34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Dual Mode Microwave Tool for Dielectric Analysis and Thermal Ablation Treatment of Organic Tissue

Margarita Puentes[1], Fahed Bashir[1], Martin Schüßler[1] and Rolf Jakoby[1]

Abstract— **A dual mode tool design to analyze organic tissue and locally perform thermal ablation treatment is presented. The tool is made of an array of split-ring resonators. It can operate on a sensing mode to track the relative dielectric changes from the organic tissue and on a treatment mode to perform thermal ablation at different input powers. The measurements were done with phantoms of human tissue. The tool is able to focus a hot spot of approximately 0.2 mm with a temperature of 109 °C at an input power of 10 W.**

I. INTRODUCTION

The use of microwave techniques not only to detect but also as treatment option of cancer is a growing field of study. The current methods for diagnosis are still based on computerized tomography (CT) scans, X-Rays or magnetic resonance imaging (MRI), and for treatment, surgery and chemotherapy are still the first choice for the physicians. These methods still present many disadvantages and risks for the patient and the success rate depends greatly on the type of cancer and stage. For these reasons, microwaves with its non-invasive approach have an open field where high frequencies devices can play an important role. In recent years, microwave thermal systems for ablation have been in extensive research as a successful alternative of a less invasive method for cancer treatment. The term ablation is defined as destruction or eradication of tissue by extreme hyperthermia (heat). As well as with surgical removal, the rise in temperature is concentrated around the tumor but in a less invasive way, allowing for lower risks for the patient and a faster recovery time [1]. The procedure can be done by using RF, microwaves, laser or ultrasound signals. The most commonly used is RF ablation but microwaves are gaining position since they can be used in all the same types of tissues as RF ablation without the problems with the properties of the tissue, such as conductivity (σ) and changes in impedance. Also microwave ablation can heat faster and larger volumes of tissue. It is also used in conjunction with radiotherapy or chemotherapy, as it is evident that hyperthermia can increase the efficiency of these therapies [2].

The use of metamaterial structures, specially split-ring resonators (SRRs), for sensor applications has been previously studied. SRRs have been used for applications such as pressure, temperature, humidity and concentration monitoring. In the medical field, they have also been used in combination with thin-films for analysis of DNA [3]. For thermal heating, there has been work for heating breast tissue using four metamaterial lenses [4] or with a planar array of SRRs excited by a small loop antenna [5]. We present here an evolution from the frequency multiplexed 2-dimensional sensor array [6] into a dual mode operation tool. The tool can operate first in a sensing mode and locate the abnormalities within the tissue under test (TUT) and then change to the second operational mode for treatment of the abnormality via thermal ablation as depicted in Fig. 1. The tool is made of microstrip-excited SRRs. For the sensing mode, the principle of operation is based on tracking the resonant frequencies independently from each SRR. For the treatment mode, the energy inserted in the structure is localized on the necessary ring by controlling the resonant frequency. To prove the concept, the delivered power was increased from 1 W to 10 W and temperatures obtained range between 25 °C and 109 °C. The TUT used for the measurements was phantom tissue with dielectric properties equal to real human tissue.

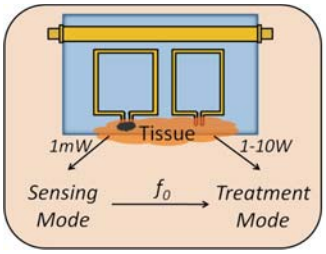

Fig. 1. Overview of the dual mode tool for analysis of organic tissue and thermal ablation treatment.

II. THEORETICAL CONSIDERATIONS

A. Split-Ring Resonators

For the development of the tool presented in this work, SRRs are considered as the basic block unit that can be organized into a multiplexed array. The reason for choosing SRRs is their strong response to an electromagnetic field due to a capacitive loading of the gap by the TUT.

