# Negative Material Inspired Microwave Water Heating System

by

Humayra Naosaba

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2014

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

# Abstract

Microwave heating is considered as a very beneficial heating methodology for liquids because it can provide non-contact delivery of energy. Recent studies are focusing on the use of an electrically small resonator, such as a split-ring resonator for liquid heating purposes for its ability to concentrate electric energy in its gap which can be translated into heating. The thesis proposes a novel and effective microwave water heating system based on split-ring resonators which cultivates a completely innovative approach resulting in more energy efficient outcomes. The thesis also provides a clear and step-by-step manual for conducting numerical analysis for microwave heating carried out by using multiple software tools, which can save valuable time for future researchers. The major section of the thesis presents the structure, dimensions and heating performance of the proposed heating elements, and different comparisons have been carried out for characteristic and performance realization of the heaters. The system provides very promising heating results numerically, such as for an input power of only 2 watts the system heats water up to 41 °C from room temperature in 60 seconds. These results establish that along with eliminating the shortcomings faced by currently employed household water heating systems, the proposed model is destined to be a promising and more energy efficient solution for meeting household water heating demand in future years.

# Acknowledgements

First of all, I express my gratitude to God Almighty for providing me the strength, self-belief and drive to accomplish this thesis work.

I would like to express my sincere gratitude to my supervisor, Dr. Omar Ramahi. He has always provided motivation and inspiration in cultivating new ideas. He always encourages asking questions, which inspires his students to nurture an inquisitive soul. I would like to thank him for his guidance that helped me improve my technical skills and academic knowledge.

I extend my deepest thanks to my committee members Dr. Rafaat R. Mansour and Dr. Bo Cui, I greatly appreciate the time they will be devoting to this.

I would like to convey my utmost gratitude to my family for their support, love and blessings. They have stood as the biggest cornerstones of my life.

I am very lucky to be a member of an active and friendly research group. I would like to thank all my colleagues in the microwave and electromagnetics research group at the University of Waterloo. Special thanks to Miguel Ruphuy, Thamer Almoneef, Ali Albishi, Dr. Babak Alavikia, Ahmed Ashoor and Mohamed Albadawi for their invaluable discussion, knowledgeable suggestions and sincere goodwill. I have learned so much from every person mentioned above, and the knowledge I acquired from them have been crucial in this research work.

# Dedication

***To my family***

## Table of Contents

**List of Tables**

**viii**

**List of Figures**

**ix**

**1 Introduction ........ 1**

1.1 Introduction ........ 1

1.2 Thesis Contribution ........ 2

1.3 Thesis Organization ........ 3

**2 Background ........ 4**

2.1 Introduction ........ 4

2.2 Microwave Heating of Liquids: History and Significance ........ 5

2.3 Recent Research Developments on Microfluidic Heating ........ 9

**3 Performance Investigation of Software Tools and Validation of Heating Process ...... 12**

3.1 Introduction ........ 12

3.2 HFSS and Ansys Multiphysics ........ 13

3.2.1 Workflow Procedure ........ 13

3.2.2 Technical Complications ........ 15

3.3 CST ........ 16

3.3.1 Workflow Procedure ........ 16

3.3.2 Comparison and decision ........ 19

3.4 Validation of heating process using CST ........ 19

3.4.1 Summary of Experimental Study ........ 20

3.4.2 Results Confirming Validation ........ 21

3.5 Non-linear Relationship of Heating with Water Volume ........ 23

3.6 Conclusion ........ 24

**4 Developing Efficient Water Heating System Model Using Metamaterial and Performance Comparison ........ 26**

4.1 Introduction ........................................................................................................ 26
4.2 Microfluidics and Metamaterial ........................................................................ 27
4.3 Properties of Water and Response to Microwave Radiation........................................ 30
4.4 SRR Design and Frequency Responses ......................................................... 33
4.5 Single Element Heater Model ........................................................................ 37
4.6 SRR-Array Heater Model................................................................................. 41
4.7 Comparison with regular household heaters ................................................... 44
4.8 Conclusion.................................................................................................... 45
**5 Conclusion and Future Work Directions.......................................................... 46**
5.1 Conclusion.................................................................................................... 46
5.2 Future Work ................................................................................................. 47
**References........................................................................................................ 49**

## List of Tables

Table 1: Non-linear trend of temperature increase ................................................................ 24

Table 2: Comparison between different input power & effect in temperature over time....... 40

# List of Figures

Figure 2.1: The heater consists of a coplanar transmission line (yellow) deposited on glass with the PDMS chip bonded on top. The fluid channel (blue) is between the ground-signal-ground conductors [18]. .......... 6
Figure 2.2: Absorption ratio as a function of frequency for empty and filled microchannels [18]. .......... 6
Figure 2.3: A schematic of the microwave heater: the microchannel carrying fluid droplets is in between two metal transmission line conductors [25]. .......... 7
Figure 2.4: Electric field distribution inside an air filled rectangular wave guide [38]. .......... 8
Figure 2.5: Electric field distribution of a rectangular wave guide with liquid layer inserted into the wave guide [38]. .......... 8
Figure 2.6: The proposed electrically small resonator heating-sensing element excited by a loop excitation structure [40]. .......... 10
Figure 2.7: The heating response of the proposed system tested on single phase water [40]. 10
Figure 3.1: Decision chart containing steps for iteration loop of HFSS-ANSYS. [1] .......... 14
Figure 3.2: Establishing link manually between HFSS and Ansys simulation structures .......... 15
Figure 3.3: Procedure of assigning simultaneous excitation (left) and combining results(right) for multiple heat sources in CST .......... 18
Figure 3.4: Assigning thermal loss in CST Mphysics studio by directing to the combined ports .......... 18
Figure 3.5: Experimental setup of microwave heating: a picture, b diagram [6] .......... 20
Figure 3.6: The comparison of the temperature distribution within the water layer between the predicted and experimental results at various positions inside water sample [6] .......... 21
Figure 3.7: CST screen shot of water sample temperature distribution after 60 s .......... 22
Figure 3.8: Temperature vs. time distribution at various positions inside water sample .......... 23
Figure 4.1: A microfluidic chemostat, dyes are used to trace the microchannels [7] .......... 28
Figure 4.2: A simple, inexpensive microfluidic diagnostic device [7] .......... 28
Figure 4.3: Different shapes of metamaterial particles proposed in the literature [8] .......... 29

Figure 4.4: Applied electric field and resultant polarization in water [14]............................ 31
Figure 4.5: Dielectric permittivity and dielectric loss of water between 0°C and 100°C [14]32
Figure 4.6: Dielectric permittivity and dielectric loss of a dilute salt solution between 0°C and 100°C; the solid lines shows pure water curve as Figure 10 .......................................... 33
Figure 4.7: Microstrip couples SRR. (a) Diagram, (b) Equivalent circuit [12]...................... 34
Figure 4.8: E-field distribution on the gap of SRR................................................................ 35
Figure 4.9: Numerical simulation result of reflection coefficient response of the bare SRR and effect on S11 due to the presence of water at the gap of the SRR .................................. 36
Figure 4.10: Design of the single SRR element microwave heater model from different angles in CST. ....................................................................................................................... 37
Figure 4.11: Temperature distribution in the water pipe ....................................................... 38
Figure 4.12: Power loss distribution in the water pipe .......................................................... 38
Figure 4.13: Power loss graph of SRR single element heater model..................................... 39
Figure 4.14: Temperature vs. time graph for various input power of the heater model ......... 41
Figure 4.15: Heating element with three resonators stacked on top of each other ................. 42
Figure 4.16 Heating element with three resonators placed side by side ................................ 43
Figure 4.17: Cross section view of a multiple element heater model showing the temperature distribution in three water channels .......................................................................... 44

# Chapter 1

# Introduction

## 1.1 Introduction

Common features of currently employed household water heating systems are significant amount of energy loss and inefficiency. Both tank-style and tank-less household heaters spend a lot of energy to heat the water to an extremely high temperature, only to have the users mix it with cold water flow during our daily use. This situation is very common and we face it multiple times during our daily life, but the implication of this is hardly ever pondered upon. The motivation for this thesis came from this exact circumstance. This phenomenon suggests that we can save a significant amount of energy by changing the way we have designed our household water heating systems. Unlike most currently employed household water heaters, the objective set out in this research work is to eliminate heating up water in a tank, storing the hot water and distributing afterwards. The proposed method offers to heat water on-the-go as if flows through the pipes, eradicating unnecessary power loss.

The work presented in this thesis is aimed at proposing a metamaterial resonator based microwave water heating system. In many recent research studies, microfluidics has been integrated with metamaterials in heating of fluids. The discussion of Microfluidics play an important role in the scope of the thesis because the work presented here has been inspired by this relatively new and exciting field, using metamaterial as the base component.

Microwave heating is a very advantageous fluid heating approach because of its preferential heating ability and non-contact delivery of energy. The use of microwave heating has been demonstrated for a variety of applications including drug discovery [19], PCR [20, 21], isolation of DNA [22] and heating of biological cells [23]. A lab on a chip system for simultaneous sensing and heating of droplets in microfluidic devices was proposed by Boybay et al. in 2013, which is an example of combining metamaterial principles in order to provide microwave liquid heating [40]. The applications of metamaterial include but are not limited to creating perfect lenses and absorbers [9, 10], crack detection [11], solar cells efficiency improvement, and even invisibility cloaks [34, 35].

The method that is proposed in this thesis work is based on the characteristic of a split-ring resonator, the most commonly used metamaterial component. The SRR is able to concentrate electric field in its gap at resonance. As a result of this electric field concentrated across the SRR gap, a voltage build up occurs in the gap allowing this energy to be harvested if a load is placed across the gap. The purpose of this work is to translate this electrical energy by heating water load placed at the gap of the SRR.

## 1.2 Thesis Contribution

The research work presented in this thesis provides three main contributions: A manual for using multiple commercial software simulation tools for conducting microwave heating experiments have been developed. A proof of concept through simulation is provided in the form of validation resulting in extremely accurate responses. Finally, multiple split-ring resonator based microwave water heating models have been proposed that eliminate these shortcomings of regular household water heating systems and are likely to be a promising and more energy efficient solution for household water heating demand in future years.

## 1.3 Thesis Organization

Chapter 2 reviews the history and development of the research advancements in the field of microwave heating using metamaterial and microfluidic systems. Some notable research works have been discussed including analysis of the system and the proposed results.

Chapter 3, detailed analysis which was carried out by using multiple software tools in order to conduct microwave heating simulations of interest. To authenticate the simulation procedure, validation of a paper published in the Food and Bioprocess Technology Journal in 2011 was conducted. Validation proofs have been provided to ensure that the simulation process that will be used for microwave heating analysis in later chapters of this thesis is correct and the results are reliable.

Chapter 4 proposes a novel and efficient water heating system based on a metamaterial element named Split Ring Resonator (SRR).The design methodology of a split ring resonator is explained along with its electric field distribution and resonant frequency phenomenon. A single SRR heating model and two SRR-array heating models has been proposed. The structure, dimensions and heating performance of the heating elements have been discussed, and different comparisons have been carried out for characteristic and performance realization of the heaters.

Finally, in Chapter 5 a summary of the thesis is presented, highlighting the contributions of the proposed microwave water heating system. In addition, some concluding remarks and suggestions for future work are provided.

# Chapter 2

# Background

## 2.1 Introduction

Before delving into the detailed analysis of the conducted research work presented in this thesis, a brief overview of the research advancements in the field of interest has been presented in this chapter. The discussion has remained focused on microwave heating with inclusion of metamaterial and microfluidic systems. Some notable research works have been discussed including analysis of the system and the proposed results.

## 2.2 Microwave Heating of Liquids: History and Significance

Researchers have investigated multiple conduction based heating methodology for microfluidic systems including resistive heating, mico-Peltier junctions, Joule heating [15-17]. A disadvantage of such methods is all of them require direct physical contact between the target fluid and the heating structure for the heat to be delivered to the fluid. Internal heaters such as Joule heaters function by applying an electric current through the fluid. Applying electric current to a localized region inside a fluid volume can be challenging, hence this type of heating methodology cannot achieve localized heating. An example of external heating system is resistive heater, which work by using the principle of heat conduction. Using infrared and laser technology to heat fluid has received attention from the researchers as they can achieve fast switching between heating and cooling. However these can require quite expensive equipment and very sensitive optical alignment, which is a limitation to their application.

Microwave heating is a very advantageous fluid heating approach because of its preferential heating ability and non-contact delivery of energy. It is considered as a direct heat transfer method where energy can be delivered to the target material with no interference from the substrate. The use of microwave heating has been demonstrated for a variety of applications including drug discovery [19], PCR [20, 21], isolation of DNA [22] and heating of biological cells [23].

In 2007, Shah et al. presented a non-contact dielectric heating methodology for micro fluidic lab on a chip systems using microwaves at various frequencies. The authors presented an experimental method which shows the effectiveness of the system. For the experiment they used several chemicals that allow comparison of temperature of fluids as they glow with increasing temperature.

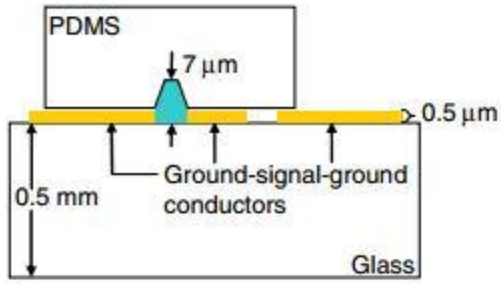


**Figure 2.1: The heater consists of a coplanar transmission line (yellow) deposited on glass with the PDMS chip bonded on top. The fluid channel (blue) is between the ground-signal-ground conductors [18].**

The system includes a thing film microwave transmission line integrated with a micro fluidic channel. The micro channel is fabricated with PDMS (Polydimethylsiloxane) and is aligned with a thin film microwave transmission line in a coplanar waveguide configuration. The fluid used for the experiment is water at different ionic concentrations. [18]

The above mentioned heating methodology achieved to heat the liquid through a non-contact energy delivery. The authors also claimed that there was no interference of the substrate material in the heating process. However, this heater structure does not achieve localized heating and exhibits low energy harvesting due to loss in the PDMS and metallic conductors. Figure 2.2 exhibits a significant amount of energy loss even with an empty microchannel.

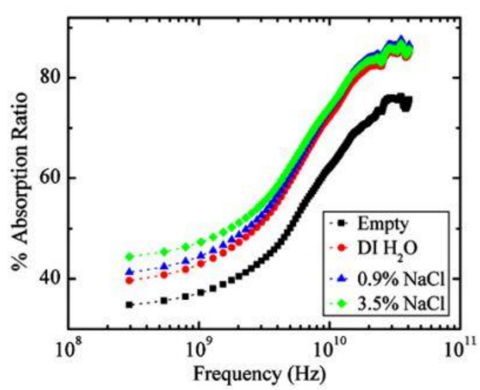


**Figure 2.2: Absorption ratio as a function of frequency for empty and filled microchannels [18].**

A coplanar waveguide (CPW) is a commonly used microwave transmission line. It has been integrated with a fluidic microchannel for on-chip spectroscopy measurements [24]. In 2009, Issadore et al. utilized this concept of using a transmission line structure as the heating element for droplet heating.

