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Design of an Ultra-wide Band Active Antenna for Medical Microwave Radiometry

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Abstract

This paper presents the design and modeling of an ultra-wide band active antenna operating over 0.5 – 4 GHz for medical microwave radiometry. A single arm Archimedean spiral antenna integrated with a pre-amplifier in a multilayer structure is designed and optimized for use with a multi-frequency medical microwave radiometer. Numerical simulations of the active antenna on a multi-layer printed circuit board is compared with passive receive antenna on a two layer board. Simulations indicate that the radiation characteristics of the receive antenna with and without the pre-amplifier remains unchanged.

Keywords – active antenna, spiral antenna, microwave radiometry.

1. Introduction

Microwave radiometer for medical applications is an instrument that can detect deep-seated thermal anomalies present inside the human body, non-invasively. The basic configuration of a medical microwave radiometer is shown in Figure 1. Since the amplitude of thermal radiation in the microwave region is on the order of nano watts (nW), the noise power captured by the antenna is fed to a radio frequency (RF) chain having a cascade of low-noise amplifiers (LNA) to boost the received power to a detectable level and a band pass filter (BPF) to gather noise power over the desired frequency range. Careful selection of components for radiometer design and good receive antenna design is essential to process the received ultra-low power signal with high signal to noise ratio.

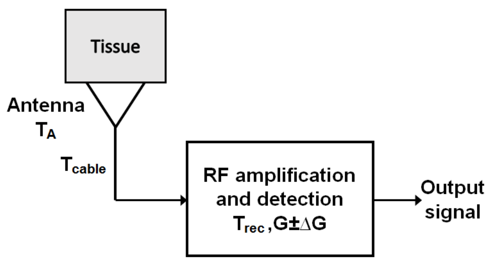

Figure 1. Basic configuration of a radiometer.

Based on the literature, spiral antennas [1] are preferred for this application due to its broadband characteristics, circular polarization, ease of miniaturization, flexibility and the ability to be fed directly by an unbalanced coaxial structure. The antenna should also be well matched to the tissue under consideration in order to effectively couple the received noise power and have a good sensing depth up to several centimeters inside the tissue.

In this paper, a single arm Archimedean ground plane backed spiral antenna is designed and optimized for better matching and power coupling efficiency to the tissue over a ultra-wide frequency range of 0.5-4 GHz. Further, the antenna is embedded with a pre-amplifier to improve the signal to noise ratio of the radiometer. EM simulations carried out for performance evaluation of the antenna with and without a pre-amplifier are presented.

2. Theory

Based on the simplified illustration in Figure 1, the effective noise temperature of the system without a pre-amplifier is given by [2],

$$T_{sys,w/o\ preamp} = T_{cable} + L_{cable} T_{rec}\ , \qquad (1)$$

where T_{cable} and T_{rec} denote the noise temperature of cable and the radiometer, respectively, and L_{cable} represents the cable loss.

For the radiometer connected to an active antenna whose pre-amplifier is having a noise temperature of T_{preamp} and a gain of G_{preamp}, it is given by Eq. 2.

$$T_{sys,with\ preamp} = T_{preamp} + \frac{T_{cable}}{G_{preamp}} + \frac{L_{cable} T_{rec}}{G_{preamp}}. \qquad (2)$$

From Eqns. (1) and (2), it can be inferred that $T_{sys,with\ preamp}$ will be lesser compared to $T_{sys,w/o\ preamp}$ if the pre-amplifier has a sufficiently low noise temperature and a reasonable gain [2].

3. EM simulation model

3.1 Passive antenna

To start with, a spiral antenna without pre-amplifier was designed using Ansys HFSS 17.0 software. The antenna model depicted in Figure 2 was loaded with a tissue block and fed with a coaxial SMA probe for near-field simulation. The dielectric property of the tissue was modeled using the Cole-Cole model reported by Lazebnik et al for healthy glandular breasts [3]. The spiral arm was designed on a RT/duroid 6006 (Rogers Corp.) substrate of 2.54 mm thickness and it was backed by a circular ground plane. A thin ground strip of 35 µm thickness surrounding the spiral arm was included for better immunity from stray electromagnetic interference (EMI). The top and the bottom ground sheets were shorted through plated via holes. Finally, the antenna was covered with a thin sheet of solder mask (13 µm thickness) for improved impedance matching with the tissue. The receive power pattern of the antenna was studied in active mode using reciprocity theorem. The antenna was optimized for return loss greater than 10 dB over 0.5-4 GHz with directional power deposition in the tissue. The design parameters of the optimized 36 mm diameter spiral are listed in Table 1.

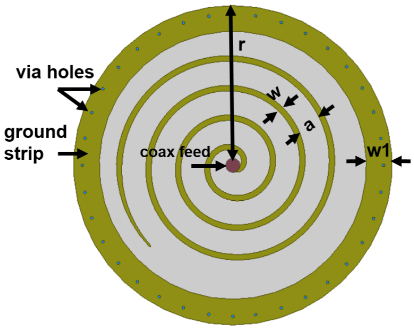

Figure 2. Layout of the passive spiral antenna.

Table 1. Optimized antenna design parameters.