The equivalent circuit of a microstrip line loaded with a single SRR [7] for the quasi-static case is shown in Fig. 2. The SRR is magnetically coupled to the transmission line with the coupling factor S. L_{ring} and C_{ring} correspond to the total SRR inductance and capacitance, respectively. The equivalent circuit yields the effective permeability with Lorentz dispersion [8]

$$\mu_{\text{eff}} = -j\frac{Z_1}{\omega p} = \frac{L_0}{p}\left(1+\frac{\omega^2 S^2}{\omega_{0\text{m}}^2-\omega^2+j\omega\delta}\right) \tag{1}$$

---

*This work was not supported by any organization

[1] M. Puentes, F. Bashir, M. Schüßler and R. Jakoby are with the Institute of Microwave Engineering and Photonics, Faculty of Electrical Engineering and Information Technology, Technische Universität Darmstadt, Merckstrasse 25, 64283 Darmstadt, Germany

978-1-4577-1787-1/12/$26.00 ©2012 IEEE

with p being the unit cell length. Between the magnetic resonance frequency and the magnetic plasma frequency the effective permeability μ_{eff} is negative, which leads, together with the constant effective permittivity

$$\varepsilon_{\text{eff}} = -j\frac{Y_2}{\omega p} = \frac{C_0}{p} \tag{2}$$

to a stopband between the magnetic resonance and plasma frequency. Loading the SRR gaps with dielectric material will increase the total ring capacity and shift the stopband to lower frequencies.

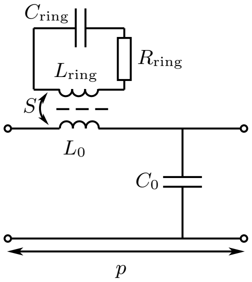

Fig. 2. Equivalent circuit of a SRR loaded transmission line.

B. Thermal Ablation

Hyperthermia with microwaves is done by dielectric heating. This phenomenon occurs when an alternating electromagnetic (EM) field is applied to a dielectric material. The heating in the tissue is produced due to the oscillation of water molecules in an out of phase and the EM energy is then absorbed and converted into heat. With tissues that contain a high water content the absorbtion is higher (e.g., most solid organs) than in tissue with low water content (e.g., fat). For microwave hyperthermia the key properties are effective conductivity and relative permittivity that are influenced by the electrical, thermal and mechanical properties of tissue. One last parameter that has to be taken into account is the rate of blood perfusion that will determine the size of the ablation zone because it will behave as a heat sink. Another reason why thermal ablation is a good choice of treatment is that dielectric properties of cancer cells are $10\%-30\%$ higher than healthy tissues, and the water content is also different allowing the cancer cells to get heated more easily than normal tissues. Thermal ablation is most suited for treatment in skin, liver, kidney, muscle, and spleen, specially for liver is widely used. Nevertheless it is also possible to use it in other organs as well, such as the lung and bone [2].

It is important to analyze if the SRRs are able to give an adequate temperature rise to actually kill the cancer cells. With temperatures up to $41\,^{\circ}\mathrm{C}$ no real long-term effect can be achieved. Above $46\,^{\circ}\mathrm{C}$ the irreversible damage in the cell begins. From 46 to $52\,^{\circ}\mathrm{C}$ less time to kill the cells is needed and above $60°C$ there is no possibility for the cell to recover and water vaporization, desiccation and carbonization occurs [2]. The tool that will be presented here for certain scenarios is able to rise the temperature well beyond $60\,^{\circ}\mathrm{C}$ and therefore is quite suitable for thermal ablation.

III. DUAL MODE TOOL DESIGN PROCESS

The tool is made of one or several SRRs that will have the dual purpose of sensing the dielectric properties of the TUT and performing the thermal ablation when necessary. The idea is to extend the sensor principle into a treatment tool. Once an abnormality is detected, the tool can change its operation mode and heat the tissue at a particular location, i.e. around one specific SRR of the structure and the hot spot can be localized around the gap of this certain SRR. The TUT is heated to the required temperatures to perform hyperthermia treatments. In general four prototypes were designed. The first two prototypes have one SRR with different geometries, circular and square. Additionally, a prototype with three circular SRRs and another with four square SRRs were also developed. The SRRs are microstrip excited and have an operating frequency range of $4-8\,\mathrm{GHz}$. The design process was done by using a full wave simulation software, CST Microwave Studio, which is suitable to not only analyze the electromagnetic behavior of the device but is capable of performing a thermal analysis as well. For the simulations, lung and liver tissue were used.