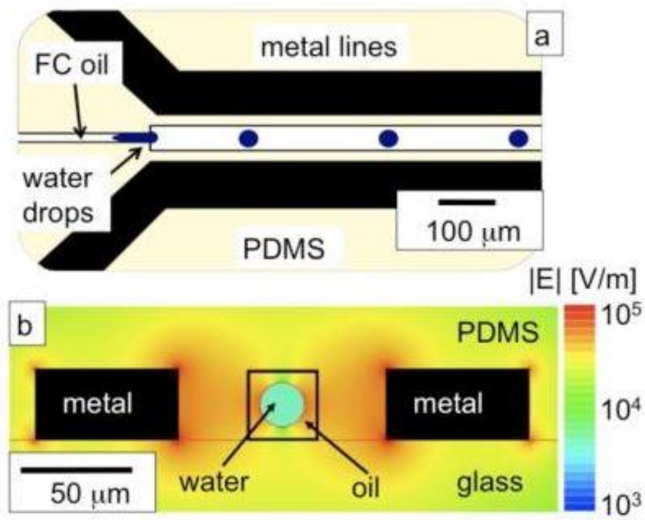


**Figure 2.3: A schematic of the microwave heater: the microchannel carrying fluid droplets is in between two metal transmission line conductors [25].**

The heating element is considerably large compared to the fluid channel and the droplets passing through it, which limits the system's ability to achieve selective heating. The heating speed was evaluated by calculating the time that is required for the droplet temperature to approach saturation under microwave power.

The above mentioned microwave heaters designs exhibit some deficiencies. Designs that are based on transmission line have limitations regarding concentrating the electromagnetic field on targeted areas. Also the energy is not harvested efficiently due to the large amount of loss in the substrate and the associated heater elements. To avoid these consequences, introducing electrically small resonators as heating elements is a better substitute of transmission line structures. It has been showed in [26] that negligible radiation is associated with these types of resonators and the bulk of the energy is dissipated in the form of heat.

Ratanadecho et al. published an interesting analysis of investigating the interactions within a liquid layer under influence of microwave heating using a rectangular waveguide. They proposed a complete mathematical model and provided experimental verification. It was documented that the variation of microwave power level and electric conductivity value changes the degree of penetration and rate of heat generation within liquid layer [38]. Figure 2.4 and figure 2.5 shows the electric field distribution inside the wave guide in presence of air and liquid.

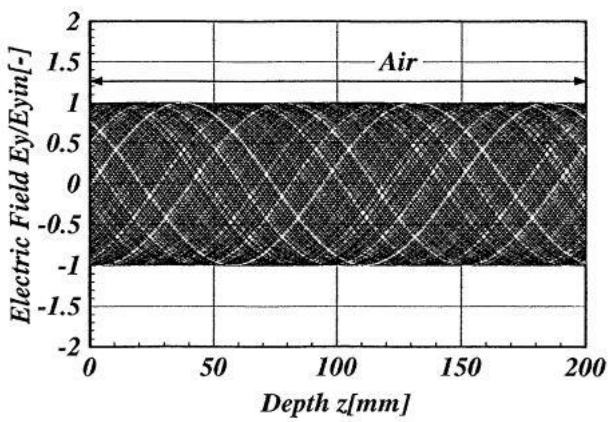


**Figure 2.4: Electric field distribution inside an air filled rectangular wave guide [38].**

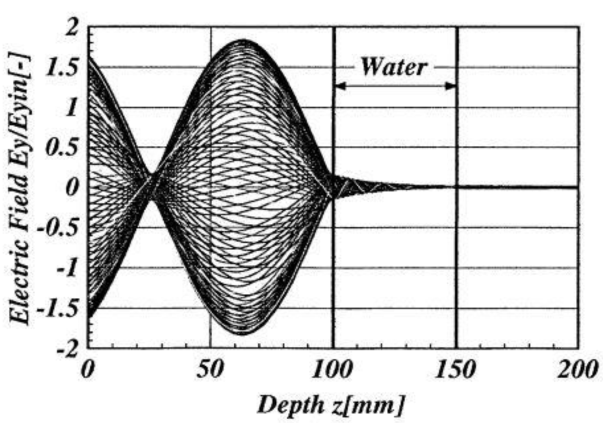


**Figure 2.5: Electric field distribution of a rectangular wave guide with liquid layer inserted into the wave guide [38].**

In 2010 Kawasaki et al. presented a novel microwave liquid heating system in an open space consisting of rectangular wave guide with numerous holes that are much smaller than the wavelength in the wave guide. As the holes in the wave guide are very small compared to the wavelength, the microwaves generated from the 2.45 GHz magnetron are confined inside the heating unit and do not radiate outside [39].

## 2.3 Recent Research Developments on Microfluidic Heating

This section focuses on the analysis of a lab on a chip system for simultaneous sensing and heating of droplets in microfluidic devices proposed by Boybay et al. in 2013. This proposed system (Figure 2.6) deals with nano liter sized droplets and the authors experimentally demonstrated the sensing capabilities and numerically demonstrated the heating capabilities. The sensing capability of the system was demonstrated through the difference in response of the system when tested with different liquids such as glycerol mixtures, saline water, Silicon oil, milk, cream, etc. They have also employed this system to thermally initiate the formation of Hydrogel particles out of the droplets that are being heated by the system. [40]

They major building block of this heating system is an electrically small resonator that has the ability to differentiate between materials possessing different electrical properties. The change in these properties causes a shift in the operating frequency of the electrically small resonator. Therefore by the perturbation theory is becomes possible to find out which material it is. As a heating element, the system acts based on the following principal: “If microwave power is delivered to the sensing region at the frequency associated with a particular material l (i.e. droplet), then only this material receives the power while passing the resonator leaving the surrounding materials (i.e. carrier fluid and chip material) unaffected.” [40]

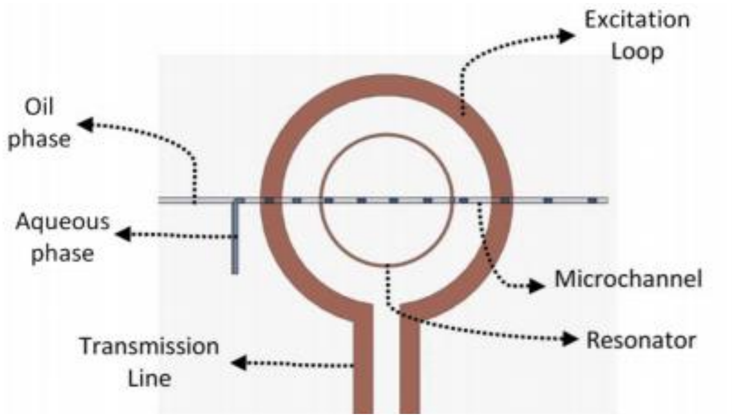


**Figure 2.6: The proposed electrically small resonator heating-sensing element excited by a loop excitation structure [40].**

Figure 2.7 represents the heating performance of the system on single phase water. The optimum operating frequency for achieving the maximum temperature depends on the dielectric constant of water. As the permittivity and the temperature has an inversely proportional relation, the optimum frequency increases with increase in temperature.

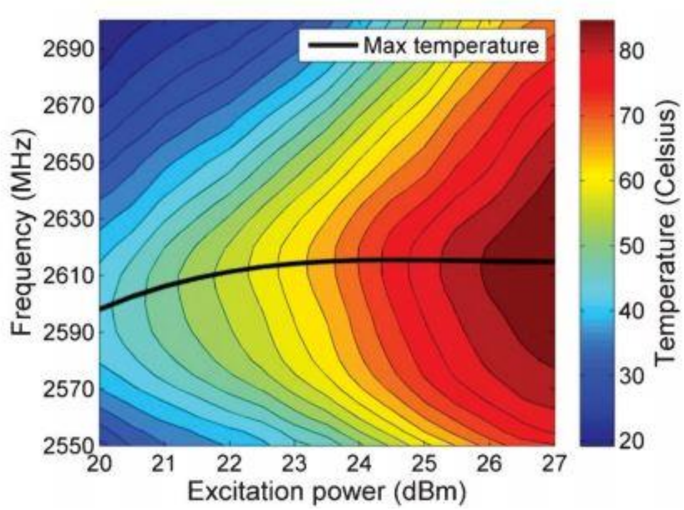


**Figure 2.7: The heating response of the proposed system tested on single phase water [40].**

The system achieves remote heating eliminating fluid contamination. It also offers simultaneous sensing and heating. The frequency shift, which indicates the sensitivity of the sensor, is a function of the permittivity contrast between the droplet and its surrounding medium & volume of droplet.

# Chapter 3

# Performance Investigation of Software Tools and Validation of Heating Process

## 3.1 Introduction

The first section of this chapter summarizes the detailed analysis which was carried out by using multiple software tools in order to conduct microwave heating simulations of interest. The objective is to document the important technical information regarding the procedures for later re-enactment. After various comparisons, CST Studio Suite was selected as the preferred software and every simulation hereafter was done using CST. To authenticate the simulation procedure, validation of a paper published in the Food and Bioprocess Technology Journal in 2011 was conducted. It is a common practice for researchers to replicate a published work to duplicate the results, in order to approve or certify the experimental process. The detailed investigation and results of this study have been documented in the second section of this chapter.

## 3.2 HFSS and Ansys Multiphysics

HFSS, or formerly known as Ansoft HFSS [2] is a very popular commercial electromagnetic simulation software. Ansoft was recently bought by the company named ANSYS, and the software is now known as ANSYS HFSS [5]. The ANSYS Multiphysics [3] is a separate software workbench that helps building coupled analyses involving multiple areas of physics. The last few versions of ANSYS have the ability to be linked to the electromagnetic simulation results conducted by HFSS. The link between HFSS and ANSYS Mechanical performs an auto mapping of the meshes between the two software products. HFSS and ANSYS branched together can act as a platform to model the thermal-electromagnetic responses of RF circuits. Both software tools are based on Finite Element Method (FEM) [1].

### 3.2.1 Workflow Procedure

During or after the installation of HFSS, it needs to be made sure that the integration operation with a similar model of ANSYS has been enabled. Once HFSS is successfully integrated with ANSYS, the electromagnetic response of the model is computed by HFSS. The following two types of losses are extracted from HFSS simulation outputs:

(i) Surface loss density ($W/m^2$), resulting from metallic losses.

(ii) Volume loss density ($W/m^3$), resulting from the dielectric losses.

These electrical results including losses are imported to ANSYS, ANSYS maps the surface and volume losses from HFSS and conducts mechanical simulations to acquire thermal responses. The thermal response will be a function of the input power level of the microwave signal and also the frequency.

The process is then reversed by importing the thermal results from ANSYS back to HFSS. EM simulations are carried out in HFSS to recalculate the losses and the process is repeated many times until a converged criterion is satisfied. The decision chart shown in Figure 3.1 explains the process [1].

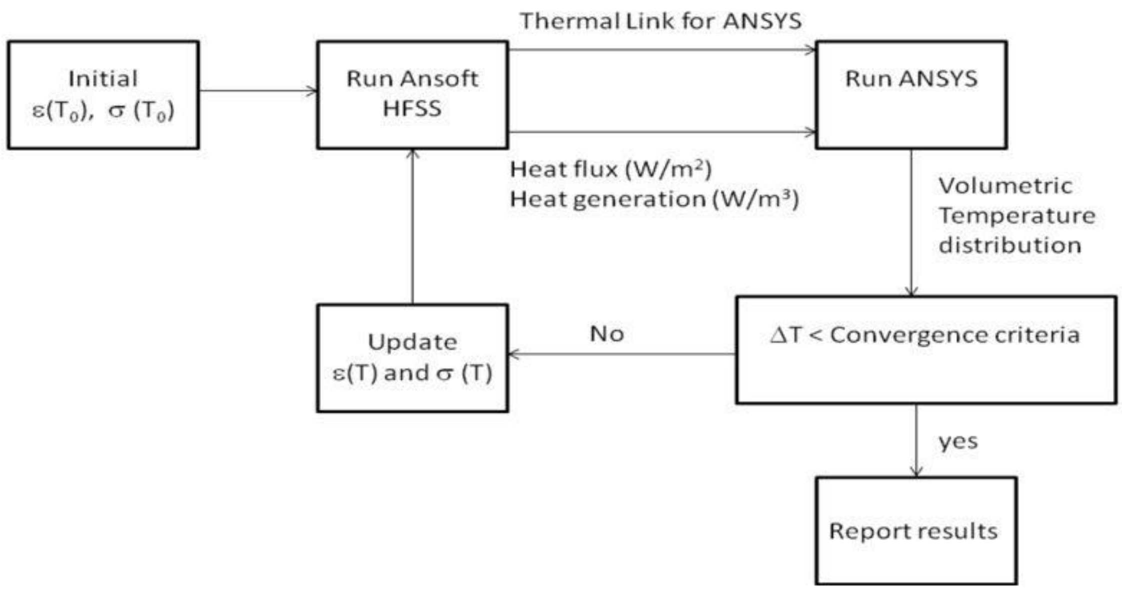


**Figure 3.1: Decision chart containing steps for iteration loop of HFSS-ANSYS. [1]**

After creating the model design and running EM simulation in HFSS, the electric field is plotted and the dissipated power is calculated. This design and simulation is then imported to Ansys and they need to be linked with each other as depicted in Figure 3.2.

