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We studied the wireless power transmission capabilities of microwave through human skin-tissue. Microwave transmission through simulated human skins was tested with rectenna array as a power receiver located under the simulated human skin tissue. Most of transplanted medical devices and sensors require power to operate autonomously but currently by imbedded battery. Wireless power transmission alleviates the needs of imbedded power source and hard-wire power network. We used human skin-like materials, such as various polyurethanes and pork skin, under X-band microwave exposure. Transmission rate through various polyurethanes under the threshold limit value (TLV) and dielectric constant was measured in this experiment. It is also critical to measure specific absorption rates (SAR) of polyurethanes and transmission rates through polyurethanes as well as pork skin. This paper presents power transmission rates under varying thickness of polyurethanes, and effectiveness and efficiency of rectennas under the TLV of microwave power. In addition, we will discuss milimeter wave thermograph and hazards the absorption characteristics of human skin under 8-13 GHz using the results of polyurethanes and pork skin.

Keywords: Microwave, Power transmission, Dielectric Constant, Transmission Rates

Introduction

The use of microwave power system has been demonstrated for smart actuators and devices to provide flexible maneuverability for aero-vehicles and robots [1-7]. This system provides an alternative power/energy source feed by wireless power transmission mechanism. The feasibility studies and development of the integrated

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system brought forth with power allocation and distribution (PAD) concept in conjunction with power control circuits [8-9]. Recently, there have been many scientific researches for developing bio-sensors in medical applications [10-12] such as measurement of glucose level in human body or health-monitoring sensors. However, these researches have not addressed power requirements for micro-sensors in practical applications. Here we address the wireless power transmission technology as one of strong candidate power source for medical applications. In medical applications, the safety under the exposure of microwave is a critical element to be clarified with intensive studies. In assessment study, both the hazard level that such exposure may entail and the safe power transmission to the embedded devices are clearly and effectively answered. There were many researches under development to understand an interaction of biological substances with handset antenna [13-14]. In this paper, we tested the interactions between rectennas and human body using polyurethane and pig skins as simulant. Specifically, we address the following issues: 1) to what extent the effect on human body with X-band microwaves; 2) how well do SAR's limit through materials reaches on rectennas; 3) how different design affects on the performance in determine of wireless power transmission for medical applications.

Rectenna Design and Experiment

A patch rectenna was designed by aligning two microstrip antenna perpendicularly, and a square patch that has slots located on the microstip. The patch and the microstrips were fabricated on a flexible membrane on which they were connected via Schottky diodes and capacitors. This configuration will mitigate the polarization effect of microstrip antenna. A patch rectenna was fabricated on polyimide membrane. Rectenna was made of 20 micron-copper strip coated on 18um-thick polyimide membrane. The patch and microstrip patterns were made on both sides of the polyimide membrane by a wet etching technique. Dielectric constant of the polyimide membrane is 3.48 at 2GHz. The Schottky diode was MA2054 series of MA-COM, which has 0.25~0.35 $V_{Forward}$ @ I_F=1mA, $I_{Reverse}$=100nA@1V_R.

A test-bed for the experiment was set up as shown in Fig. 1 (a) and measured the output voltages and currents by using a 20 W amplifier microwave. A combination of signal generator and amplifier provides 20 W of microwave power to the Narda horn antenna at a frequency range set at 7 - 18 GHz. The 20 W microwave power was delivered through a TWT waveguide connected with a rectangular horn. This microwave power will be irradiated on various rectenna array fabricated for various applications. The voltage and current output of rectenna are produced by a microwave power through various polyurethanes and pig skin, and measured their outputs as shown in fig 1. (b) and (c). All other items listed in the equipment and material section were externally placed and connected to the horn antenna and the rectenna via a backplate at the rear of the chamber. The Narda horn antenna was connected to the 20 W amplifier by a waveguide, and again to the signal generator a coaxial cable. The polyimide rectenna arrays were connected to a power measurement system that was located at the exterior of the anechoic chamber by means of a dual output BNC connector. The distances between the horn antenna and the rectenna arrays varied as 10 - 70 inches.

