EE491
Senior Design Project Midterm Report

Design of an implantable antenna for microwave hyperthermia

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1. Introduction

The recent technological advancements are revolutionizing the way healthcare is being delivered and they are also a key factor driving the advances of surgical treatment. Joint replacement surgery (hip and knee replacement) is considered the most effective intervention for severe osteoarthritis and hip fractures, reducing pain and disability and restoring some patients to near normal function. [1] As a consequence, hip replacement surgery shows increasing trends in most OECD countries. On average, the rate of hip replacement increased by 30% between 2000 and 2015.[1] Revision burden can be seen as a rough measure of the success of hip replacement surgeries. In the USA the revision burden was 10.2% for hips between 2012 and 2015 [2], but revision surgery of the hip is expensive owing to the increased cost of pre-operative investigations, surgical implants and instrumentation. [3]

The six most common indications for revision after primary hip replacement (listed in order of frequency) are aseptic loosening, pain, adverse soft tissue reaction to particulate debris, dislocation, infection and peri-prosthetic fracture.[4] Especially performing the revision surgery for infection is riskier considering the instrumentation. Staphylococcus aureus and Staphylococcus epidermidis are the leading etiologic agents of orthopedic implant infection.[5] Traditional antibiotic therapy will never be successful against these pathogens after the biofilm is formed. [6] This property of bacteria is called antimicrobial resistance (AMR) and it is a major concern worldwide. The other modes of treatment will be needed to prevent biofilm formation in the first place.

A hip implant can be equipped with sensors and microelectronics forming a wireless communication link between the implant and an on-body sensor to collect continuous data or provide real-time feedback.[7] In this project it is aimed to design an antenna taking action against infection before and during the biofilm formation through microwave hyperthermia with the help of the feedback from the antenna which monitors its environment.

2. Objectives

The objective of this project is to take action against infection through microwave hyperthermia. In this context, the electrical characteristics of the tissue surrounding the implant will be determined immediately after the operation. (when the infection is present) In addition to that, numerical and physical modelling of the propagation environment will be performed. After all of the optimizations are completed, the optimum working frequency for the microwave hyperthermia will be determined and the antenna design will be completed.

The second objective of this project is to develop the phantom and to build the measurement setup on which the measurements will be performed next semester.

3. Approach and Methodology

a. *Optimizations for microwave hyperthermia*

Because the human body absorbs electromagnetic waves it is often difficult to connect an implanted device to the outside world. The effect of hyperthermia depends on the depth of the implant, surrounding tissues and near field losses. It should be noted that the surrounding tissue properties and depth of the implant vary from patient to patient, but only in one patient as the patient ages. Therefore, an antenna which can adapt to the changing environment and target energy to the required region should be designed for microwave hyperthermia. The antenna parameters will be optimized considering both the thermal and electromagnetic distribution.

b. *Phantom development and building of measurement setup*

1- *Digital 3D design of the phantom model*

A 3D model will be developed to mimic the environment in which the hip implant will be located in real life. The model should include the hip implant, a portion of the femur, pelvis, body fluid, hip muscle, fat and skin.

2- *The integration of 3D phantom model with liquid/gel phantoms*

The printed 3D model should be filled up with liquid/gel in accordance with the approximate dielectric constant and conductivity values of the corresponding parts described above.

3- *Development of measurement setup*

A test kit will be developed for measuring the input response and the transmission response of the designed antenna. The test kit will consist of a mini vector network analyzer (VNA), a rotary stage and absorber material. The test kit will be used in system level tests too.

4. Work Completed

a. *Literature review*

After literature review it is decided to use a cavity-backed slot antenna, because the cavity backed slot antenna (CBSA), where the slot is backed with rectangular cavity, achieves unidirectional radiation and has advantages of low profile, light weight and ease of integration. [8] The CBSA can be fed by probe, metal waveguide, substrate integrated waveguide (SIW), and microstrip, but the microstrip-fed CBSA has simple structure and small size. [8]

b. *Power density based and temperature-based optimization in single layer*

a. *Antenna design in vacuum*

In this step a CBSA is designed to operate at 2.4 GHz. The industrial, scientific and medical (ISM) 2.40 GHz radio band is an allowed band for body area networks or medical applications. [9] The performance of designed antenna is judged by its return loss and radiation pattern.