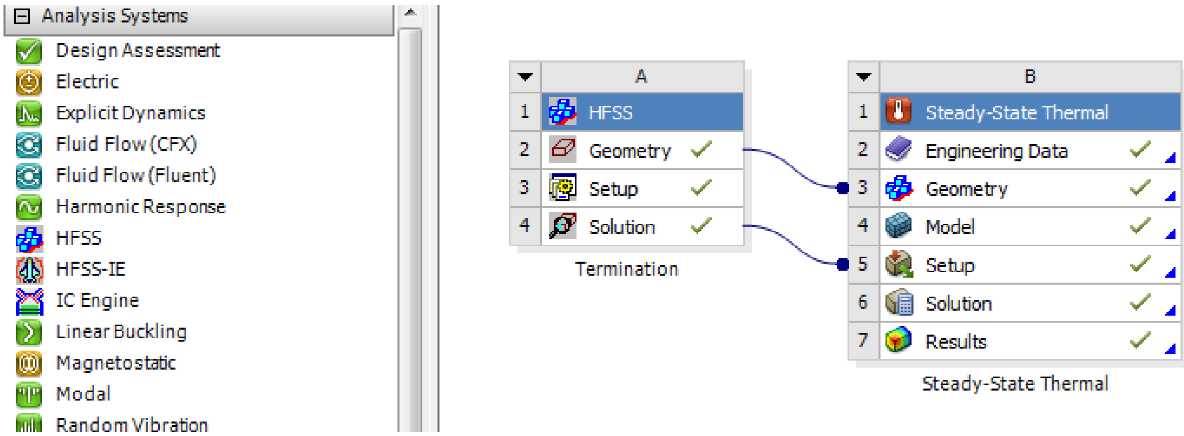


**Figure 3.2: Establishing link manually between HFSS and Ansys simulation structures**

The data gathered from HFSS simulation results need to be transferred to Ansys workbench, thermal properties need to be set up and the materials in Ansys workbench need to be manually selected and assigned to the structure to replicate the HFSS model. After the structure geometry has been updated in Ansys workbench thoroughly, the heat flux and heat generation is assigned to the structure in order to complete the thermal analysis. Heat flux is imported from HFSS simulation and assigned to the outer faces while heat generation is assigned to the inner volumes. Heat dissipation is specified by assigning convection to the outer faces of the structure. A convection coefficient also needs to be assigned. Having completed all these steps, one can run the simulation and generate thermal result data.

### 3.2.2 Technical Complications

The major complication with this HFSS-ANSYS coupling was importing the HFSS simulation results to ANSYS. After importing the results from HFSS, one needs to link the geometry of HFSS to ANSYS workbench and the solution from the HFSS needs to be linked to the setup of ANSYS workbench. The geometry in Ansys needs to be manually updated to mirror the exact geometry of the design in HFSS. However, the material library of ANSYS workbench does not have an adequate amount of materials, and often I was unable to find the exact material in ANSYS library that was used prior in HFSS.

After importing the results from HFSS, heat flux and heat generation needs to be assigned in ANSYS. Temperature dependency for material under test (water) also needs to be defined by modifying dielectric constant and loss tangent. As dielectric constant is temperature dependent, we need to add thermal modifier for that too. The equations and variables to use for setting up these relations is not explicit and the way of conducting these procedures were not well documented and well explained in any literature or documentation found online. All the drawbacks discussed in this section were inspected during early January 2014 using HFSS 14.0 (64-bit) and Ansys workbench 14.5. Recent software updates may have eradicated the drawbacks discussed here.

To sum up, many deficiencies in the ANSYS workbench discouraged me from choosing this as the software tool to be used for the research simulations at that time. The procedure was ambiguous and complex, there was lack of available online technical support and the software was not found to be user friendly.

## 3.3 CST

CST Studio Suite [4] is one of the popular commercial electromagnetic simulation software tools that comprises of a range of different modules. The modules include CST Microwave Studio, EM Studio, Particle Studio, Cable Studio, PCB Studio, Mphysics Studio and Design Studio. CST benefits from an integrated design environment which gives access to the entire range of solver technology. All the different studios are integrated in a user friendly design environment. The Time Domain Solver is based on Finite Integration Technique (FIT) and the Frequency Domain Solver is based on Finite Element Model (FEM).

### 3.3.1 Workflow Procedure

A combination of two CST Model Suits is necessary for gathering microwave heating information for the model: CST Microwave Studio and CST Mphysics Studio. Data can be easily transferred between the high frequency CST MWS EM simulation codes and CST MPS. First the model is designed in the Microwave Studio and EM simulations are carried out normally, with storing a power loss field monitor and generating thermal loss. Once EM simulation finishes, we go to Mphysics Studio to find out the thermal response of the model.

In the thermal simulation, the power loss from the plane wave acts like a heat source, and it is included via the thermal loss specification which points to the EM simulation. This is a notable difference from using ANSYS Workbench as thermal simulator. Recall in ANSYS it was essential to manually assign the heat source and the heat flux in the structure model. Few additional steps that need to be considered are:

- Background material: We need to assign an appropriate thermal property to the background material.
- Field monitor: These monitors are assigned to observe the results of the heating process in the time domain for either a point inside the structure or the whole volume.
- Surface condition: Assigning a thermal surface condition is essential for realistic implementation of the numerical model and to receive results as close to experimental reality as possible.

In addition to these, appropriate EM and thermal boundary conditions need to be applied for the simulations. To observe the temperature increase, timing information needs to be provided. For temperature dependent properties of material, an iteration loop can be assigned using CST Design Studio to conduct EM-thermal analysis automatically.

In order to use multiple heat sources, which have been used in chapter 4 for SRR-array heating element, one may choose to use either a combined result or simultaneous excitation. One of the proposed array heating models consists of three excitation ports. In such cases, after finishing the electromagnetic simulation one needs to combine results on the post processing tab and then select the combine action as showed in Figure 3.3. The amplitude column next to the excitation column denotes the power by which the individual ports are being excited. Assigning 1 to these fields denote delivering a peak input power of 0.5 Watt to the system. The next step would be to import the combined power loss into MPhysics studio for thermal analysis.

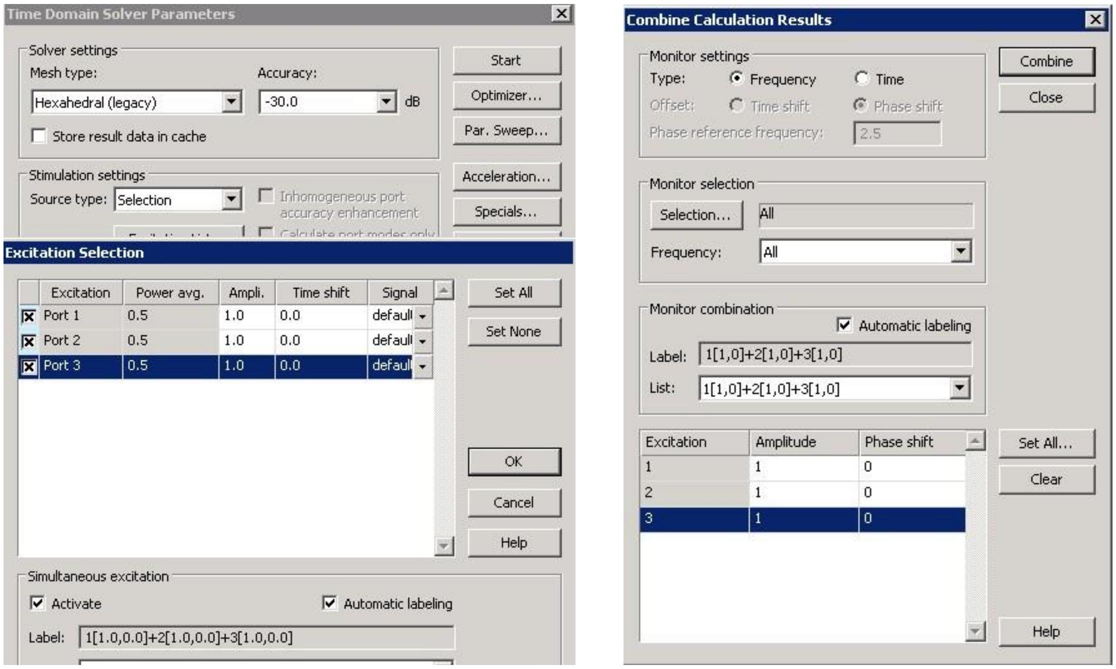


**Figure 3.3: Procedure of assigning simultaneous excitation (left) and combining results(right) for multiple heat sources in CST**

While defining the thermal loss distribution in CST Mphysics studio, one needs to make sure to choose the power loss generated via the combined excitation as showed in Figure 3.4.

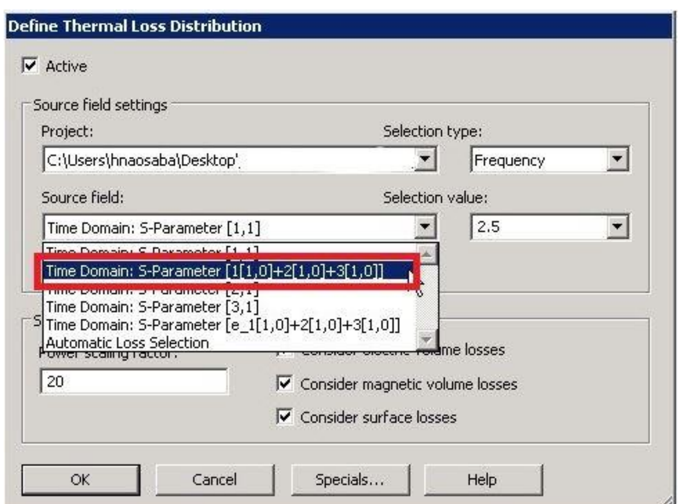


**Figure 3.4: Assigning thermal loss in CST Mphysics studio by directing to the combined ports**

### 3.3.2 Comparison and decision

Few key factors that highlight the differences in terms of workflow procedure of using the above mentioned software tools for conducting microwave heating simulations have been listed below:

- The fact that there is no requirement of importing or exporting simulation results made the procedure very straightforward in CST.
- The process of assigning heat source is so much simpler in CST compared to ANSYS. There is no room for complication as the power loss from the EM simulation in CST Microwave Studio acts as the heat source in the CST MPhysics Studio, eradicating the need for specifying any additional information about the field/ports and manual designation of heat source and heat flux.
- The process of adding temperature dependent dielectric constant is very clear compared to ANSYS. First two iterations of EM and thermal are done as normal, and the field results achieved from the thermal simulation is imported to the old EM simulation to add temperature dependency. In the material properties section, the dielectric constant needs to be assigned as a temperature dependent property and provide the relationship between permittivity and temperature. CST has a specified simulation platform assigned for automation of multiple loop iteration of EM-thermal-EM-thermal type called CST Design Studio.
- Also prompt and efficient online technical support was available.

All these factors played a crucial role in making the decision to select CST Studio Suite for all numerical analysis of the thesis.

## 3.4 Validation of heating process using CST

In 2009, Rattanadecho et al. [6] conducted experimental and numerical investigation on the heating process of water and oil using microwave oven using rectangular waveguide. They first developed a numerical model which was legitimized using experimental study. In this thesis, the experimental model from [6] has been duplicated in CST Microwave Studio and the heating results achieved by CST simulation are very close to the experimental study which validates the simulation process used for microwave heating in CST.

### 3.4.1 Summary of Experimental Study

In the experimental apparatus, a magnetron generates plane wave at 2.45 GHz at microwave power of 300 Watts, which travels along the z- direction of a rectangular wave guide. The wave guide contains a water load of dimensions of 54.61 (X) x 54.61 (Y) x 54.61 (Z) $mm^3$. To prevent the damage of the magnetron by any microwave reflected from the sample, an isolator is used. As the plane wave travels through the wave guide it heats up the water sample and the temperature readings are plotted. A wattmeter using a directional coupler measures the power of the incident and transmitted waves. The temperature measurement is carried out by using fiber optic probes which are inserted into the sample. The sample container is made out of polypropylene which does not interact with microwave, hence does not get heated [6]. The experimental setup is demonstrated in Figure 3.5.

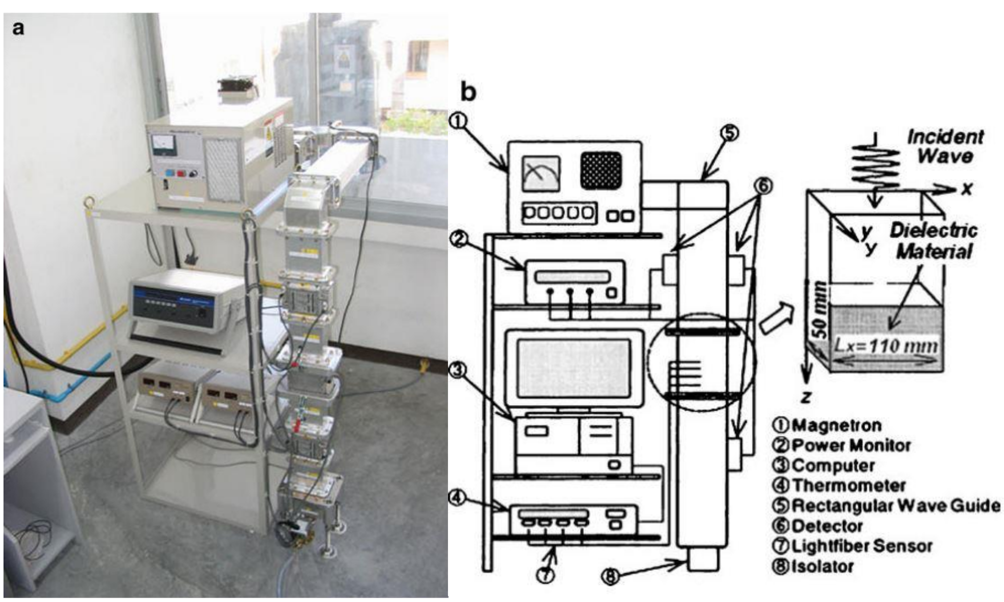


**Figure 3.5: Experimental setup of microwave heating: a picture, b diagram [6]**

### 3.4.2 Results Confirming Validation

To compare the heating results achieved by the experiment and our simulation, we inspect the Figure 3.6 provided in the paper [6].

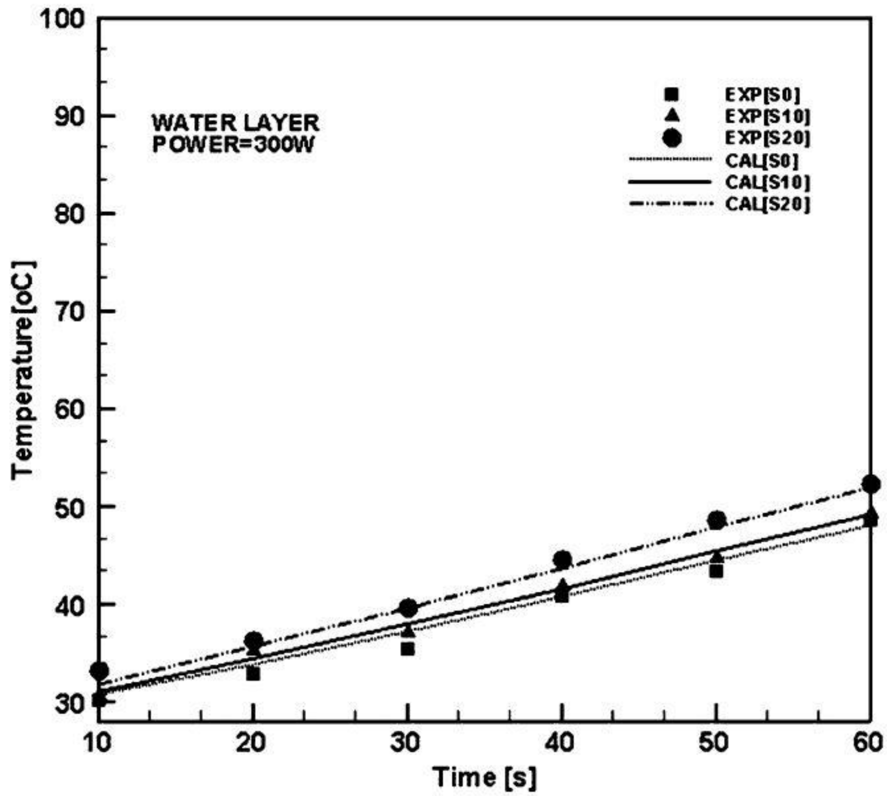


**Figure 3.6: The comparison of the temperature distribution within the water layer between the predicted and experimental results at various positions inside water sample [6]**

Focusing on the experimental results, we can see that the maximum temperature the water sample reaches after 60 s is around 51 degree Celsius. The initial temperature is 28 degree Celsius for all cases. In the numerical analysis conducted in CST, the water sample reached to a maximum temperature of 49.26 degree Celsius after 60 s, which is shown in Figure 3.7.