Design parameter	Optimized value
Strip width (w)	0.65 mm
Spiral growth rate (a)	0.55 mm
Radius (r)	18 mm
No. of turns (N)	4
Via holes diameter	0.35 mm
Ground strip width (w_1)	3 mm

The simulated return loss at the antenna port is more than 10 dB over the entire frequency range of 0.5 GHz-4 GHz as shown in Figure 3(a). This indicates that the antenna is well matched to the tissue load. The power distribution profile at 1.3 GHz (the centre frequency of the low frequency radiometer) is shown in Figures 3(b), 3(c) and 3(d) at varying depths in the tissue. The plots were normalized with respect to the maximum power value at 10 mm depth. It can be seen that the power received by the antenna decreased with increase in depth. Thus, the power gathered by the antenna from a thermal anomaly in the tissue will decrease with increase in the depth of the thermal anomaly from the tissue surface.

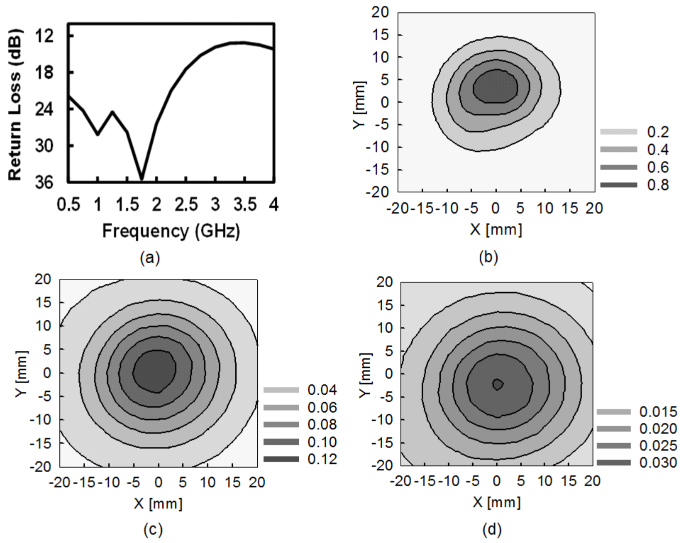

Figure 3. Simulation results of passive antenna. (a) Antenna return loss, and normalized power distribution at (b) 10 mm (c) 20 mm and (d) 30 mm depths in the tissue.

3.2 Active antenna

Using multilayer printed circuit board (PCB) technology, an active antenna was modelled by embedding a pre-amplifier just below the passive spiral antenna. For this purpose, a low-noise, moderate gain, internally matched amplifier (RAMP-33LN+, Mini-Circuits, USA) was chosen. The output of the passive antenna was coupled to the input of the pre-amplifier through a plated via hole that was optimized for maximum coupling between the antenna and the pre-amplifier. The four layer stack-up details are shown in Figure 4.

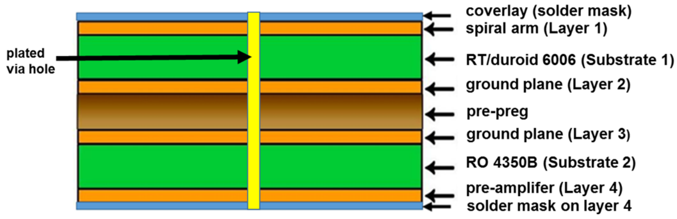

Figure 4. Multilayer stack-up for active antenna design.

For EM simulation, the passive antenna was fed with a 50 Ω co-planar waveguide (CPW) feed line through a plated via hole. The feed line represented the input port of the pre-amplifier with internal impedance matching for 50 Ω transmission line. The simulated return loss at the antenna port is shown in Figure 5(a). Figures 5(b), 5(c) and 5(d) show the power distribution profiles at 1.3 GHz for the same depths in the tissue as described in section 3.1.

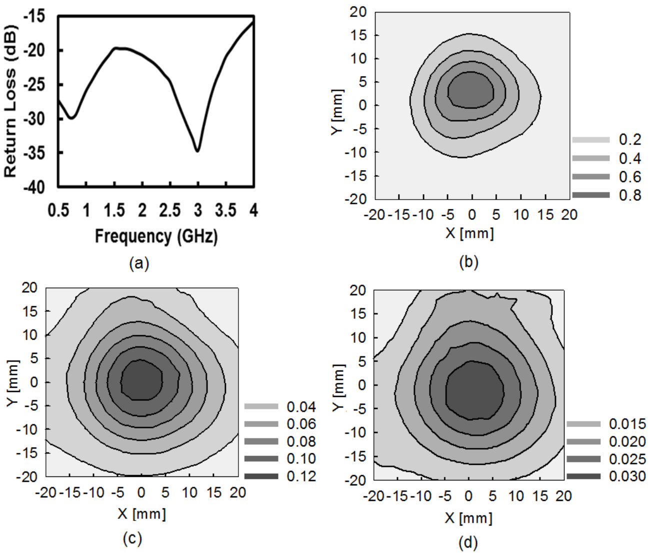

Figure 5. Simulation results of the active antenna. (a) Antenna return loss, and normalized power distribution at (b) 10 mm (c) 20 mm and (d) 30 mm depths in the tissue.

From Figures 3 and 5, it can be inferred that the near field radiation characteristics of the active antenna in the tissue is similar to that of the passive antenna. Thus, it can be concluded that the addition of the pre-amplifier with antenna on the multi-layer PCB did not significantly alter the receive characteristics of the ultra-wide band active spiral antenna designed for multi-frequency microwave medical radiometer.

4. Conclusion

The design and simulations of a single arm Archimedean spiral antenna with a ground plane were presented. The ultra-wide band antenna with return loss greater than 10 dB over 0.5-4 GHz was further integrated with a pre-amplifier to eliminate the cable loss that connects the antenna to the radiometer. From the antenna simulations, it can be concluded that the power reception characteristics of the active antenna was not altered by the pre-amplifier board.

5. Acknowledgement

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6. References

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