Results and Discussions

The performance of various vertically polarized patched rectenna (2 cm x 6.5 cm) was tested with a 20 W microwave amplifier in the anechoic chamber. The 20 W microwave amplifier was used to irradiate the microwave through the horn antenna. Figures 2 and 3 show the output voltage and current of the rectenna array when the array was placed from 10" to 70" from the form. The rectenna was positioned to the vertical direction. The results of output show 10 VDC and 2.5 mA from the polyimide rectenna at 10" from the horn as a maximum. The trend of output reduced by $1/r^2$ rule as the distance is increased. However, the output current of the rectenna shows that there is no significant preferential output trends in term of frequencies at distance of 10 " due to near field effects. As the distance is increased, the output shows a clear maximum at 9 GHz instead of 10 GHz. In terms of output power, Fig 4 shows a distinguish preferential output as approximately 25 mW/cm^2 at 9 and 10 GHz. The optimum output power at 10 GHz under the TLV [15] showed approximately 12 mW/cm^2 at 20" of the distance.

The rectenna was designed for 10 GHz, the output of current is approximately 12 mA at 10 GHz while the voltage output showed 3.5 VDC. With various polyurethanes, the output voltages at 40" distance from the horn were measured as shown in fig. 5. The absorption coefficient of the microwave through polyurethanes could be calculated based on the result.

The attenuation of the electric field through materials can be calculated as,

$$|E(z)| = E_o e^{-\alpha z} \quad \text{(v/m)} \qquad (1)$$

Where, z is the thickness of the materials. The attenuation constant, α, is given in Nepers/meter. The effective units of α are then 1/m, so that αz is unit less.

Power is proportional to the square of the electric field, so the power as a function of distance from the initial point, P_o, is calculated as:

$$|P(z)| = P_o e^{-2\alpha z} \quad \text{(W)} \qquad (2)$$

Based on the result, the absorption coefficients of polyurethanes varies from 0.3 to 0.5 mm^{-1} while the α for the pig skin varies from 1.1 to 2.5 mm^{-1} depends on the frequencies.

With various polyurethanes, the output voltages at 40" distance from the horn were measured as shown in fig. 5. The transmission of the microwave could be calculated based on the result. The output voltages of the rectenna behavior through various polyurethanes were in similar with the output through without the materials on various frequencies. However, at near 9 to 10.5 GHz ranges, the output voltages significant decreased as much as 50% in one inches thickness. Since the Threshold Limit Value (TLV) for 10 GHz is approximately10 mW/cm^2, the experimental was performed under the TLV level. Fig. 6 showed output voltages of polyimide rectenna through a pig skin (0.067 to 0.90 " thickness) at various distances. The output voltages decreased rapidly especially at 9 to 10 GHz ranges. The outputs powers of polyimide rectenna through the pig skin (1.7 mm to 2.2 mm) are shown in figure 7. It shows a significant absorption over 10. 5 GHz frequencies, but the transmission at the 9 to 10 GHz showed preferential result. The transmission rate of the output voltages varied 8 to 43 %. The output power is also plotted in figure 7 in a logarithm scale. The transmission rate of the output power varied from 3 % to 31 %. A maximum transmission rate of 31 % was achieved at 8.5 GHz while the transmission rate of 12% was achieved at 10 GHz.

Conclusions

The two different types of materials such as polyurethanes and pig skin used in simulation of human skin-tissues have tested with microwave power in ranges of 8 to 12.5 GHz. Absorption coefficients of those materials on various frequency ranges have measured. Based on the result of the experiment, the absorption coefficients of polyurethanes varies from 0.3 to 0.5 mm^{-1} while the α for the pig skin varies from 1.1 to 2.5 mm^{-1} depends on the frequencies. Typically, the skin depth (= $1/\alpha$) at 10 GHz is about 1.7 mm for the pig skin, while the polyurethane is about 2.5 mm. The result showed significant different absorption coefficients depends on materials or frequencies. Therefore, microwave transmission through simulated human skins need to be carefully tested with various human skin tissue, muscle, and heads in terms of TLV and SAR (specific absorption rate) of all parts.