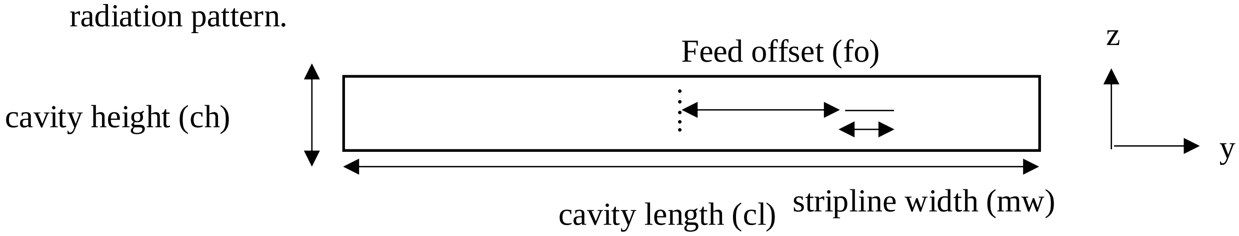


Fig. 1. Modelled antenna in yz plane

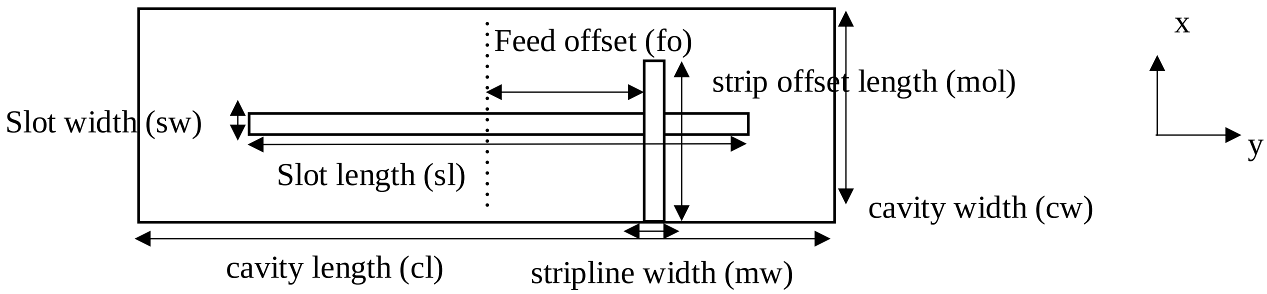


Fig. 2. Modelled antenna in xy plane

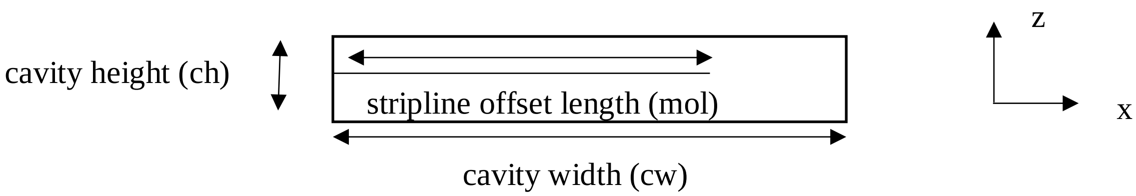


Fig. 3. Modelled antenna in xz plane

The model of the designed antenna can be seen in Fig. 1, Fig. 2 and Fig. 3 from different perspectives. The dimensions of the model can be found in Table I.

The cavity is formed from a 3.15 mm thick (cavity height) substrate with a dielectric constant of 4.4 (FR-4). The slot is fed by a 50Ω stripline located in the vertical midplane of the antenna in z direction.

The initials dimensions other than the cavity height are determined using the HFSS Antenna Toolkit Software. Prior to the start of the optimization, the software introduces a microstrip feed slot antenna with the initial values of Table I, but this is not the desired antenna. After some modifications, the desired antenna is achieved, the model of which is shown in Fig. 1, Fig. 2. And Fig. 3.