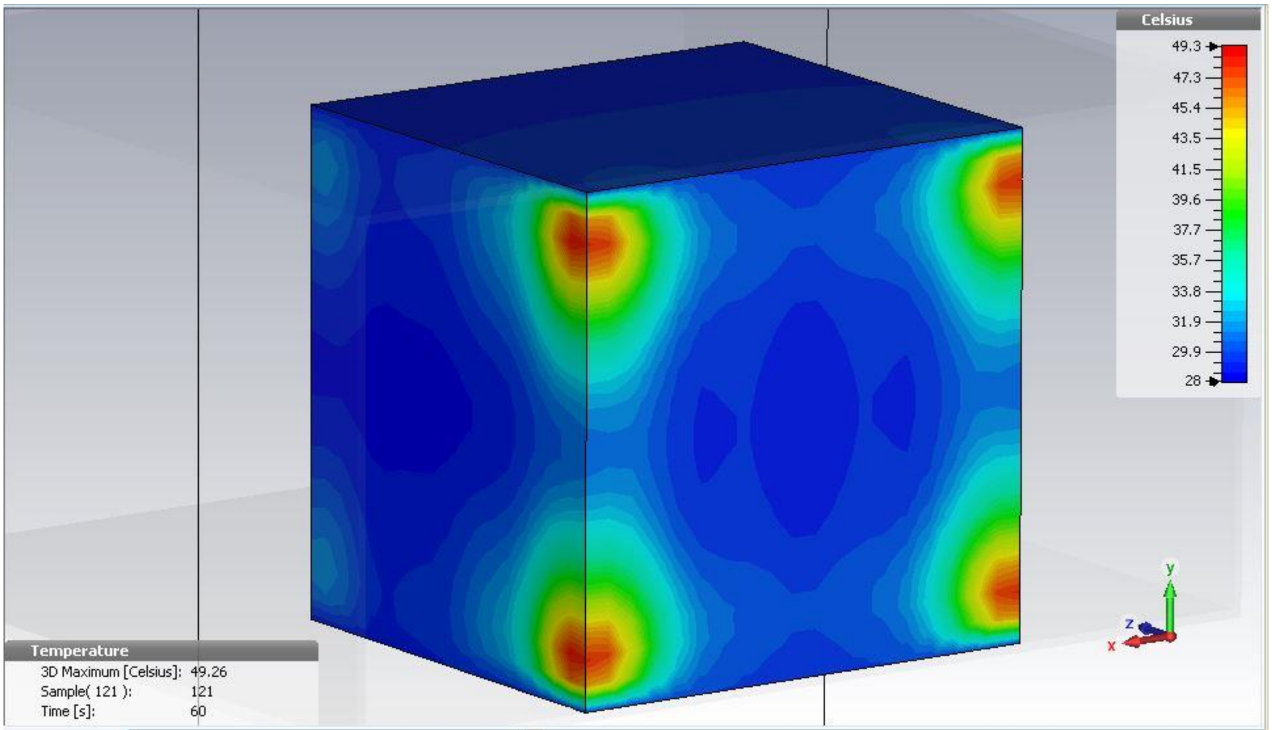


**Figure 3.7: CST screen shot of water sample temperature distribution after 60 s**

This result of temperature increase is extremely close to the experimental results achieved in the discussed paper. According to the paper, as plane wave travels along the Z-direction of the waveguide and hits the water sample, the rate of temperature increase is lowest at the center of the sample and temperature is highest 20 mm away from the center. This is exactly same as the results found during the experimental study conducted in literature [6].

In Figure 3.8, temperature reading after 60 s in various points inside water sample (From center to the edge) is plotted over time. Keeping in mind that the dimensions of water sample are 54.61 (X) x 54.61 (Y) x 54.61 (Z) $mm^3$, temperature rise is minimum at the center of the sample which conforms to the experimental results stated in the paper. As we start getting away from the center, at 27 mm in the X-direction and 21 mm in the Y-direction we get to see much higher temperature after 60 s.

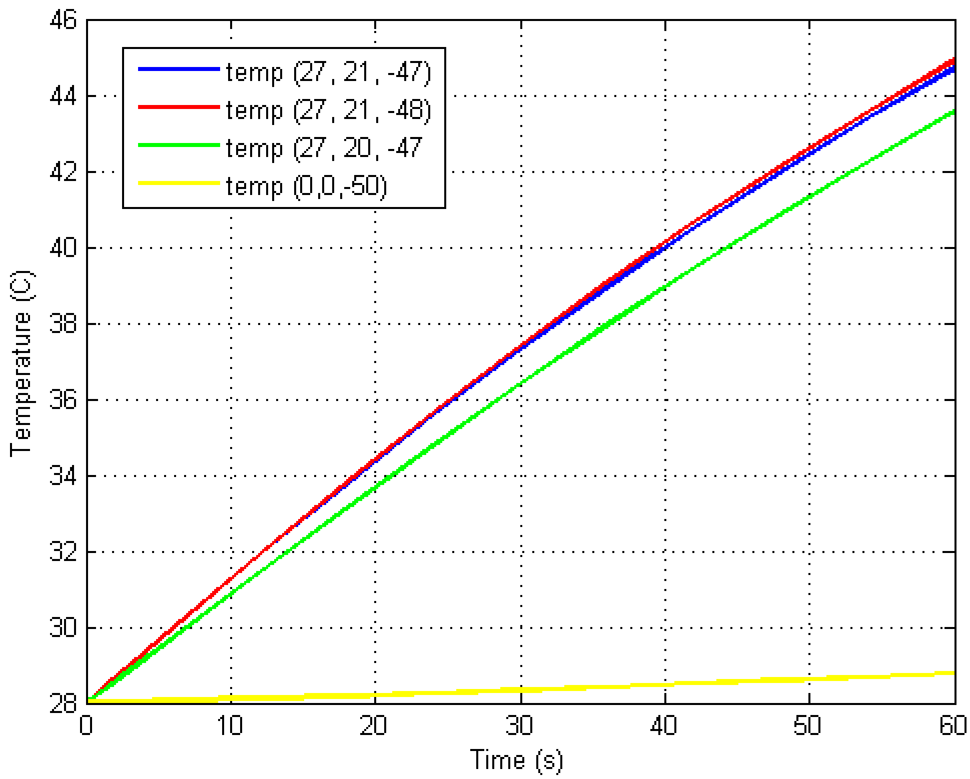


**Figure 3.8: Temperature vs. time distribution at various positions inside water sample**

Analyzing the results provided above, we can conclude that the numerical results achieved using CST is very similar to the experimental study presented in the paper which was verified by a mathematical model. We can safely state that the simulation methods used in CST for microwave heating analysis is correct.

## 3.5 Non-linear Relationship of Heating with Water Volume

For this analysis the same experimental setting as Chapter 3 has been used and the thickness of the water layer has been varied to examine how the temperature response changes with the volume of water sample. The microwave power is 300 W and dimensions of water sample is 54.61 (X) x 54.61 (Y) x 54.61 (Z) $mm^3$. As the plane wave travels through the wave guide it heats up the water sample and the temperature readings are plotted. The thickness of the water layer has been varied to examine hoe the temperature response changes with the volume of water sample. The thickness in the Z-direction is decreased at a liner rate of 2.5 mm and the temperature response is monitored. The objective is to investigate how the water temperature responds to microwave heating as the volume is reduced.

The results show a nonlinear trend of increase in temperature with volume of water which can be observed in the table below.

| Sample Thickness: Z-direction (mm) | Temperature after 60 seconds (℃) |
|---|---|
| 50 | 49.26 |
| 47.5 | 49.5 |
| 45 | 50.1 |
| 42.5 | 50.99 |

**Table 1: Non-linear trend of temperature increase**

## 3.6 Conclusion

This chapter looks at the operation principles and performance of multiple software tools in terms of microwave heating and presents the advantages and disadvantages of these tools from experience. Thorough discussion has been presented regarding HFSS, Ansys and CST Studio Suite for EM-thermal simulations. Several key points that were observed and experienced on the course of this research work have been discussed, important factors have been highlighted and solutions have been presented. These provide as a clear step-by-step manual for conducting numerical analysis of this nature, which can save valuable time for future researchers at the commencement of their research work. A justification of using CST as preferred tool has been presented. Validation proofs have been provided to ensure that the simulation process that will be used for microwave heating analysis in later chapters of this thesis is correct and the results are reliable. A description of the experimental setup has been presented along with the result data that is the means of comparison between the presented numerical method and the published experimental study. The simulations results obtained are almost identical to the experimental results presented in the literature, which confirms that the undertaken procedure is correct.

# Chapter 4

# Developing Efficient Water Heating System Model Using Metamaterial and Performance Comparison

## 4.1 Introduction

This chapter introduces a novel and efficient water heating system based on a metamaterial element named Split Ring Resonator (SRR). First a brief introduction to microfluidics and metamaterial has been presented. The design of an SRR and its frequency response has been inspected. A single SRR heating model and an SRR-array heating model has been proposed, the design principles and performance of both heating models have been analyzed.

## 4.2 Microfluidics and Metamaterial

Handling of biological samples and fluid volume has entered the era of miniaturization. This has resulted in numerous great findings in fields including drug discovery, genetic sequencing and synthesis, cell sorting, single cell gene expression studies and low cost portable medicine [27-33].

Microfluidics is a fairly new and active field of scientific research that combines both science and technology and promises radical potential for the future. This field is still at an early stage of development, emerging in the beginning of the 1980s, but already has shown rapid growth and numerous early stage applications such as biomedical and chemical synthesis, fluidic MEMS, high throughput screening, miniature robotics, etc. It can also be a pivotal method to study the physical properties of the fluids moving in the microchannels.

The term microfluidics can be defined the following way: "It is the science and technology of systems that process or manipulate small ($10^{-9}$ to $10^{-18}$ liters) amounts of fluids, using channels with dimensions of tens to hundreds of micrometers. The field of microfluidics has four parents: molecular analysis, biodefence, molecular biology and microelectronics'' [7]. The technology or methods of fabrication to make microfluidics more accessible to the researchers is an important aspect of the commercial development of microfluidics. In Figure 4.1 a microfluidic chemostat used to study the growth of microbial populations has been shown, and Figure 4.2 displays a device to perform sandwich immunoassay tests which are in extensive use in biomedical research.

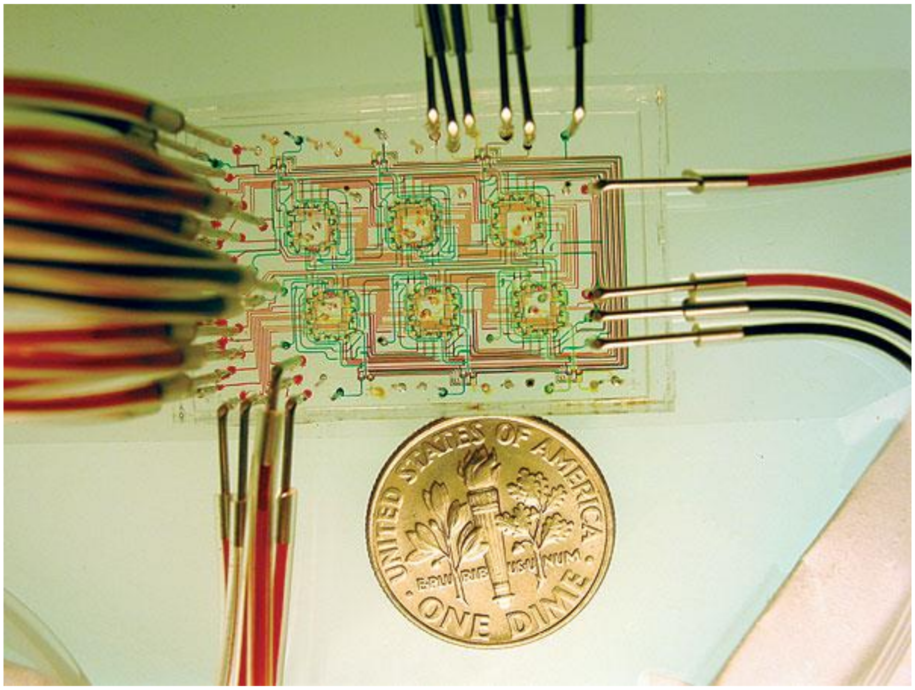


**Figure 4.1: A microfluidic chemostat, dyes are used to trace the microchannels [7]**

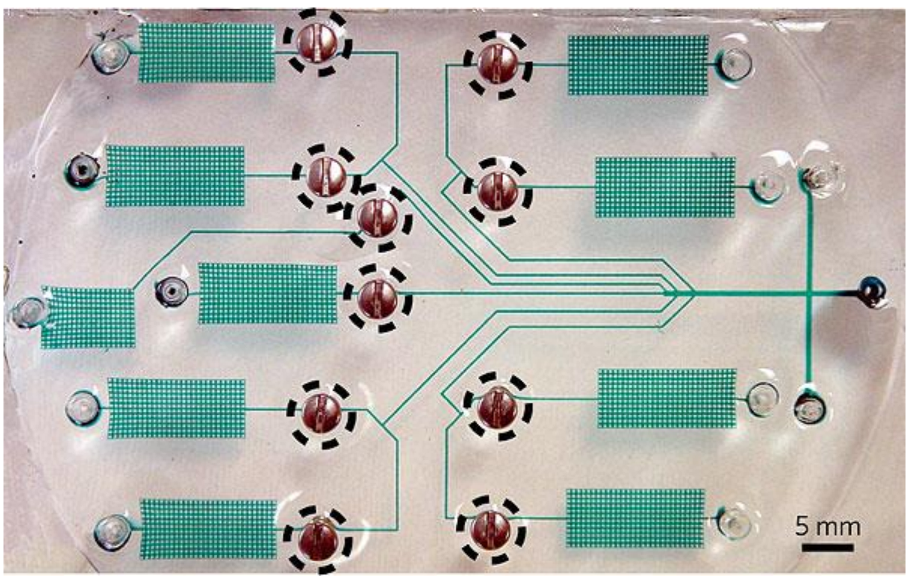


**Figure 4.2: A simple, inexpensive microfluidic diagnostic device [7]**

In many recent research studies, microfluidics has been integrated with metamaterials in heating of fluids. A unique definition of metamaterial does not yet satisfactorily exist, but the characteristics of such materials are adequately established. Metamaterials are artificialy engineered and they are gaining increasing popularity from researchers and engineers from various streams of science due to the exciting applications they offer. The electromagnetic properties of metamaterials are inherited from their unique structure rather than the material composition itself. Electrically small resonators in various shapes, forms and discontinuities are used to engineer metamaterial particles and one of the most common forms of such resonators is the Split-ring Resonator or SRR. Single of multiple electrically small metallic rings in a parallel or concentric geometry is used to form SRR, different shapes of which are shown in Figure 4.3.