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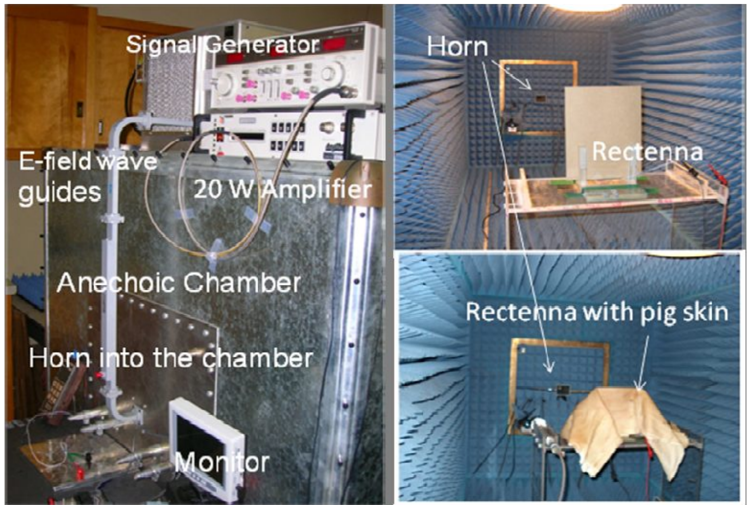

Fig. 1. Experimental Setup for rectenna performance measurement for polyurethanes and pig skin