The CBSA has been optimized for operation at 2.4 GHz with -20dB return loss. The optimization is done using software ANSYS Electromagnetics Suite. The dimensions given in Table I are parametrized and optimized for a return loss -20dB.

One conclusion that can be drawn from the optimization process is that the most critical parameters for matching are the parameters for the width of the stripline and the length of the stripline. In addition, sloth length is the most critical parameter in terms of CBSA resonance frequency.

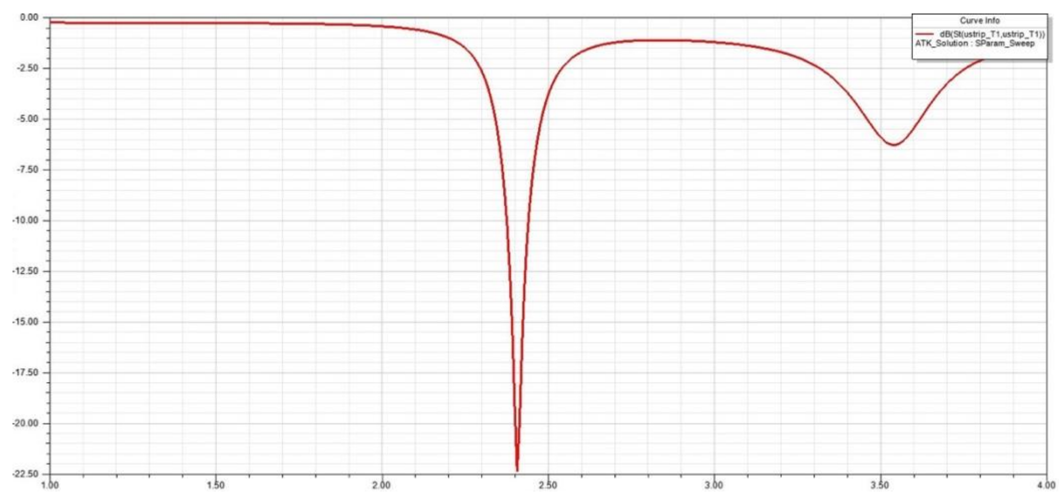
The return loss curve of the optimized antenna can be seen in Fig. 4.

Table 1. Parametrized dimensions of CBSA in vacuum

Dimension	Initial value	Final value
Slot length	5.56 cm	5.2 cm
Slot width	0.28 cm	0.21 cm
Feed Offset	1.55 cm	1.8 cm
Stripline width	0.31 cm	0.15 cm
Stripline offset length	1.71 cm	0.53 cm
Cavity length	11.1 cm	8.1 cm
Cavity width	8.3 cm	3.2 cm

Fig. 3. Simulated S_{11} vs Frequency

$|S_{11}|$ (dB)