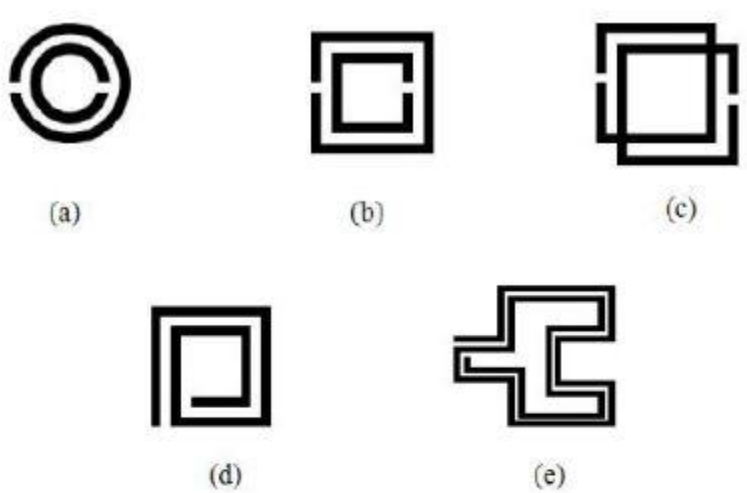


**Figure 4.3: Different shapes of metamaterial particles proposed in the literature [8]**

The uniqueness of metamaterials lies in its properties of having negative permittivity and/or permeability. As effective medium, metamaterials can be characterized by a complex refractive index:

$$n = n_1 + in_2$$

Here $n_1$ is related to the phase velocity and $n_2$ to losses [36]. The applications of metamaterial include but are not limited to creating perfect lenses and absorbers [9, 10], crack detection [11], solar cells efficiency improvement, and even invisibility cloaks [34, 35]. The work discussed later in this chapter has been inspired from microfluidics using metamaterial as the base component, the water channel has been scaled larger keeping in mind the feasibility to use the model to serve household heating need.

## 4.3 Properties of Water and Response to Microwave Radiation

It is an interesting study to learn how the water interacts with microwave to efficiently heat it up. The water can be assumed as if formed of countless dipoles. In the presence of the oscillating electric field of electromagnetic radiation, the water dipoles make effort to reorient. This process of attempted re-orientation in dipoles continues as long as there is the presence of EM radiation. As the electric field is oscillating, depending on the frequency the dipole can either lead or lag the field, or remain completely unaffected. Considering scenario when the dipole is lagging behind the electric field - this interaction between the water dipole and applied EM field gives rise to energy loss in the form of heating. The movement of the water dipole is restricted by the strength of the hydrogen bonds. This dipole movement occurs at different frequency range for different size and physical form of water volume: at GHz range for free liquid water, at MHz range for bound water volume and at KH

In free liquid water this dipole movement occurs at GHz frequencies (microwaves), whereas is bound water volume it occurs at MHz frequencies and in ice at KHz frequencies. [14]

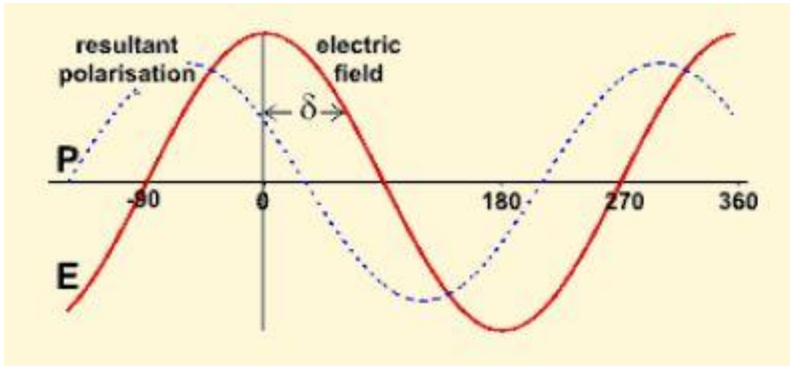


**Figure 4.4: Applied electric field and resultant polarization in water [14]**

The applied field, E (volts), is expressed as the following equation:

$$E = E_{max} * \cos(\omega t)$$

Where, $E_{max}$ is the amplitude in volts

$\omega$ is the angular frequency in radians/seconds

t in the time in seconds

If the polarization lags behind the field by the phase δ (radians), then after a few steps of derivation we get the equation for power (**P**, watts) dissipated as heat in the water as following:

$$\mathbf{P} = 0.5\, P_{max}\, E_{max}\, \omega \sin(\delta)$$

Where $P_{max}$ is the maximum value of the polarization

Figure 4.5 depicts the effect in dielectric constant and dielectric loss of water over temperature and frequency, where the arrows show the effect of increasing temperature. The wavelength range is equivalent to 3 THz - 0.3 GHz.

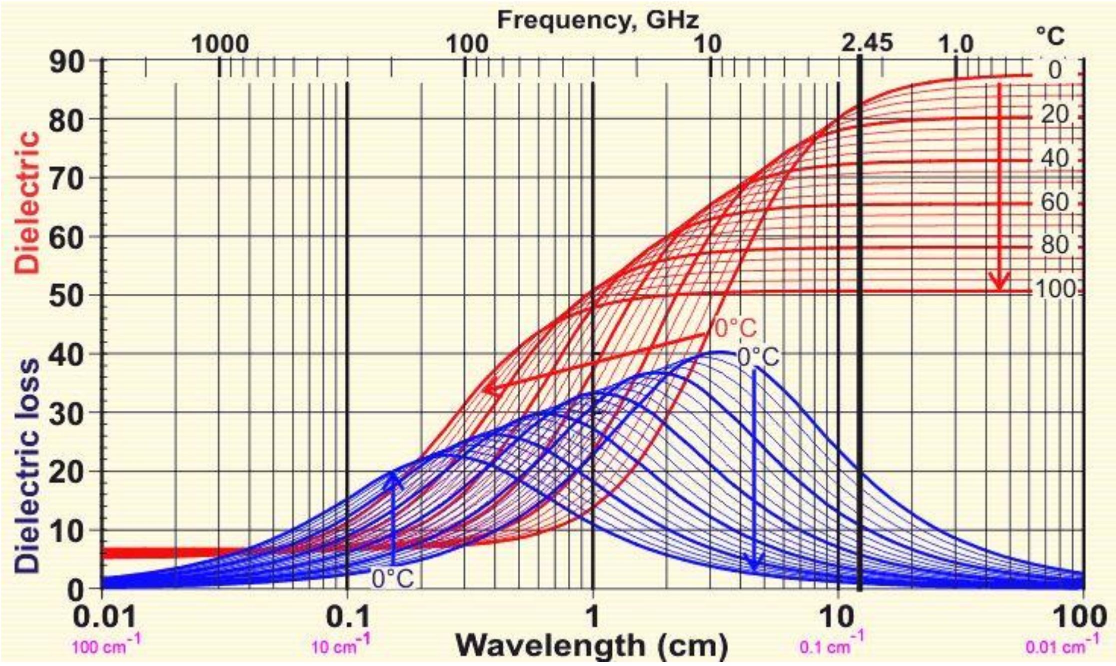


**Figure 4.5: Dielectric permittivity and dielectric loss of water between 0°C and 100°C [14]**

If salt is added to water this effects in a change of natural structuring of water and hence changes the dielectric constant. We can observe from Figure 4.6 that at lower frequencies the ions are more freely responding (via movement) to changing potential. This increasing movement results in emission of heat through friction and the loss factor increases. Loss factor is the efficiency by which electromagnetic energy is converted to heat. The higher the temperature goes, the lower the dielectric constant gets. The complex dielectric permittivity can be expressed as:

$$\varepsilon^* = \varepsilon r' - i\mathbf{LF}$$

Where εr′ is the ability of the material to be polarized by applied external field

**LF** is the loss factor

$i = \sqrt{-1}$

Hence sea-water or salt-dissolved water has a reduced static dielectric permittivity.

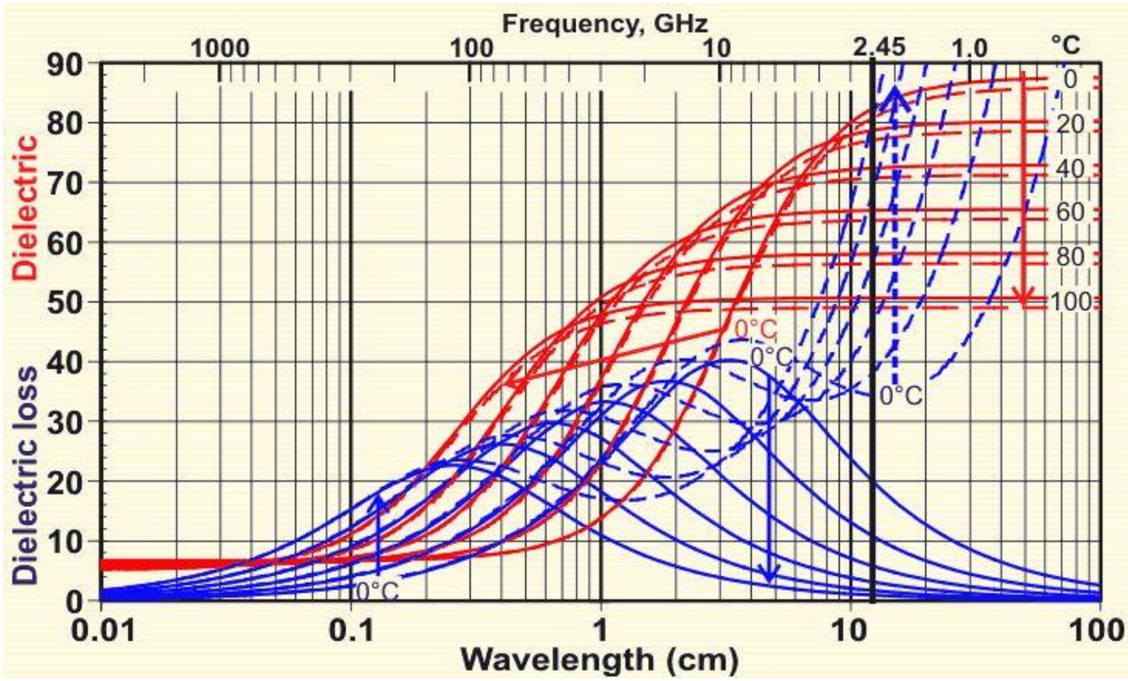


**Figure 4.6: Dielectric permittivity and dielectric loss of a dilute salt solution between 0°C and 100°C; the solid lines shows pure water curve as Figure 10**

## 4.4 SRR Design and Frequency Responses

SRR or Split-ring Resonators are the most used forms of metamaterial resonators. The base component of the proposed SRR heater is a microstrip-coupled SRR which has similar design as the literature published in the Sensors and Actuators A: Physical by Withayachumnakul et al. [12] who used this as a microfluidic sensor. For our design the gap of the SRR has been scaled bigger to accommodate the water chanel which will be placed at the gap. The diagram of the SRR is shown in Figure 4.7(a) which has dimensions as follows: l = 7mm, w = 7.5 mm, g = 1.5 mm, r =0.2 mm, c = 0.65 mm, $w_s$= 1.7 mm. The rectangular SRR with a split in one side is a metallic loop which is excited by a microstrip line placed 0.65 mm away from the SRR side. The substrate is a Rogers RT6010, and there is copper ground plane at the back of the substrate. A discrete port provides the power to the microstrip line. In Figure 4.7(b) the SRR and the transmission line is depicted using an equivalent circuit containing fundamental circuit elements.The inductance of the microstrip line is $L_m$, the inductance of the SRR loop is $L_s$, the capacitance at the SRR gap is $C_s$, the parasitic resistance of the loop itself is $R_s$ and the mutual inductance between the SRR loop and the transmission line is M [12].

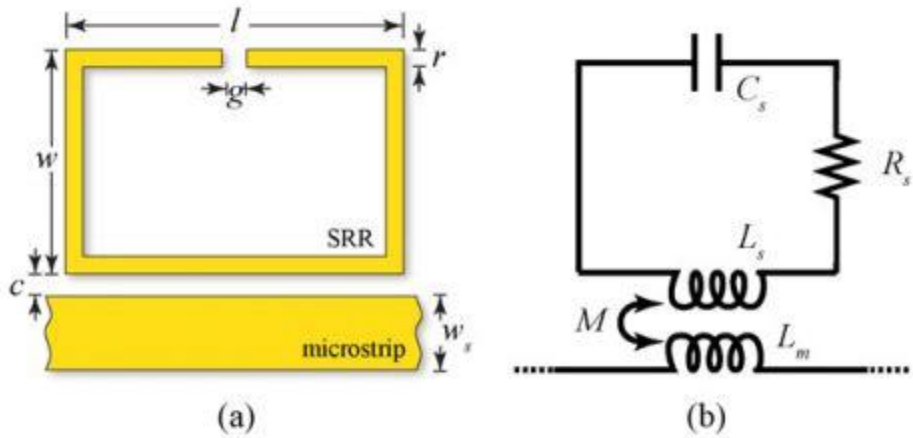


**Figure 4.7: Microstrip couples SRR. (a) Diagram, (b) Equivalent circuit [12]**

When microwave power is launched in the stripline, the quasi-TEM mode of the wave propagation is excited. This generates an oscillating currant along the microstrip and a circulating magnetic field around the stripline. This magnetic field circulating around the microstrip line induces current to the SRR placed in close proximity of the stripline when the magnetic field component and the SRR axis is parallel to each other. SRR excitation results in the emergence of a highly concentrated electric field across the SRR gap. When the electric energy stored in the SRR gap is equal to the magnetic energy stored in the SRR loop, resonance phenomenon occurs. Figure 4.8 depicts the electric field distribution of the SRR at the resonance. As a result of this electric field that is concentrated across the SRR gap, voltage builds up in the gap which means if a load is placed across the gap of the SRR this energy could be harvested. The purpose of this work is to harvest this electrical energy by heating water load placed at the gap of the SRR.