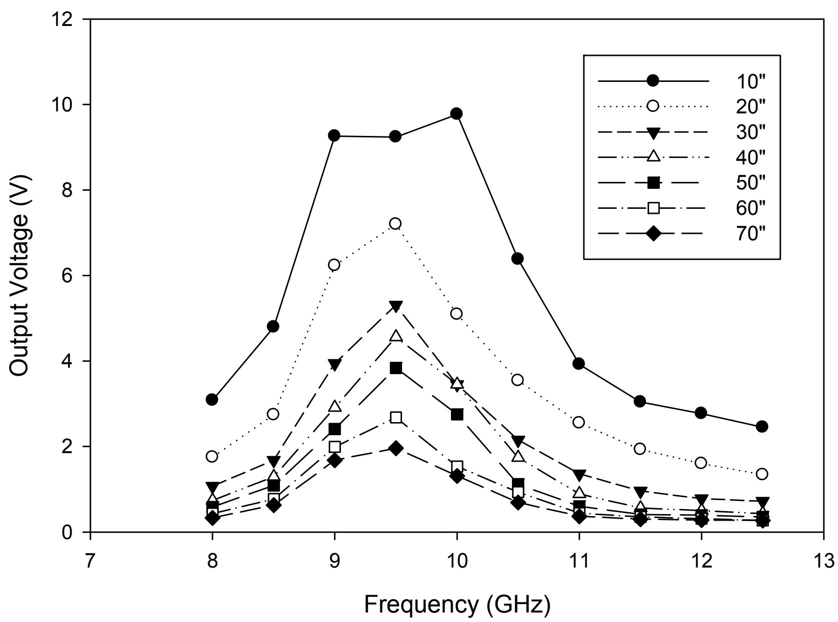

Fig. 2. Output Voltage of Polyimide Rectenna vs Distances from the Horn

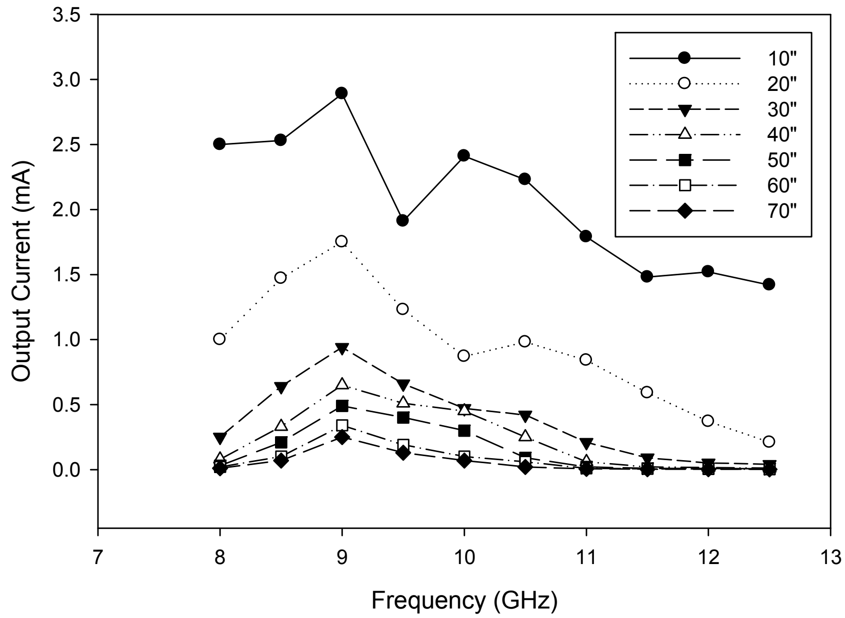

Fig. 3. Output Current of Polymide Rectenna vs. Distances from the Horn

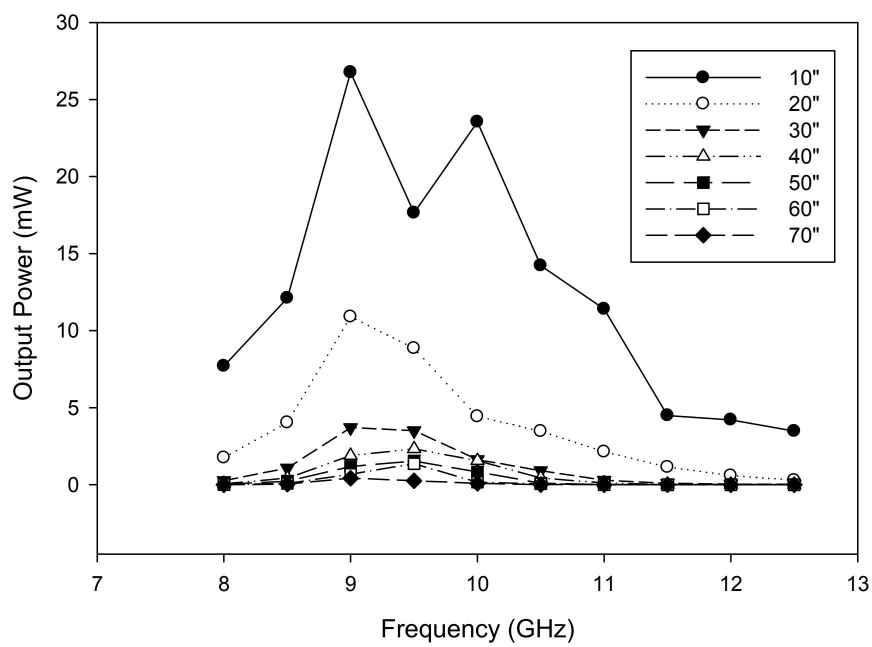

Fig. 4. Output Power of Polyimide Rectenna vs Distances

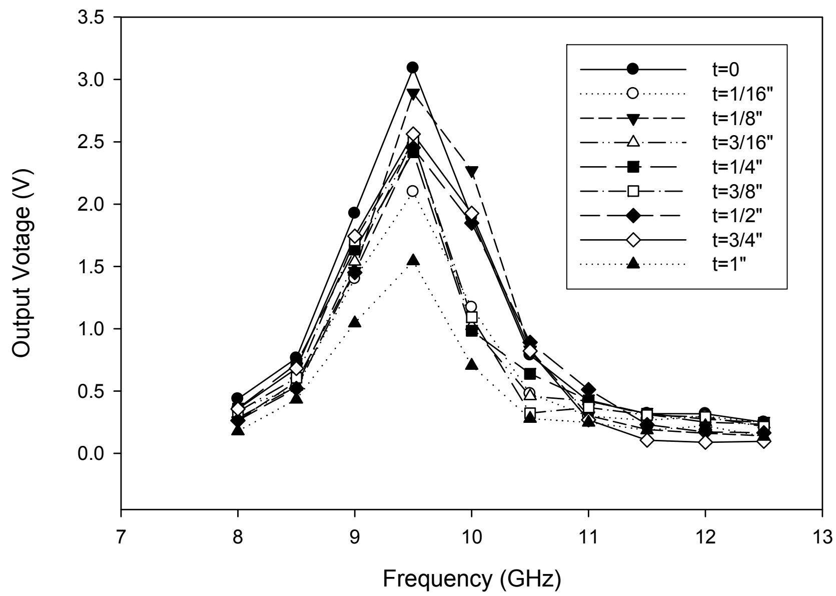

Fig. 5. Output Voltage of Polyimide Rectenna
through Various thicknesses of Polyurethanes

