennas above (a) PEC plane (=metallic plate) and (b) EBG plane inside biological tissues (42x 42x 17 cm^3).

Simulation results for horizontal loop antenna above PEC and EBG plane are compared in TABLE III. The EBG case gives higher radiated power in the free space than the PEC case. Furthermore, the maximum 1-g SAR value of the EBG case is lower than that of the PEC case. In terms of antenna's matching characteristics to 50 Ω systems, it is expected that the EBG structure is able to facilitate the design of horizontal loop antennas for implantable biotelemetry systems because the return loss of the EBG case (7.6 dB) is better than that of the PEC case (1.6 dB).

TABLE III
EFFECTS OF PEC AND EBG PLANES ON BIOTELEMETRY LINKS IN BIOLOGICAL TISSUES (FREQUENCY =1.5 GHZ)

Antennas	Horizontal loop above PEC plane	Horizontal loop above EBG plane
Length	0.9 λ_0	0.9 λ_0
Rad. Efficiency	14.2 %	17.7 %
Max. SAR*	100.6 W/kg (=20.0 dB)	89.1 W/kg (=19.5 dB)
Input Impedance	24.3-j102.1 Ω	21.6-j7.5 Ω
Return Loss	1.6 dB	7.6 dB

(*: Delivered power=1W)

When the antennas were assumed to deliver 1 W, the 1-gram averaged SAR distributions over the x-z plane (y=the center of the antenna) are given in Fig. 7. As expected, the peak SAR of the both horizontal antennas are calculated at the tissues in front of the antenna.

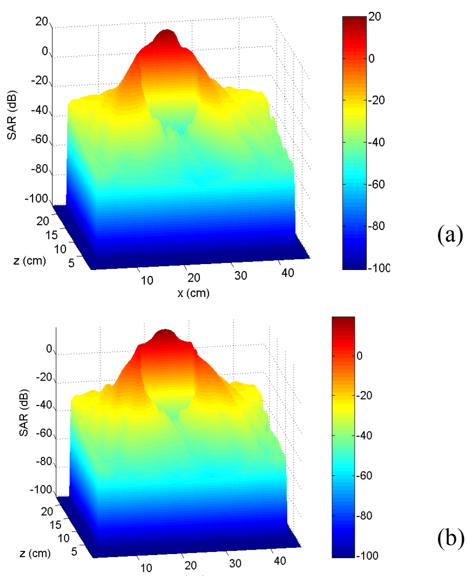


Fig. 7. Horizontal 1-g SAR distributions (xz plane, y=center of the antennas) of the loop antennas above (a) the PEC plane and (b) the EBG plane inside biological tissues.

If the peak delivered power is estimated for the safe use of biotelemetry systems, the horizontal loop antenna above the metallic plane can deliver less than 16 mW in order to satisfy the ANSI SAR limitation (1.6 W/kg) [3] and the horizontal loop antenna above the EBG structure can deliver maximally 18 mW.

IV. CONCLUSION

Based on the numerical simulations, a study of implantable biotelemetry links was performed in this paper. By comparing the radiation characteristics of small dipole/loop antennas in biological tissues, it is shown that loop antennas would be better candidates for biotelemetry links than dipole antennas for the radiation performances and safety issues.

To consider the telemetry systems installed on implantable metallic medical devices, PEC planes are included in FDTD simulation structures for the characterization of small loop antenna in biological tissues. The radiation efficiency of the vertical loop antenna is improved because of the effect of the image. Horizontal loop antennas are more appropriate for biotelemetry link implementation than vertical loop antennas because of physically small geometry (low profile). The radiation performances of horizontal loop antennas above PEC and EBG planes are observed to check the usefulness of EBG structures for biotelemetry links. The FDTD simulation results show that EBG structures are helpful for the design of implantable biotelemetry systems for better 50 Ω matching without the loss of the radiation efficiency in the free space if compared with the case of the horizontal loop antenna above the metallic ground plane.

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