A. Sensing Mode

The operation of the tool as a sensor is thoroughly discussed in [6]. For the sensing mode, the tool needs to have each SRR independent and decoupled from the other ones, i.e. each SRR has its own resonance frequency. To achieve this goal the size of the SRRs must be different at least in one dimension, for the square SRR the width was altered and for the circular SRRs the diameter was changed. The structure tracks relative dielectric changes in the tissue due to its interaction with the SRR. A change of the capacitance due to the change of the effective permittivity is produced and therefore differences on the tissues, such as abnormalities, can be detected. With this information a dielectric image of the TUT can be obtained with a resolution equal to the number of SRRs. The used power in this mode of operation is $1\,\mathrm{mW}$ and represents no danger to the tissue of being heated. As for the localization limitations of the sensor; the maximum dimensions that the tissue can have and the sensor can still detect its properties are $2300\,\mu\mathrm{m}$ in length, $1\,\mathrm{mm}$ in height and a distance from the ring of $210\,\mu\mathrm{m}$. The minimum frequency shift necessary to make the detection depends on the accuracy of the electronic circuit used to extract the information and not on the sensor itself.

B. Treatment Mode

For the treatment mode of operation, extensive thermal simulations were performed. The thermal simulations can represent stationary or transient temperature distributions. In our case the thermal source used was a thermal loss distribution computed from electromagnetic fields and then included into the thermal simulation. The most interesting feature about this solver is that biological heating/cooling mechanisms such as blood perfusion and basal metabolic rate can be taken into account. The background temperature for simulation is $37\,^{\circ}\mathrm{C}$ (normal body temperature). In Fig.

3 the results of the thermal distribution for the structure with three circular SRRs is shown. The inset shows the scattering parameters and the resonant frequencies are clearly independent and unique. It is clear that the hot spot is located around the second ring by selecting the appropriate resonance frequency and the temperature at this point rose to $50.6\,^{\circ}\mathrm{C}$ with an input power of $5\,\mathrm{W}$. With the same power, the first SRR of the structure manages to rise the temperature to $51.4\,^{\circ}\mathrm{C}$ and the third SRR to $50.5\,^{\circ}\mathrm{C}$.

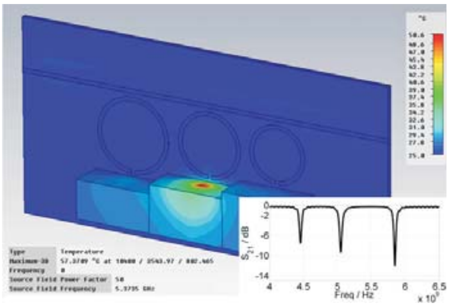

Fig. 3. Simulated model and thermal results for the structure with three circular SRRs. The inset shows the S_{21} parameters.

For the structure with square rings the same procedure for the thermal analysis was made. In Fig. 4 the results of the thermal distribution for the structure with four square SRRs is shown. The second ring was used for the ablation treatment and reached a temperature of $74\,^{\circ}\mathrm{C}$ with an input power of $10\,\mathrm{W}$. In Fig. 5 the relation between the power and the correspondent temperature obtained at the hot spots for this structure is shown.

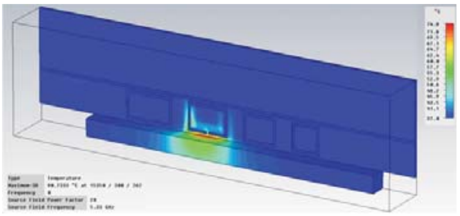

Fig. 4. Thermal simulation of the structure with four square SRRs.

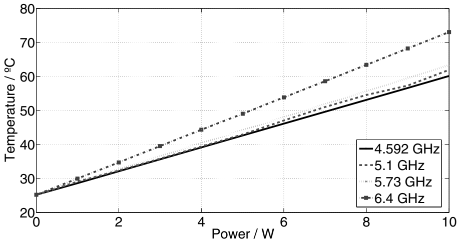

Fig. 5. Results of the thermal simulation for the structure with four SRRs.

C. Prototypes

In Fig. 6 the four designed structures are shown. They were constructed on a Rogers 6010 substrate with $\epsilon_r = 10.2$ and thickness of $254\,\mu\mathrm{m}$. The dimensions of the structures are depicted and it should be emphasized that a reduction in size for an actual tool that can be used on real patients is possible with the tradeoff of a higher frequency of operation and higher sensitivity to the imminent losses from the biological tissues.

