NONINVASIVE NEAR-FIELD ARRAY PROBE DESIGN FOR INTERNAL BODY TEMPERATURE MEASUREMENT

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Abstract—The array antenna designed in this paper is used to receive the EM wavewhich come from human thermal radiation of the muscle tissue underthe real skin based. The simulation is based on the phantom model made by pig skin gelatin. The proposed array antenna is a 2×2 circular patch antenna, and the microstrip line is used to control the antenna phase. The impedance bandwidth of the 10dB return loss is about 1.573-1.734 GHz, which is equivalent to 9.7%, which covers well on 1.575GHz Radiometer operating band. The study found that the weighting function of receiving a layer of interest (muscle layer) from a single antenna and an array antenna increased from 48.4% to 53.2%, and the influence of the presence or absence of the overlay increased from 32.5% to 53.2%. The results show that the array antenna can increase the sensitivity of the radiation temperature measurement system.

Index Terms—Array antenna, radiometry, Near-field probe, Patch antenna

I. INTRODUCTION

In recent years, people's health awareness has gradually increased. Medicine emphasize early prevention to avoid the best time to rescue after a serious illness. Therefore, monitoring changes in the temperature inside the body is important for health management applications, such as early cancer detection, diagnosis or therapy treatment. tracking body temperature is important for disease prevention. For example, changes in the body during tumor formation can be known from the changes in the body temperature to achieve a preventive effect. Temperature measurement use radiometer to catch the EM energy of thermalradiation to provide important timely information for a variety of treatments. Measuring blackbody spectral radiation over a given frequency band is one method of temperature measurement.

Using a human phantom model for subcutaneous temperature measurement by radiometry in the laboratory has been proposed [1]. Ahmed T. et al. studied how to produce an artificial human phantom [2]. Yilmaz et al. proposed using gelatin to make phantoms to approximate the ideal human body's characteristics [3]. Popvic et al. presentedsome antenna probes and radiometers in various frequency bands to discuss how to obtain enoughpower from the tissue stack [4-5]. They also attempted to design a wearable radiometer for body temperature measurement[4]. They sensed the depth of microwave radiation through a dipole antenna for internal body temperature measurement [5].However, the power radiated from the antenna and then penetrated internal tissue layer is still not enough for contemporary radiometer.

Based on the theory of black body radiation, the designed near-field probe is used to receive the thermal radiation generated from the inside of the human body in the workingmicrowave frequency. The EM radiation in the microwave frequency range can penetratethe subcutaneous tissue to achieve effect of the non-invasive temperature measurement.The goal of research is to develop a near-field array antenna for non-invasive human internal temperature measurement to receive more energy to enhance the sensitivity of the microwave radiometry measurement systems. The near-field array antenna is designed on the human immersive model to facilitate experiments. The developed antenna must cover 1.575 GHz band which is allocated for the Global Positioning System (GPS). The simulation software HFSS is employed to analyze the energy distribution into the human body.

II. PHANTOM AND SIMULATION MODEL FOR TISSUE

A. Phantom for Tissue

The near-field probe designed in the presentation will be applied to subcutaneous temperature measurement.Since human experiments must be permitted by the government in Taiwan, a phantom model is used to substitute the real human testin order to avoid illegal and carrying out related experiments. The key point will focus on how to make the material of the phantom human body model and measure its electrical characteristics and parameters.Afterthe phantom is fabricated, we hope grasp the characteristics of the mannequin and hope its characteristic is close to the real human body. Then the antenna attached to the phantom can be designed and matched to the real human body.

Before making the phantom human body model, it is necessary to know the electrical parameters inside the human body under ideal conditions. It is assumed that there are three layers inside the human body, which are skin layer, fat layer and muscle layer, and their thicknesses are 2 mm, 4.8 mm and 50 mm, respectively. The phantom model produced in the paper is cylindrical. It is referred to the electrical characteristics of human tissue provided on the US Federal Communications Commission's website [6].