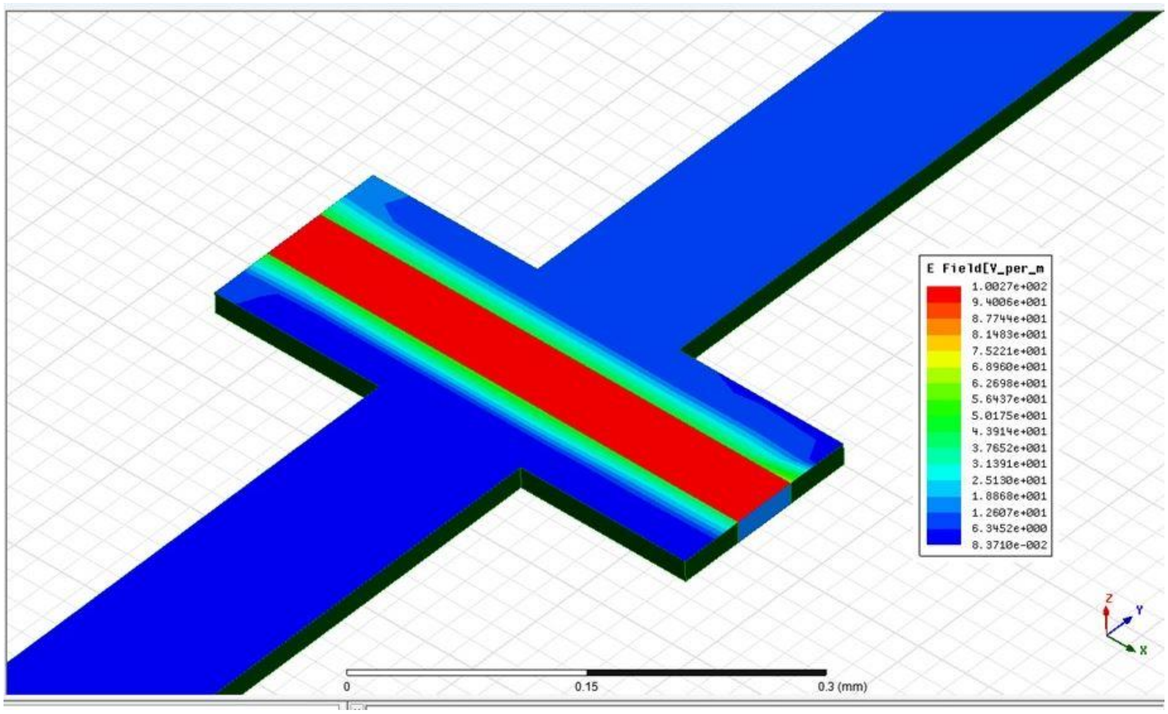


**Figure 4.8: E-field distribution on the gap of SRR**

The resonance frequency of this SRR is around 2.2 GHz, which can be observed by the red trace in the reflection curve shown in Figure 4.9. When water is placed at the gap of the SRR the resonant frequency gets lower and the q factor also gets lower, which can be seen by the blue trace of Figure 11. This curve was obtained by data extracted from CST Studio simulations. The reason for this effect is, by adding water at the gap we are increasing the capacitance Cs in the gap. By definition, resonant frequency is:

$$f= \frac{1}{2\pi\sqrt{fc}}$$

When C gets higher, f gets lower, which is the explanation why the resonant frequency gets lower. Every SRR is designed for a particular frequency and it has particular input impedance. When water or any other material is placed at the gap of the SRR, this input impedance changes and it creates a mismatch. If we put a port in between the gap of the SRR and add water in the gap, lots of power will be reflected back due to this mismatch. This is the reason why the level of the S11 gets higher and the Q factor gets lower.

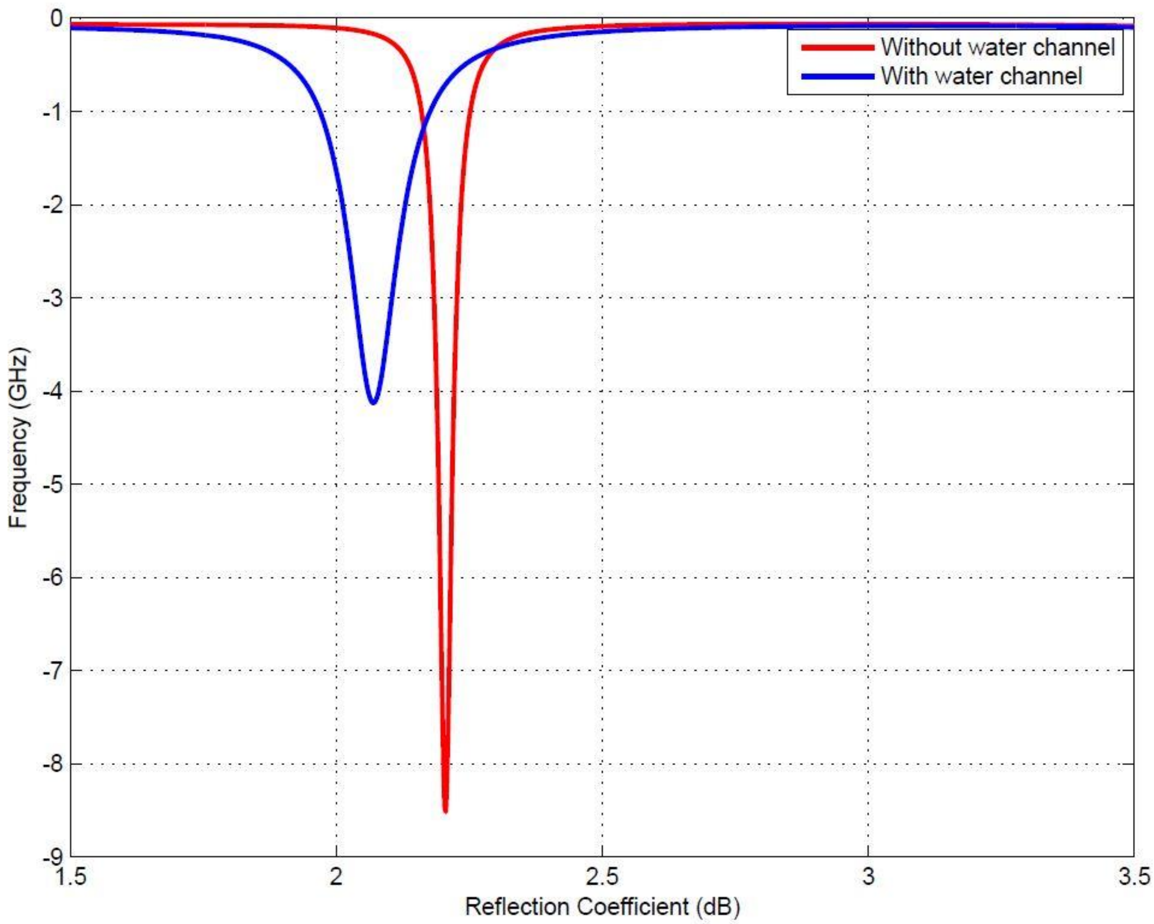


**Figure 4.9: Numerical simulation result of reflection coefficient response of the bare SRR and effect on S11 due to the presence of water at the gap of the SRR**

Initially a plane wave excitation was considered to excite the SRR instead of microstripline excitation. This was also experimented using numerical simulations. However, the idea was discarded for the heating element and arrays proposed in the scope of this thesis. While exciting a single SRR using plane wave excitation in CST Studio Suite, it was observed that a very weak electric field was generated at the SRR gap which is not sufficient to result in a good heating performance. To achieve a noticeable resonance effect, an SRR medium consisting of lots of

SRRs and an extensive amount of sample is needed. The same observation was also stated in the literature by Withayachumnankul et al. [12]

For implementing the structure in household heating operations, multiple SRRs will be used as depicted in section 4.6, which makes plane wave excitation as a possibility. A magnetron can be used as the energy source to excite multiple SRR elements inside a confined pipe to heat water flowing through smaller pipes across the SRR gaps.

## 4.5 Single Element Heater Model

As a continuation to the SRR design discussed in the above section, we now move to the design and performance of the heating model consisting of a single electrically small resonator. The SRR is mounted on a 1 mm thick substrate of Rogers RT6010. A water pipe that has a diameter of 1.5 mm has been inserted into the gap of the SRR in the circuit explained in section 4.4. The structure is captured from different angels in Figure 4.10. The water pipe contains sea water with material properties as such: relative permittivity = 74, permeability = 0.999991, thermal conductivity = 0.6 W/K/m and heat capacity = 4.2 kJ/K/kg.

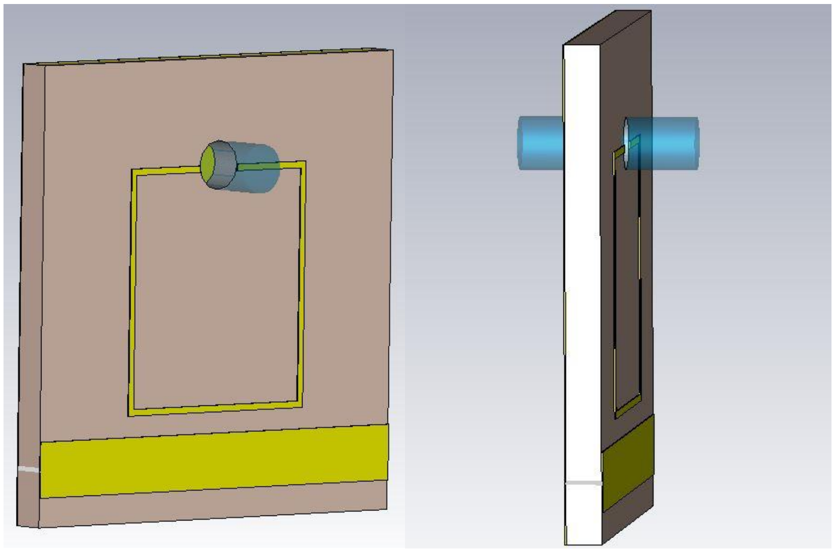

**Figure 4.10: Design of the single SRR element microwave heater model from different angles in CST.**

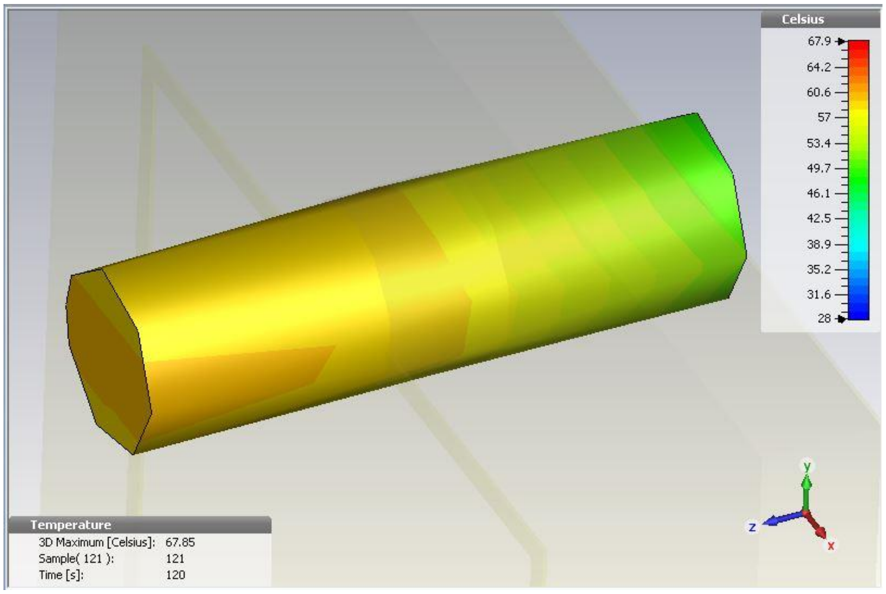


**Figure 4.11: Temperature distribution in the water pipe**

Figure 4.11 demonstrates the temperature distribution of the water pipe for an input power of 5 watts. A step width of 1s has been assigned to gradually see how the temperature rises with time in an increment of 1s and a screenshot has been captured at 120 second timeframe, which shows he temperature increased to 67.85 °C from room temperature in 120 seconds.

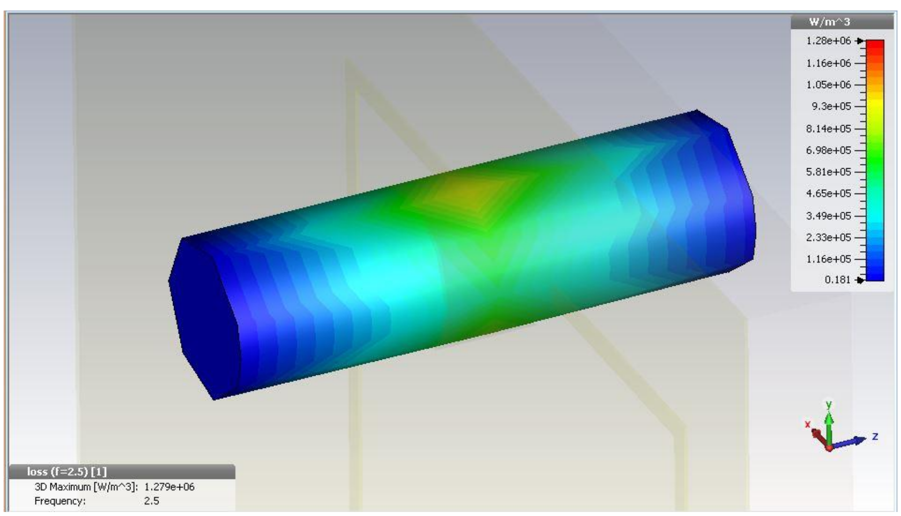


**Figure 4.12: Power loss distribution in the water pipe**

Figure 4.12 presents the power loss distribution inside the water volume. The fact that the bulk of the applied microwave power is being dissipated inside the water volume is apparent from Figure 4.13.

The 1 D result of power loss per material presented below confirms that very little amount of power is dissipated as volume loss in the Rogerts RT6010 substrate and as metal loss in the transmission line and SRR loop. The majority of the input power fed in is dissipated as heat in the water pipe as volume loss.