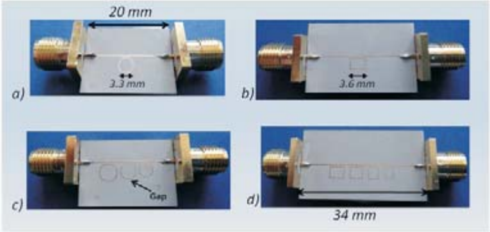

Fig. 6. Developed prototypes. a) One circular SRR, b) One square SRR, c) Three circular SRRs and d) Four square SRRs.

IV. MEASUREMENTS AND RESULTS

Measurements are done using phantoms of organic tissue. The recipes to construct this phantoms were obtained from [9]. The selected phantoms are based on glycerin and by changing the ratio of water, salt and poly-ethylene powder, the dielectric prototypes can be controlled to mimic a specific tissue that ranges from skin, muscle to any organ in the body and most important can include malignant tissue as well.

The first step is to operate the tool at the sensing mode to identify where the abnormality is located. After the shifted resonance frequency of the loaded structure is obtained, the tool is switched to the treatment mode and the input power is slowly increased to $10\,\mathrm{W}$. For the measurements a special setup is constructed specially to be able to operate the sensor in the treatment mode. The setup is depicted in Fig. 7. The resonant frequency of the SRR that will perform the heating is introduced in a synthesizer that will generate the signal to be delivered into the structure. The signal must be then amplified to the appropriate power which is controlled manually and displayed in a power meter thanks to the connection of a directional coupler. Then a circulator is used to protect all the equipment from undesired reflected signals and finally the amplified signal is delivered to the structure and the heating of the tissue around the desired SRR is performed.

The measured temperature distribution for the structure with one circular ring is shown in Fig. 8 and the temperature reach $48\,^{\circ}\mathrm{C}$ with $10\,\mathrm{W}$ of input power.

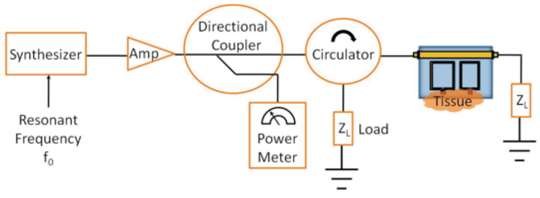

Fig. 7. Measurement setup for thermal ablation of phantom tissue.

Another example is depicted in Fig. 9. Here the four square structure was used and the malignant tissue around the first ring was subjected to thermal ablation. The temperature reaches $109\,^{\circ}\mathrm{C}$ with $10\,\mathrm{W}$ of input power. The inset plot shows the scattering parameter S_{21} with four independent resonant frequencies are depicted. In Fig. 10 a summary of the obtained temperatures at different power levels for both

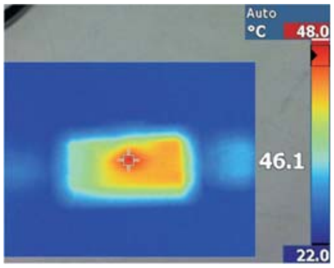

Fig. 8. Thermal measurements of the structure with one square SRR.

structures is presented. For the four square SRR structure the depicted results corresponds to the measurement with the first SRR. An interesting result from this experiment is that different structures and furthermore different rings from the same structure exhibit divergent temperature response when excited by a constant input power. This will be addressed in future work.

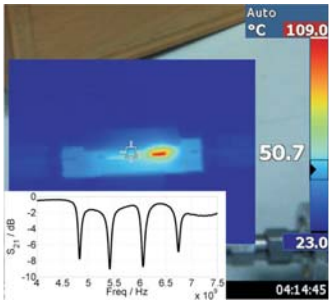

Fig. 9. Thermal measurements of the structure with four square SRR. The inset shows the S_{21} parameters.

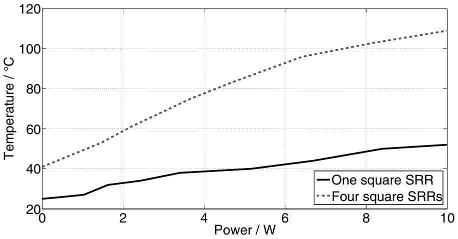

Fig. 10. Summary of the obtained temperatures at different power levels for the structure with one square ring and four square rings.