In the designed frequency band, the relative dielectric constant of ideal skin layeris about 39.2 and electrical conductivity is about 1.09 S/m, the relative dielectric constant ofideal fat layer5.3 and electrical conductivity 0.07 S/m. The relative dielectric constant of the ideal muscle layer is about 53.8 and electrical conductivity is about 1.22 S/m. Realizing the electrical characteristics of various layers inside the human body, we found that thecharacteristic of the fat layer is close to that of the FR4 substrate. Therefore, FR4 was employed to replace the fat layer.The recipe ofmaterial for the phantom human body model material designed in [3] is used to make the phantom skin layer and muscle layer. The material is mixed by gelatin, water and salt (NaCl). In the 1.575 GHz band, the ratio is 70 grams of pig skin mixed with 300 grams of water and 1.3 grams of salt. The steps to make the material are relatively easy, as follows:

1. Prepare a cylindrical measuring cup (not wide and narrow)
2. Calculate the material ratio
3. Put the material into the measuring cup
4. Pour the prepared hot water
5. Slow agitation reduces the number of bubbles and makes the material evenly soluble in water
6. Use tissue paper to remove excess bubbles from the upper layer.
7. Place the model toa refrigerator (the placement time varies with the required thickness).

The finished product will be a jelly-like solid. It will replace the skin and muscle layers of the human body, and we replace the fat layer by FR4.Thus, completed the human phantom model used in the paper.

B. Simulation of phantom model

By using the transmission line model, the electrical properties of unknown media can be measured [7].To find the complex dielectric coefficient ($\varepsilon' - j\varepsilon''$), the end of the coaxial probe must be immersed in the dielectric to be tested. A 50 ohmsemi-rigidcoaxialwhich outer diameter 1.68 mm, inner diameter 0.51 mm and length 10 cm was employed to measure the input impedance by the network analyzer andthen calculated by using the formulareferred to [7].

Fig. 1 shows an equivalent model of a coaxial cable probe immersed in a test object.The equivalent transmission line model (dashed line) is used to replace the lossy medium during measurement.The complex dielectric coefficient of the lossy mediumis related to the measured admittance. The measurement method of the transmission line model is suitable for the measurement of relatively high loss material [7]. Whenapplyingthe 5071B network analyzer to measure the admittance, the reference plane of the coaxial probe must be calibrated to the end surface of the probe for correct measurement. Here, pure water is used as a reference standard. It is well known that the relative complex permittivity of pure water [8] is represented by the following formula(1):

$$\epsilon_{water} = \epsilon_\infty + \frac{\epsilon_S - \epsilon_\infty}{1 + (j\omega\tau)^{1-\alpha}} \quad (1)$$

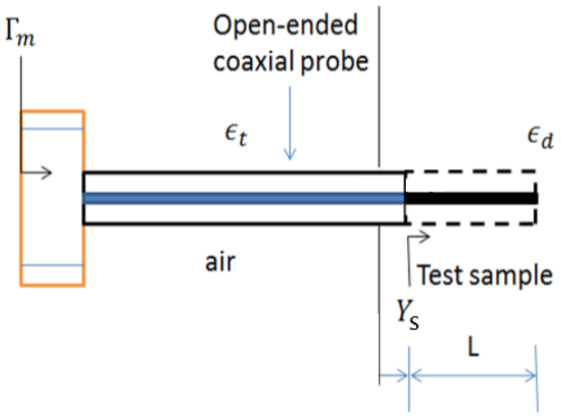


Fig.1 Equivalent transmission line model

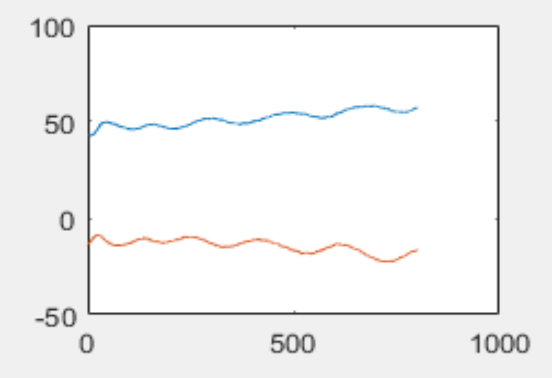


Fig.2 complex dielectric constant of the phantom model produced by gelatin.