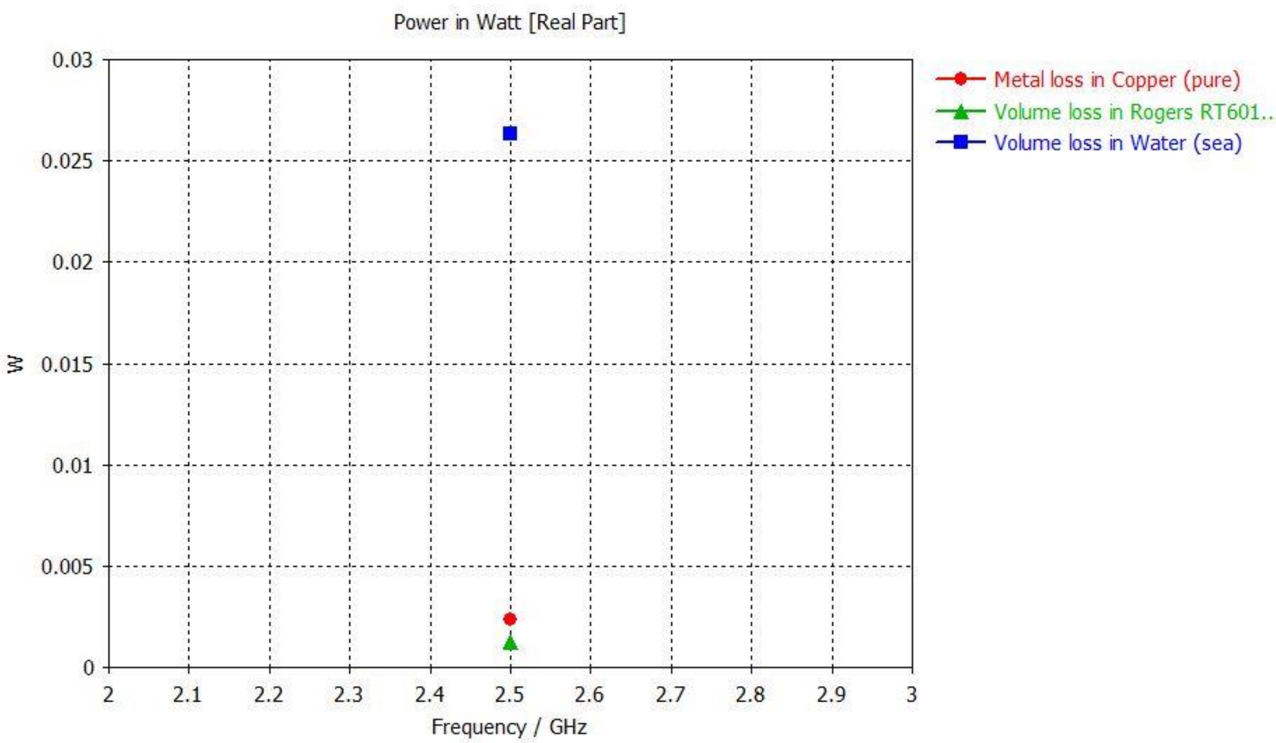


**Figure 4.13: Power loss graph of SRR single element heater model**

EM and thermal simulations were conducted using CST Microwave Studio and CST Mphysics Studio in order to study the effect of temperature rise in the water for different input power. The following table shows the comparison of the heating response at presence of different input power to have a clear realization of how the water is heated up gradually. Each result was obtained by following the same method of CST workflow procedure explained in

Chapter 3 section 3.3.1.of EM simulation>generating thermal loss> importing thermal loss in MWS for thermal calculation>running MWS simulation> evaluating temperature results at different time.

| Time (s) | 2 W Temp °C | 5 W Temp °C | 10 W Temp °C |
|---|---|---|---|
| 0 | 28 | 28 | 28 |
| 15 | 36.9 | 50.26 | 72.49 |
| 30 | 38.7 | 54.75 | 81.61 |
| 60 | 41.07 | 60.68 | 93.28 |

**Table 2: Comparison between different input power and effect in temperature rise over time**

The following graph presented in Figure 4.14 generated from the values in Table 2 gives a clear picture of the linear relation of the input power and the temperature increase. It is very promising to see that at an input power of only 2 W the water gets heated up to 41 °C from room temperature in 60s. The water channel has a diameter of 1.5 mm and a length of 5 mm. The same numerical simulations can be carried out for a water pipe with larger dimensions, but as SRRs are scalable resonators it is simple to design the heating element that treats a larger volume of water.

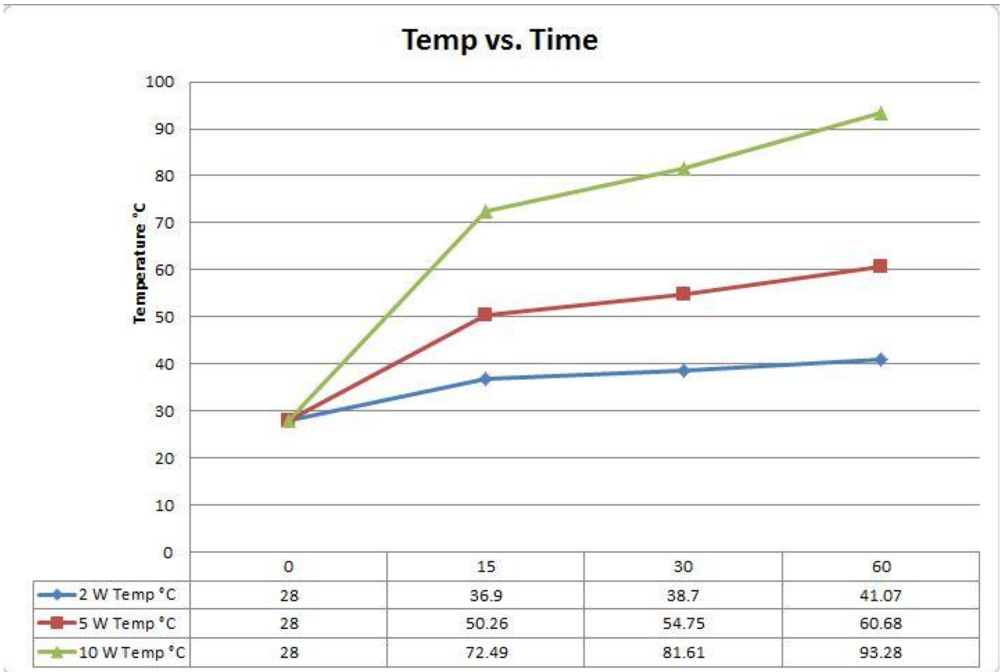


**Figure 4.14: Temperature vs. time graph for various input power of the heater model**

Commercial household heaters uses from 1500 W to up to as much as 4500 W to heat up water, of course they handle a much higher volume of water but the results we can see here can confirm that even with a larger volume of water than used here, the SRR heater will be able to successfully heat up water as it is flowing in the pipes.

## 4.6 SRR-Array Heater Model

In this section two designs of heating elements consisting of multiple resonators are proposed. Figure 4.15 shows the heating element designed by stacking three resonators on top of each other. This consists of three single element heating models with a gap of 9 mm in between each element. Three separate lumped port excitation provides microwave power to the microstrip lines which in turn excite the SRRs.

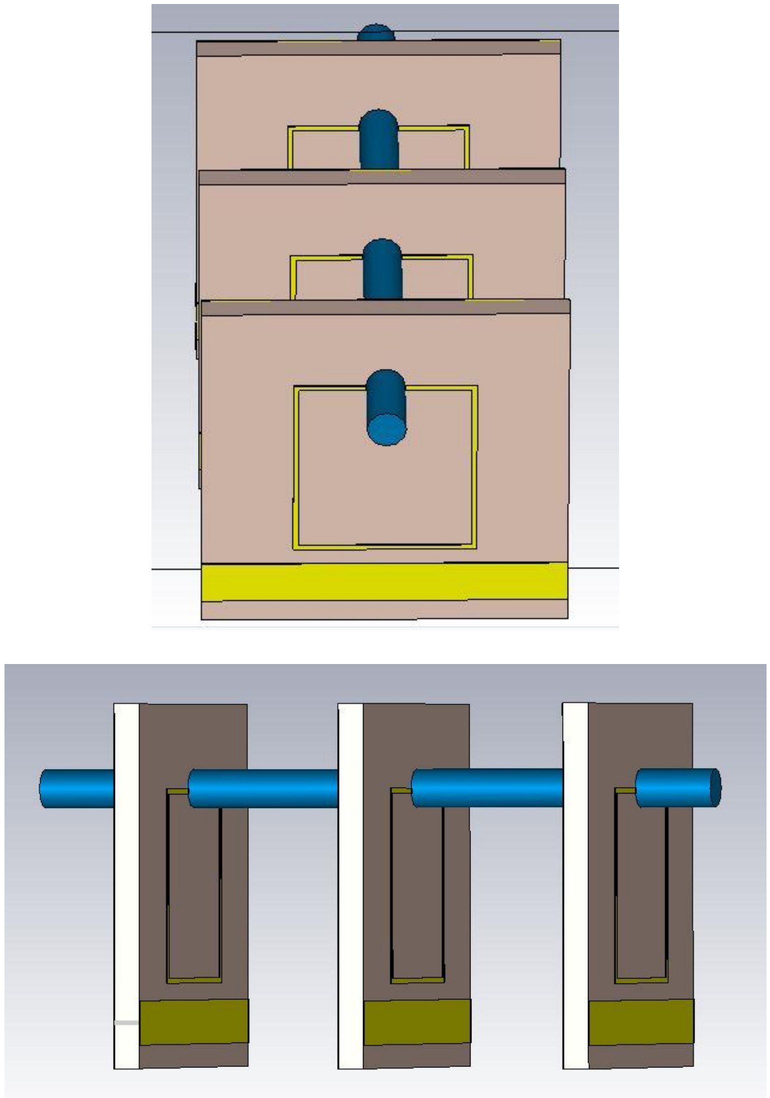

**Figure 4.15: Heating element with three resonators stacked on top of each other**

Figure 4.16 presents the heating element designed by stacking three resonators on side by side. Each identical point in the design have a gap of 14 mm in between. One single lumped port excitation provides microwave power to the microstrip lines which in turn excite the three SRRs.

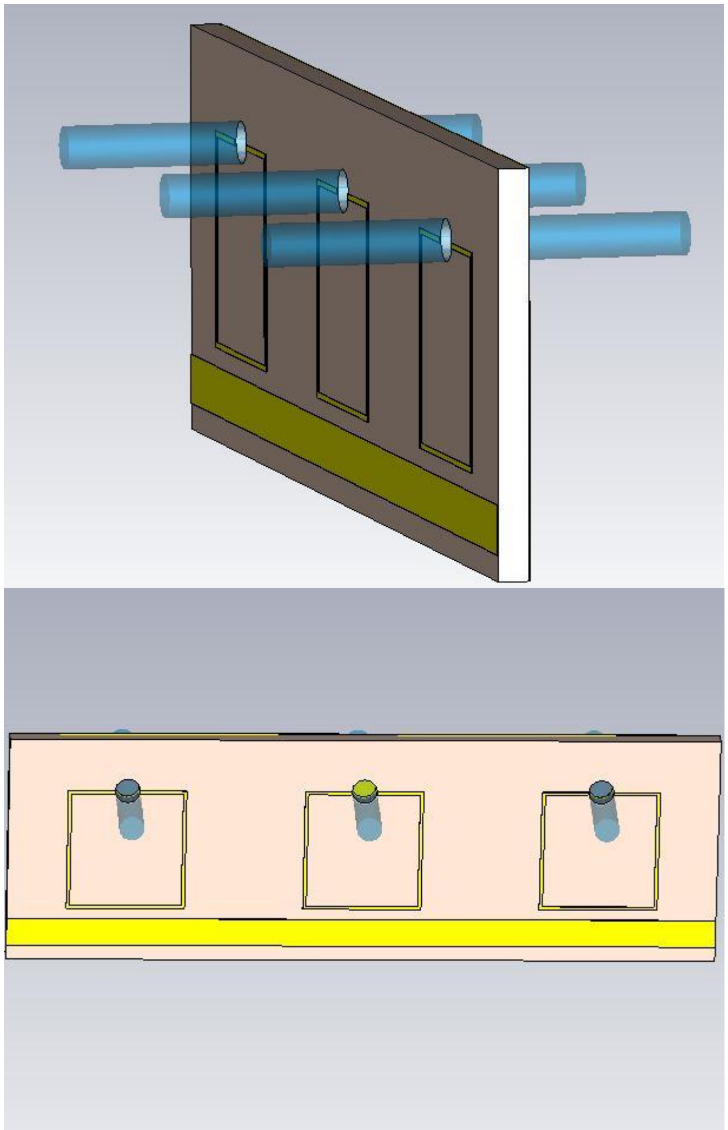

**Figure 4.16 Heating element with three resonators placed side by side**

Similar electromagnetic-thermal simulations were carried out for each of these models, and it was noted that the rate of temperature increase is much higher than the single element heater model which is expected. Figure 4.17 demonstrates the temperature distribution in the water channels of the heating model presented in Figure 4.16.