Frequency

b. Antenna design in fat

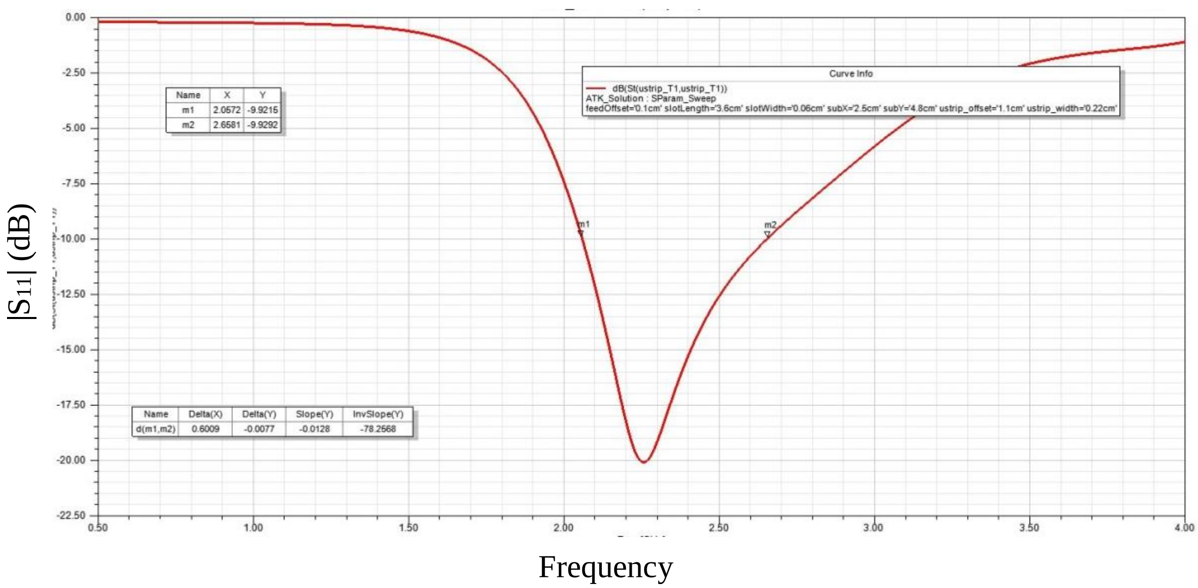
The same procedure is used as in vacuum. The initial values of parametrized dimensions of the antenna optimized in fat are the final values of the antenna optimized in vacuum. It is obvious that the dimensions should change significantly to cause a return loss of -20dB, since the electrical properties of vacuum and fat are completely different. The dimensions of the model shown in Fig. 1,2 and 3 are shown in Table II. The return loss curve of the optimized antenna can be seen in Fig. 5.

Table II. Parametrized dimensions of CBSA in fat

Dimension	Initial value	Final value
Slot length	5.2 cm	3.6 cm
Slot width	0.21 cm	0.06 cm

Feed Offset	1.8 cm	0.1 cm
Stripline width	0.15 cm	0.22 cm
Stripline offset length	0.53 cm	1.1 cm
Cavity length	8.1 cm	4.8 cm
Cavity width	3.2 cm	2.5 cm

Fig. 4. Simulated S_{11} vs Frequency



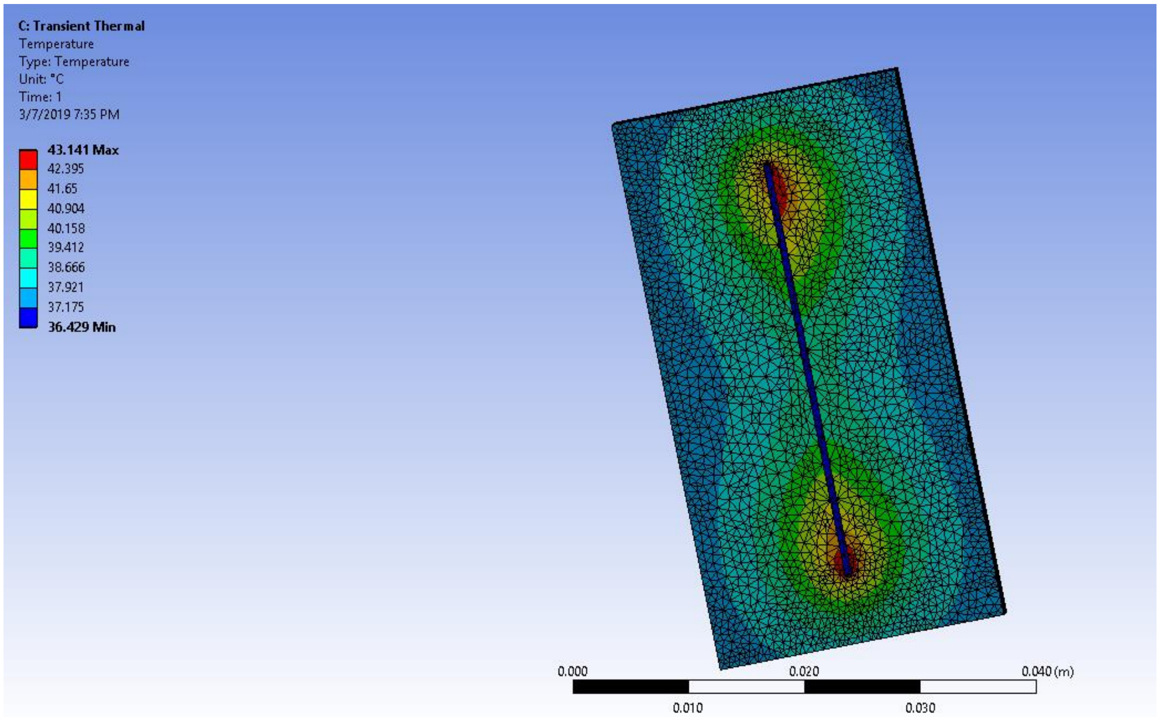
c. Transient thermal analysis of designed antenna