Table. 1 Electrical characteristics of the phantom model at 1.575 GHz

	Material	Dielectric coefficient	Conductivity	Loss tangent
Skin	Gelatine model	46.19	1.02	0.25
Fat	FR4	4.4	0.0077	0.02
Muscle	Gelatine model	46.19	1.02	0.25

where ϵ_S=78.3, ϵ_∞=4.6, τ=8.08 ps, α =0.014, ω=2πf, i.e., means that the complex dielectric constant of water is affected by the frequency.

By measuring the water toobtain Ys, the complex dielectric constant and the admittance of pure water are taken into the formula (2) [7] shown below to obtain *L*:

$$Y_s = i\frac{\sqrt{\epsilon}}{\sqrt{\epsilon_t}}\tan\left(k_0\sqrt{\epsilon}L\right) \approx \mathrm{i}\frac{\epsilon k_0 L}{\sqrt{\epsilon_t}} \quad (2)$$

Where $k_0$is 2π/λ and ϵ_t is 2.04. Assuming *L* is a fixed value, the complex dielectric constant of the phantom model can be measured by the above formula. Fig. 2 shows the measured complex dielectric constant of the gelatin. The complex model has a complex dielectric coefficient. The calculated points are 801 points from 1 GHz to 5 GHz.The upper line is ε', and the lower is

ε". The dielectric constant of gelatin model ε' is around 46.19 and ε" is around 11.69 at 1.575 GHz band.

The complex dielectric coefficient can be converted into the body's dielectric constant. The electrical conductivity, loss tangent, dielectric constant is ε′, conductivity is $\omega\varepsilon_0$ ε″, loss tangent isε′/ε″.The computation is carried out bythe Matlab software based onthe above formulas. In the following experiments, the pig skin gelatin model is applied for simulation and experiment. Table 1 lists the measured phantom model data used in the paper.

III. NEAR FIELD CIRCULAR PATCH ANTENNA DESIGN ON PHANTOM MODEL

The circular printed antenna [9] which is suitable for attaching on the human body is easier to fabricate than other antennas. The substrate of the printed antenna is FR4, which hasdielectric constant of 4.4 and loss tangent of 0.02. One side on the substrate is the antenna body and the other side is the ground plane. The advantage is that when the antenna radiates, the energy is concentrated on the antenna main body, and the ground plane will have almost no radiation. It is a directional antenna which meets the requirement of detecting the thermal radiation from the human body. The patch antenna is fed bya 50-ohm microstrip line terminated with a SMA connector.

The near field probe antenna is attached with the phantom model to design.Fig. 3 shows the top view of the probe antenna which measures60 mm × 60 mm, and the radius of the circular patch is 27 mm.Inserting a layer of superstrate (FR4) between the patch and the skin surface of the phantom model can reduce the absolute value of electric field but help matchingthe probe to the deeper tissue layers and increase the power transfer into the muscle layersince high dielectric contrast ratio between the antenna and the skin is not suitable for wave to transmission [1].

The study used an EM simulation software ANSYS HFSS to design and then evokesan EM simulator, Feko, toverify the correctness of the simulation. ANSYS HFSS and Fekohave different numerical methods to simulate and evaluate. The method used by ANSYS HFSS is finite element method (FEM) butFekoused is the Method of Moments (MoM). If the answers evaluated by different simulation methods are the same by the two different approaches, it representsthe simulation is sufficiently correct. Fig.4 shows the simulation results of the antenna's return loss. The designed antenna is matched in the 1.575 GHz band. The simulated results by HFSS show well agreement with those byFeko. Fig. 5 shows current distribution on the designed circular patch antenna. It shows that half-wavelength resonant mode is excited. Fig. 6 show volume power loss density (VPLD)inside the three layers.