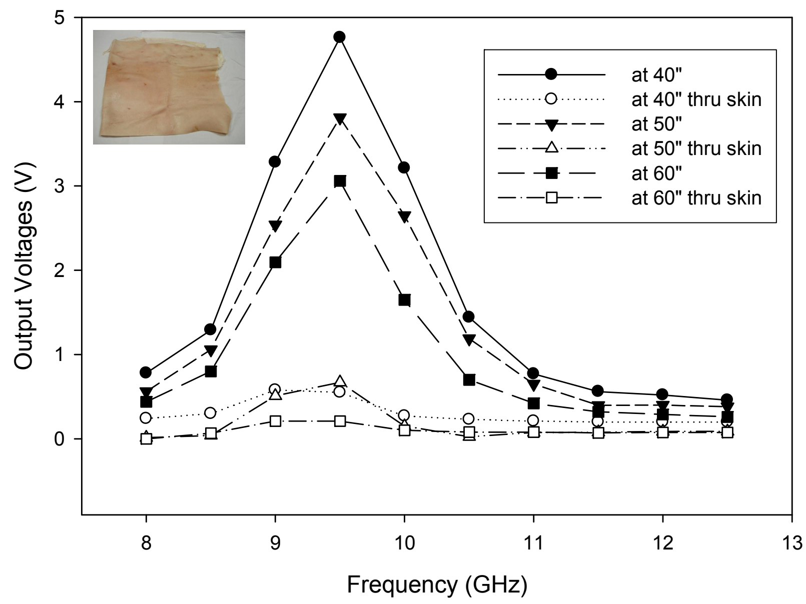

Fig. 6. Output Volatge of Polyimide Rectenna through a pig skin
(t= 0.067-0.90")

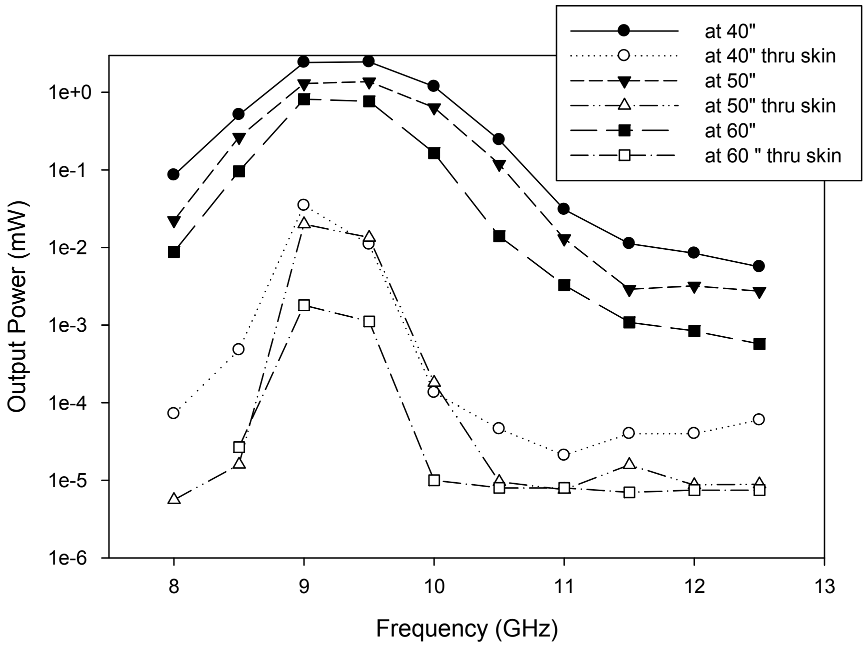

Fig. 7. Output Power of Polymide Rectenna
with pig skin and without the skin