a. Single layer

The model is already set up in HFSS to prepare it for thermal analysis. The HFSS geometry and the associated solution data should be transferred to ANSYS Workbench and the thermal analysis carried out in ANSYS Workbench. The thermal properties of the materials should be introduced to the software. [10] Thereafter, heat dissipation should be specified by assigning convection to the exterior surfaces of the structure. In addition, it should be introduced into software which objects introduce heat effect to calculate the thermal properties. There are two types of imported loads: heat flux, heat generation. The designed model should have both, because there exist volume losses caused by currents flowing in the volumes of lossy dielectrics and surface losses caused by currents flowing in the volumes of lossy dielectrics. After completing these steps, the temperature of the entire model can be displayed.

The first demo I achieved is shown in Fig. 5. Although it looks quite good and appears to satisfy the aforementioned evaluation criteria, namely whether the 1mm neighborhood of the designed antenna can be heated to 40°C, the demo in Fig. 5 does not reflect the truth. Because I have found that the system power for gain calculations is not 0.1W as intended. I believe that I can fix this problem soon.

Fig. 5. Transient Thermal Analysis



5. Work to Be Completed

Power-density-based optimization	Cylindrical Layer	20.03.2019 – 19.04.2019
	Detailed Layer	
Temperature-based optimization	Cylindrical Layer	
	Detailed Layer	
Phantom development and building of measurement setup		19.04.2019 – 13.05.2019
Report & Presentation		13.05.2019 – 27.05.2019
Prototyping	Antenna element	EE 492
	Phantom	
Measurements	System level measurements	
	Heating measurements	
Report & Presentation		

The antenna parameters will be optimized using outputs of each layer structure as feedbacks step by step from the simplest one (single layer) to the most complicated one (detailed layer) considering both power density-based optimization and temperature-based optimization and hence, they will be considered as a whole.

6. Realistic Constraints

a. Social, Environmental and Economic Impact

Although from an economical point of view, the project does not aim for any profit or further labor, if the project will turn out to be a real success, then it will yield a great economic and social benefits for users and device manufacturers. Moreover, using the designed antenna will save the patients and physicians a lot of time, because the implant antenna has its own feedback mechanism. Implicitly it will reduce the cost associated with the healthcare and it will improve the healthcare provided. It is a fact that implanted wireless devices are going to find wider application in tomorrow's world. Whether my project will be completed successfully is not going to change this fact.

b. Cost Analysis

The project requires a workstation on which the simulations to be implemented. I will be using the workstation of BOUNTENNA during my project. To create the measurement setup a vector network analyzer (VNA), a rotary stage and absorbers will be used. In addition to these costs, a 3D printer and chemicals will be used to create the phantom which should imitate the biological tissue. These materials should also be included in the costs. Moreover, I will be investing a specified amount of time for this project throughout the year. My plan is to work at least for three days each week for a faster progress.

c. Standards

In this project, the engineering ethics and code of conduct will be considered. Besides, the IEEE, IET, ETSI and EU standards will be followed in addition to Turkish standards.

7. References

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