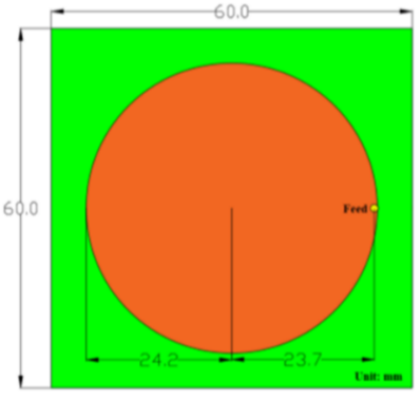


Fig.3 Top view of the probe antenna

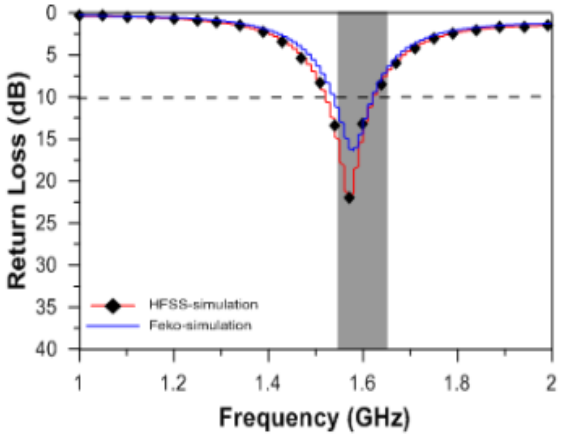


Fig. 4Feko and HFSS simulation results of the antenna's return loss.

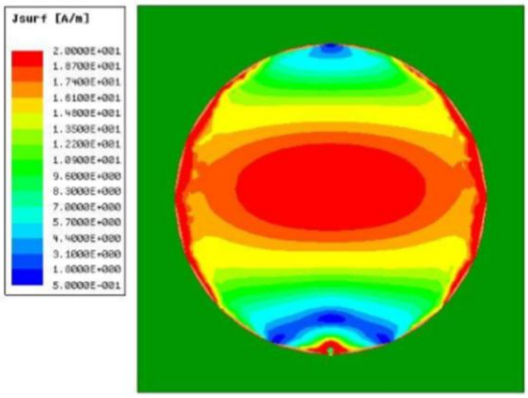


Fig.5 Current distribution on the probe antenna.

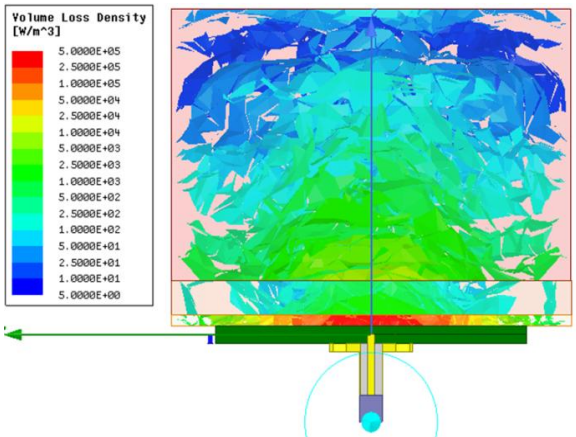


Fig.6Volume power loss density of the probe antenna.

IV. NEAR FIELD ARRAY ANTENNA DESIGN ON PHANTOM MODEL

Using array to design near-field probe can maximize power to deposition into the buried muscle layer. After implementing a single element antenna designed on the phantomhuman body model and completing the impedance matching, array antenna is designed to achieve maximize power transfer into the muscle layer in order to increase the power loss density in the deep tissue layer. The designed array antenna has four-elements. The geometry of the proposed circular patch array antenna with detailed design parameters is shown in Fig. 7(a) and (b).It occupies a volume of 110 (L) x 110 (W) x 2.4 (H) mm^3. The array antenna has a two-layer substrate where comprises 2 x 2 circular patches on the top layer and a