Finally a comparison between the measurements and simulations for the single circle SRR structure is depicted in Fig. 11. The difference is mainly due to the fact that we do not have the means to obtain the absolute dielectric value of the used phantom and the influence from the measurement setup components i.e. the losses inserted by these elements is unknown. Thermal ablation with microwaves is a promising approach for cancer treatment. It has the advantage over RF ablation that the size of the tool can be shrink substantially and the treatment time is shorter. RF ablation takes minutes to produce the same impact that microwaves can accomplish in seconds at a much lower power. For future work, a temperature feedback control will be included in order to perform more accurate the thermal ablation procedure.

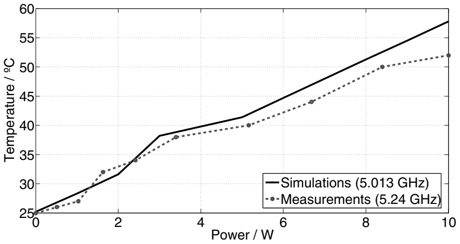

Fig. 11. Temperature measurements Vs. simulations for the single square SRR.

V. CONCLUSIONS

A dual mode tool based on microstrip-excited SRRs for analysis of the dielectric properties of organic tissue and localize thermal ablation treatment was presented. The design process with the corresponding thermal simulations was explained. Four prototypes were developed and the results from measurements with phantoms of human tissue were presented to prove the concept. The key point in the design corresponds to the ability of each SRR to be completely independent from its neighboring rings on both operation modes. With this characteristic it is possible to extract a dielectric image of the TUT with a resolution dependent on the size and the number of pixels separated by a constant distance and to heat the tissue around the gap of each SRR independently as well. It was proven that this tool can be used to not only sense the dielectric properties of organic tissue but perform a highly located thermal ablation therapy for areas where abnormalities are detected. In future work the different temperature behavior for different SRR when subject to the same input power will be addressed as well as further studies with human tissue phantoms.

ACKNOWLEDGMENT

The authors would like to thank the company CST for providing the CST Microwave Studio Suite software package.

REFERENCES

[1] R. Habash, R. Bansal, D. Krewski, and H. Alhafid, "Thermal therapy, part iii: Ablation techniques," *Critical Reviews in Biomedical Engineering*, vol. 35, no. 1-2, pp. 37–121, 2007.

[2] C. Brace, "Thermal tumor ablation in clinical use," *IEEE Pulse*, pp. 28–38, Sep-Oct 2011.

[3] J. O'Hara, R. Singh, X. Peralta, I. Brener, E. Shaner, D. Branch, J. Han, A. Taylor, and W. Zhang, "Sensing liquid properties using split-ring resonator in mm-wave band," in *CLEO/QELS 2008*, San Jose, USA, May. 2008, pp. 1–2.

[4] Y. Gong, H. Wang, and G. Wang, "Microwave heating by using flat lhm lens," in *International Workshop on Metamaterials*, 2008, pp. 370–373.

[5] M. Velazquez-Ahumada, M. Freire, and R. Marques, "Metamaterial applicator for microwave hyperthermia," in *Proc. URSI General Assembly and Scientific Symposium of International Union of Radio Science*, Istanbul, Turkey, Aug. 2011.

[6] M. Puentes, M. Maasch, M. Schüßler, and R. Jakoby, "Frequency multiplexed 2-dimensional sensor array based on split-ring resonators for organic tissue analysis," *IEEE Transactions on Microwave Theory and Techniques*, Accepted for publication 2012.

[7] J. Baena, J. Bonache, F. Martin, R. Sillero, F. Falcone, T. Lopetegi, M. Laso, J. Garcia-Garcia, I. Gil, M. Portillo, and M. Sorolla, "Equivalent-circuit models for split-ring resonators and complementary split-ring resonators coupled to planar transmission lines," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 4, pp. 1451–1461, April 2005.

[8] J. Pendry, A. Holden, D. Robbins, and W. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE Trans. Microwave Theory Tech.*, vol. 47, no. 11, pp. 2075–2084, Nov. 1999.

[9] A. Trehan and N. Nikolova, "Numerical and physical models for microwave breast imaging," *Department of Electrical and Computer Engineering. McMaster University*, 2009.