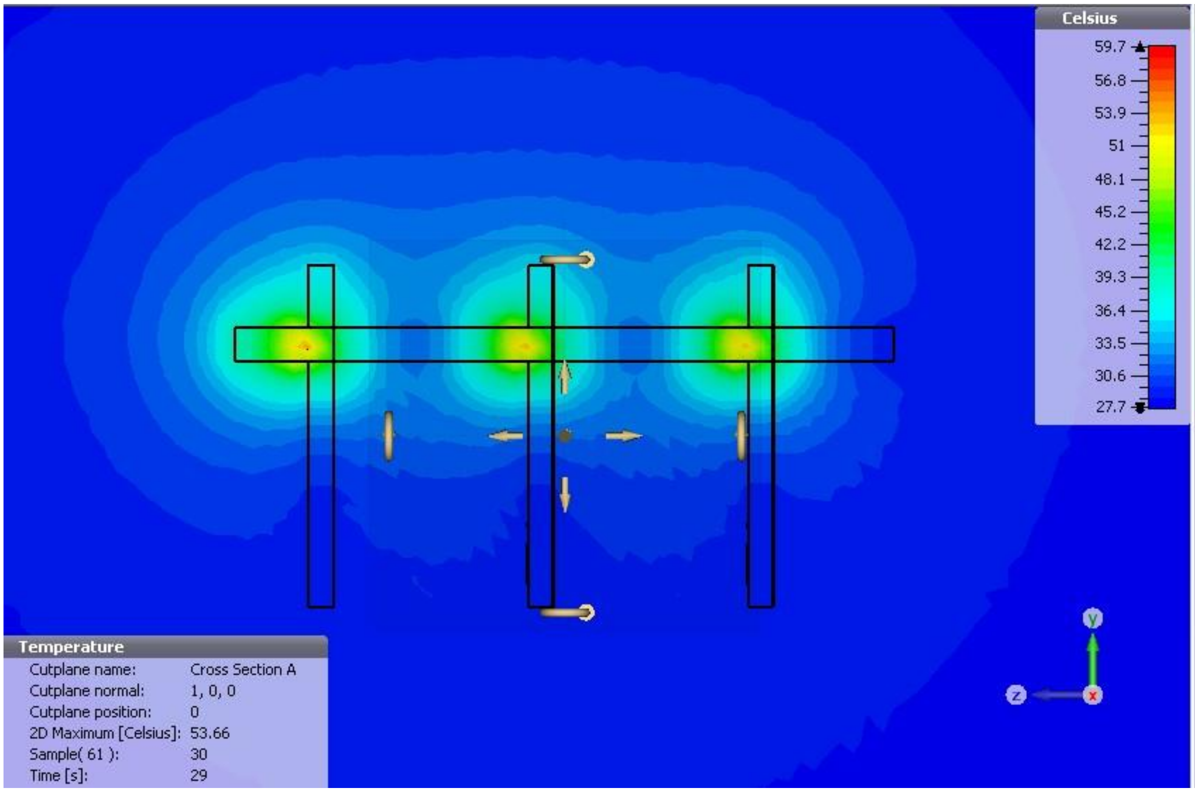


**Figure 4.17: Cross section view of a multiple element heater model showing the temperature distribution in three water channels**

## 4.7 Comparison with regular household heaters

One of the very common household water heating systems is the tank-type storage water heater. They are bulky and require a dedicated area or closet inside the house consuming unnecessary space. Another problem with these is the fact that they often tend to leak water with increasing use; also the storage tank can get rusty over time. Most importantly, they also store the hot water which equates to standby energy loss. This leads to a noticeable amount of money being wasted, as the heater is still unnecessarily storing hot water when the user is on vacation or outside of the house eight hours a day. Also these are very expensive for both installation and maintenance phases and result into high electric bills due to large amount of power consumption.

Commercial household heaters uses from 1500 W to up to as much as 4500 W to heat up water.Even though these heaters handle a much higher volume of water than what has been experimented here, the results we gathered for even just the single element heater model can confirm that with a larger volume of water the SRR heater will be able to perform successfully. The objective of this thesis is to heat the running water as it is flowing through the pipes. We are not considering heating up water in a tank, storing it for a while and then distribute it; as these result in a great amount of unnecessary power loss. We want to heat the water as it is flowing inside the pipe and hence we do not need to achieve a scalding temperature; because the current household heaters heat the water up to a very high temperature which is most of the time saturated by mixing with cold water flow for comfortable regular use. This energy loss is also present and prominent in the recently introduced tank-less water heaters. The microwave split-ring resonator based water heating models that have been proposed in this thesis eliminate these shortcomings and are likely to be a promising and more energy efficient solution for household water heating demand in future years.

## 4.8 Conclusion

Chapter 4 presents the design and performance of the different heating elements proposed in the scope of this research. Adequate background information was demonstrated which is the basis of the modelling conducted here. The design methodology of a split ring resonator is explained along with its electric field distribution and resonant frequency phenomenon. Justification for choosing the excitation structure of the resonator has been provided. In the following sections, the structure, dimensions and heating performance of the heating elements have been discussed, and different comparisons have been carried out for characteristic and performance realization of the heaters. Finally a performance comparison has been carried out between the proposed novel SRR-based heating system and regular household heaters.

# Chapter 5

# Conclusion and Future Work Directions

## 5.1 Conclusion

The investigation was set out to develop a microwave water heating system that incorporates the use of negative material or metamaterial. In this thesis, a review of liquid heating using microwave power has been presented. The growing influence of metamaterial principles on microwave heating has been explored and relevant thesis literature works have been thoroughly investigated. Detailed analyses have been presented which was carried out by using multiple software tools in order to conduct microwave heating simulations of interest. The purpose is to document the important technical information and provide a thorough manual regarding the procedures for later re-enactment.

To authenticate the simulation procedure, validation of a paper published in the Food and Bioprocess Technology Journal was conducted. Validation proofs have been provided to ensure that the simulation process that will be used for microwave heating analysis in later chapters of this thesis is correct and the results are reliable.

The design methodology of a split ring resonator is explained along with its electric field distribution and resonant frequency phenomenon. Justification for choosing the excitation structure of the resonator has been provided. A single SRR heating model and two SRR-array heating models has been proposed. The structure, dimensions and heating performance of the heating elements have been discussed, and different comparisons have been carried out for characteristic and performance realization of the heaters. The results from these simulations show that such resonator based heating models can indeed be used as an efficient microwave water heater. Finally a performance comparison has been carried out between the proposed novel SRR-based heating system and regular household heaters. The microwave split-ring resonator based water heating models that have been proposed in this thesis eliminate these shortcomings of regular household heaters and is likely to be a promising and more energy efficient solution for household water heating demand in future years.

## 5.2 Future Work

The thesis has consolidated a good amount of numerical data and provided adequate evidence of heating performance of split-ring resonator based microwave water heating system. Throughout the course of this research few areas of further research work were identified. The suggestions listed below are worth pursuing for future work.

- Develop a model using magnetron as a source to of plane wave generation and using multiple array elements, more elements than what have been explored in the scope of this thesis, to observe the performance of the proposed system.
- To make the system more energy efficient, the system dimensions can be further optimized to reduce the metal loss in copper and the volume loss in the substrate.

- The sensing abilities of similar metamaterial resonator systems have been wildly acclaimed [26, 40]. The SRR's local resonant field is very sensitive to the change in dielectric constant of the liquid flowing through the gap. Water containing a high amount of dissolved minerals, in other words 'hard water', can be harmful for daily use. The proposed system can be modified to act as a monitor for water mineral content.
- Study the effect of different shapes of split-ring resonators in the heating performance. A round shaped resonator can be a better fit to be used around cylindrically shaped water pipes instead of square shaped SRRs.
- Investigate the effect of coupling between the SRRs and its resulting influence in efficiency of the proposed multiple resonator element water heating system.

# References

[1] EL Sabbagh, Mahmoud. (2011). "Electromagnetic-Thermal Analysis Study Based on HFSS-ANSYS Link." *Electrical Engineering and Computer Science Technical Reports.* Paper 46.

[2] High Frequesncy Simulator (HFSS), Ansoft Corporation, Pittsburgh, PA. Ver. 12.1, 2010.

[3] ANSYS Workbench, ANSYS Inc., Canonsburg, Ver. 12.1, 2009.

[4] CST Studio Suite, CST Computer Simulation Technology AG, San Antonio, Ver. 2014.

[5] Agreement to Acquire Ansoft, ANSYS Advantage, Volume ii, Issue 2, 2008.

[6] Cha-um, W. & Rattanadecho, P., Pakdee, W. (2011). “Experimental and numerical analysis of microwave heating of water and oil Using a rectangular wave guide: Influence of Sample Sizes, Positions, and Microwave Power.” *Food Bioprocess Technology, Volume 4*, Pages 544-558.

[7] Whitesides., G., M. (2006). “The Origins and the Future of Microfluidics.” *Nature 442*, Pages368-373.

[8] Bait-Suwailam, M. M. (2011). “Metamaterials for decoupling antennas and electromagnetic systems.”*PhD thesis, University of Waterloo.*

[9] Pendry, J. B. (2000) “Negative Refraction Makes a Perfect Lens.” *Physical Review Letters,Volume 85,* Page 3966.

[10] Landy, N. I., Sajuyigbe, S., Mock, J. J., Smith, D. R., & Padilla, W. J. (2008). “Perfect metamaterial absorber.” *Physical Review Letters, Volume 100, Issue 20,* Page 207402.

[11] Albishi, A., M., Boybay, M. S., & Ramahi, O., M. (2012). “Complimentary split-ring resonator for crack detection in metallic surfaces.”*IEEE Microwave and Wireless Components Letters, Volume* 22, Issue 6, Pages 330-332.

[12] Withayachumnankul, W., Jaruwongrungsee, K., Tuantranont, A., Fumeaux, C., & Abbott, D. (2013). “Metamaterial-based microfluidic sensor for dielectric characterization.” *Sensors and Actuators A: Physical, Volume 189,* Pages 233-237.

[13] Almoneef, T. (2012). “Antennas and materials for electromagnetic energy harvesting.” *MASc thesis, University of Waterloo.*

[14] Chaplin, M. *“Water Structure and Science”*, available at: http://www1.lsbu.ac.uk/water/microwave_water.html (accessed 14 October, 2014).

[15] Lee, C. Y., Lee, G. B., Lin, J. L., Huang, F. C., & Liao, C. S. (2005). “Integrated microfluidic systems for cell lysis, mixing/pumping and DNA amplification.” *Journal of Micromechanics and Microengineering, Volume 15,* Pages 1215–23.

[16] Maltezos, G., Johnston, M.,& Scherer, A. (2005). “Thermal management in microfluidics using micro-Peltier junctions.” *Applied Physics Letter, Volume 87,* 1541051–3.

[17] de Mello, A. J., Habgood, M., Lancaster, N. L., Welton, T.,& Wootton, R. C. R. (2004). “Precise temperature control in microfluidic devices using Joule heating of ionic liquids*.”* *Lab on a Chip, Volume 4,* Pages 417–9.

[18] Shah, J. J., Sundaresan, G. S., Geist, J., Reyes, R. D., Booth, C. J., Rao, V. M., & Gaitan, M. (2007). “Microwave dielectric heating of fluids in an integrated microfluidic device.” *Journal of Micromechanics and Microengineering, Volume 17,* Pages 2224-2230.

[19] Kappe, C. O., & Dallinger, D. (2006). “The impact of microwave synthesis on drug discovery.” *Nature Reiews Drug Discoery, Volume 5,* Pages 51–63.

[20] Fermer, C., Nilsson, P., & Larhed, M. (2003). “Microwave-assisted high-speed PCR” *European Journal of Pharmaceutical Sciience, Volume 18,* Pages 129–32.

[21] Auroux, P. A., Shah, J. J., Booth, J., Rao M. V., Locascio, L. E., & Gaitan, M. (2006). “Microfluidic method for thermal cycling by microwave dielectric heating.” *Proc. Micro Total Anal. Syst., Volume 2,* Pages1465–7.

[22] Goodwin, D. C., & Lee, S. B. (1993). “Microwave miniprep of total genomic DNA from fungi, plants, protists and animals for PCR.” *Biotechniques, Volume 15*, Page 438.

[23] Nikawa, Y., Yamamoto, K., Izumidate, S., & Kubota, N. (1996). “An Irradiation System of Pulsed Modulation Microwaves to Culture Cells.” *18th International Conference IEEE Eng. Med. Biol. Soc. Volume 5*, Pages 1865–6

[24] Facer, G. R., Notterman, D. A., & Sohn, L. L. (2001). “Dielectric spectroscopy for bioanalysis: from 40 Hz to 26.5 GHz in a microfabricated wave guide.” *Applied Physics Letter, Volume 17*, Pages 996-8.

[25] Issadore, D., Humphray, J. K., Brown, A. K., Sandberg, L., Weitz, A. D., & Westervelt, M. R. (2009). “Microwave dielectric heating of drops in microfluidic device.” *Lab on a Chip, Volume 9,* Pages 1701-6.

[26] Ren, Z., Boybay, S. M., & Ramahi, O. (2011). “Near-field probes for subsurface detection using split ring resonators.” *IEEE Transaction on Microwave Theory and Technniques, Volume 59-2,* Pages 488-495.

[27] Whitesides, G.M., Ostuni, E., Takayama, S., Jiang, X., & Ingber, D. (2001) “Soft lithography in biology and biochemistry.” *Annual Review of Biomedical Engineering, Volume 3,* Pages 335-373.

[28] Stone, H. A., Stroock, A. D., & Ajdari, A. (2004). “Engineering flows in small devices: Microfluidics toward a lab-on-a-chip.” *Annual Review of Fluid Mechanics*, *Volume 36,* Pages 381-411.

[29] Tabeling, P. (2005). *Introduction to Microfluidics*, Oxford University Press, ISBN 978-0-19-958816-9

[30] Yager, P., Edwards, T., Fu, E., Helton, K., Nelson, K., Tam, M. R., & Weig, B. H. (2006). “Microfluidic diagnostic technologies for global public health.” *Nature, Volume 442(7101),* Pages 412-418.

[31] Martinez, A. W., Phillips, S. T., Wiley, B. J., Gupta, M., & Whitesides, G. M. (2008). “FLASH: a rapid method for prototyping paper-based microfluidic devices.” *Lab Chip, Volume 8,* Pages 2146-50.

[32] Lee, H., Ham, D., & Westervelt, R. M. (2007). *CMOS Biotechnology*, Springer; New York, ISBN 978-0-387-26049-9

[33] Hunt, T. P., Issadore, D., & Westervelt, R.M. (2008). “Integrated circuit/microfluidic chip to programmably trap and move cells and droplets with dielectrophoresis.” *Lab Chip, Volume 8,* Pages 81-87.

[34] Schurig, D., Mock, J. J., Justice, J. B., Cummer, A. S., Pendry, B. J., Starr, F. A., & Smith, R. D. (2006). “Metamaterial Electromagnetic Cloak at Microwave Frequencies.” *Science, Volume 314,* pages 977-980.

[35] Valentine, J., Li, J., Zentgraf, T., Bartal, G., & Zhang, X. (2009). “An Optical Cloak Made of Dielectrics.” *Nature Materials, Volume 8,* Pages 568-571.

[36] Smith, R. D., Padilla, J. W., Vier, C. D., Nemat-Nasser, C. S., & Schultz, S. (2000). “Composite Medium with Simultaneously Negative Permeability and Permittivity.” *Physics Review Letters, Volume 84, Issue 18,* Pages 4184-4187.

[38] Ratanadecho, P., Aoki, K., & Akahori, M. (2002). “A numerical and experimental investigation of the modelling of microwave heating for liquid layers using a rectangular wave guide (Effects of natural convection and dielectric properties).” *Applied Mathematical Modelling, Volume 26*, Pages 449-472.

[39] Kawasaki, S., Daito, Y., Kawai, T., Ohta, I., Amano, O, Matsui, Y. (2010). “A fundamental study of microwave liquid heater.” *Proceedings of Asia-Pacific Microwave Conference*, Pages 1336-1339.

[40] Boybay, S. M., Jiao, A., Glawdel, T., & Ren, L. C. (2013). “Microwave sensing and heating of individual droplets in microfluidic devices.” *Lab on a Chip, Volume 13, Issue 19,* Pages 3840-3846.