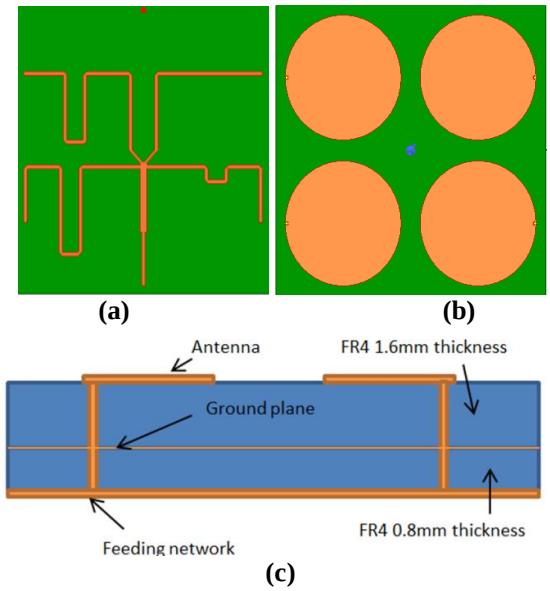


Fig.7 Array antenna architecture (a) feeding network (b)antenna, and (c) cross-section view.

microstrip feed network on the bottom layer.The middle layer between the two substrates is the ground plane player. The substrate thickness on the antenna side is 1.6 mm and the thickness of the substrate on the array feeding side is 0.8 mm. In our design, a circular patch resonating at 1.575 GHz was simulated and then fabricated on a FR4 substrate with a dielectric constant ε_r and a loss tangent equal to 4.4 and 0.02. The diameter of each patch is approximately equal to the half-wavelength of 1.575 GHz. Unlike conventional array designs, two rows of components are fed back to back to further increase the electric field strength on the near field region of the array antenna.

Fig. 7 (c) showscross-section view of the array antenna.Due to size considerations, we design a 2×2 array antenna. So we need to design a array feeding network to let each antenna element has different feeding phases(0^0, 0^0, 180^0, 180^0). The feeding network connected to a 50-ohm microstrip lineis designed on the ground plane side and through the vias to feed the antenna elements. By adjusting the width of the quarter-wavelength microstrip line can help impedance match between each element of the array antennas.

Prototypes of the proposed near field circular patch array antenna have been fabricated and tested. Measurement results were made by using a network analyzer (Agilent E5071B). Fig. 8 shows the simulated and measured return loss ofthe array antenna, where some of the differences between them may be primarily because of the effects of the SMA connector and the antenna imperfectly fitting with the phantom model in the measurement. The proposed 10dB return loss of the array antenna depictsthe fractional impedance bandwidth between 1.573-1.734 GHz is about 9.7%. It covers the operating band of the 1.575 GHz radiometer.

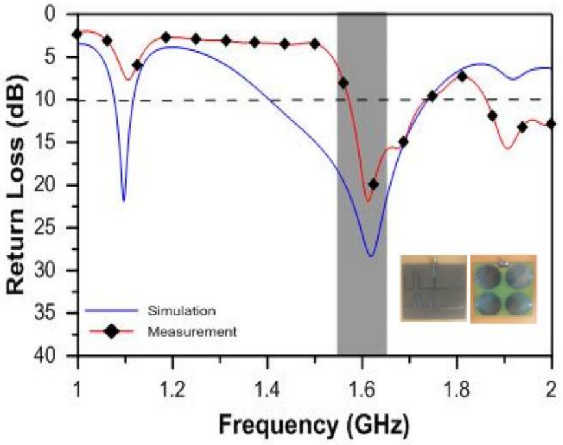


Fig.8 Simulated and measured return loss of array antenna

The antenna designed in the paperis mainlyemployed to receive the thermal EM radiation energy. According to the theorem of reciprocity in EM or antenna field, the received and emitted behavior is reciprocal [1]. That is to say, if the emission is observed to be the strongest in one direction, it means,itwill receive the most energy from that direction.The goal of the array antenna design hope the power can be maximized into the buried muscle layer, about a few centimeters. The volume power loss density (VPLD) in the HFSS simulation software is used to express the power density on each layer of the phantom model. The signal fed is excited and fixed at 1W in the input port. Table 2 listed thecomparisons of the difference of the powerratios on the each layer. The study finds that the power ratio transfer into the muscle layer of the array antenna increases from 48.4% of the single antenna to 53.2%.

Next, we discuss the VPLD performed by HFSS for the cases with or without superstrate. Fig. 9 shows the simulated VPLD results on the side views of the two antennas. The antennas are matched well by adjusting the width of the quarter-wavelength microstrip line. Fig. 10 showsthe return loss of antenna for the cases with or without superstrate, respectively.The study finds that they arewell matched in the 1.575 GHz band. Fig. 11 shows the comparison of the VPLD. By

adjusting VPLD to the same scales,we found that the signal launched into the interesting layer has increased. Since the FR4 which we used replaces the fat layer, the power in the fat layer is small.The energy of the fat layer in Fig. 11(b) cannot be displayed so the display of the VPLD has adjusted. Table 3 shows comparisons between the antennas with and without superstrate. The power ratio transfer into the muscle layer of the array antenna with the superstrate increases from 32.5% to 53.2%, as compared with the case without the superstrate.

Table 2 Compare power ratio transfer into the tissue layer for the single and array antennas.

	Skin(%)	Fat(%)	Muscle (%)
Single antenna	50.7	1.5	48.4
Array antenna	44.8	1.9	53.2

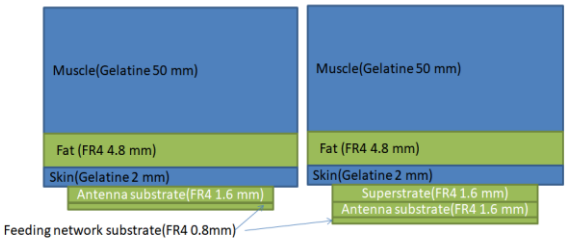


Fig.9side views for the cases with and without superstrate.

Table 3 power ration comparison between the antennas with and without superstrate.

Array antenna	Skin (%)	Fat(%)	Muscle(%)
Without superstrate	65.1	2.2	32.5
With superstrate	44.8	1.9	53.2

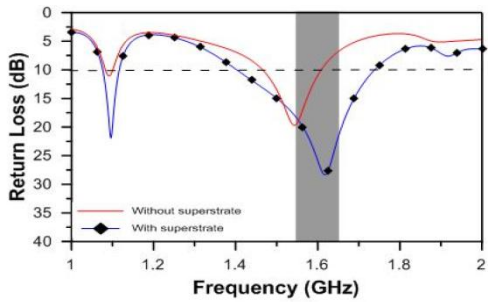
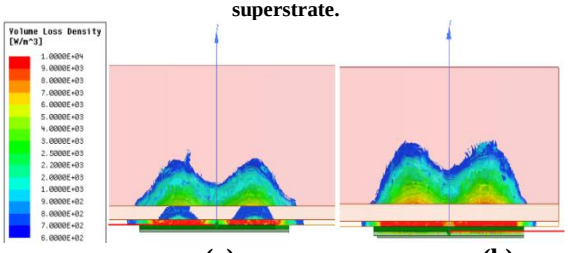


Fig.10 Simulated return loss for the caseswith and without superstrate.



(a) **(b)**

Fig.11 simulatedvolume power loss density for the cases, (a)without and (b)with superstrate.

CONCLUSIONS

The array antenna is proposed to maximize power deposition to the buried muscle. Adding a superstrate between the antenna and the phantom demonstrates can reduce the power absorbed by the skin layer and increase the power transfer into the muscle layer. The phantom model made by gelatin has been fabricated and its electrical characteristics have been measured in the paper. The impedance bandwidth of the proposed array attached on the phantom is allocated in 1.573-1.734GHz. Itsfractional bandwidth is about 9.7%, which covers well in 1.575GHz radiometer operating band. The study found that the power ratio transfer into the muscle layer of the array antenna increases from 48.4% of the single antenna to 53.2%.The power ratio transfer into the muscle layer of the array antenna with the superstrate increases from 32.5% to 53.2%, as compared with the case without the superstrate.

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