A K-Band Low-Power Miniaturized Hyperthermia System

Dongki Kim · Kihyun Kim · Jungmin Oh · Youngrak Park · Youngwoo Kwon

Abstract

A K-band low-power miniaturized planar-type hyperthermia system was developed to replace massive and expensive equipment. The system consists of a VCO with a buffer amplifier, a high-power amplifier module, a 20-dB-coupled line coupler, a chip circulator and two power detectors for signal generation, amplification and power monitoring. All these components have been implemented in planar form on two module blocks. The total size of the hyperthermia system was less than $10\times6.5\times3$ cm^3. In order to verify the system performance, ablations were carried out on nude mice xenografted with human breast cancer. Ablation results show performance comparable to the massive components-based system. This work shows the feasibility of a low-cost miniaturized hyperthermia system for practical clinical applications.

Key words : Hyperthermia, Ablation, Bio System.

Ⅰ. Introduction

A key concept of therapeutic hyperthermia is the difference in thermal sensitivity between cancerous tissue and normal tissue[1]. This is due to the fact that tumor cells have a disorganized and compact vascular structure and therefore have difficulty dissipating heat. As a result, hyperthermia may cause cancerous cells to undergo apoptosis in direct response to applied heat, while healthy cells can more easily maintain a normal temperature[2]. Therefore, through the careful application of heat, cancerous tissue can be destroyed, while leaving the surrounding normal tissue undamaged.

Microwave ablation systems can be categorized into interstitial and non-invasive ones. The interstitial ablation system presents the advantage of selective heating, and with optimal design, can be minimally invasive. However, this method of cancer treatment has yet to establish clinical practicality due to difficulties such as poor power efficiency, resulting in the use of extremely high power levels, along with the lack of acceptably small applicator sizes. With regards to patient discomfort and pain, the non-invasive system seems to be the most attractive approach. However, the method is not feasible unless multiple probes are inserted into the body for focusing and temperature monitoring[3]~[7]. As a result, interstitial ablation is much more favorable to microwaves due to practical considerations. The existing microwave/RF ablation systems need huge power ranging from tens of watts to more than 1 kW[3]~[10]. Most of all, the system complexity of bulky and various equipment make it difficult to apply such systems in clinical treatment. The goal of this work is to develop a compact and portable interstitial hyperthermia system for low-power microwave ablation. The target is to make the hyperthermia hardware small enough to be hand-carried. This is achieved by the integration of key microwave components into two separate boards without any performance degradation.

Ⅱ. Design and Fabrication

Fig. 1 is a block diagram of the miniaturized microwave hyperthermia system. The hyperthermia frequency choice in this work can be explained with the frequency-dependent permittivity plot of Fig. 2, which shows the measured complex permittivity of fat and human breast cancer xenografted onto the nude mice at up to 40 GHz[11],[12]. Also, it can be seen from Fig. 2 that the difference of the dielectric loss(imaginary part) of the cancer and the fat reach their maximum around 20 GHz. The choice of hyperthermia frequencies around 20 GHz will result in low-power/high-efficiency heating with significantly reduced collateral damage. The target frequency was 18 GHz in consideration of the above aspects.

The total system is divided into two modules. The first one is a high-power amplifier module(PAM) and the second one is the integrated circuits of a voltage-controlled oscillator(VCO) with a buffer amplifier, a coupler, a circulator and two power detectors. Two-module design was required to effectively dissipate the heat

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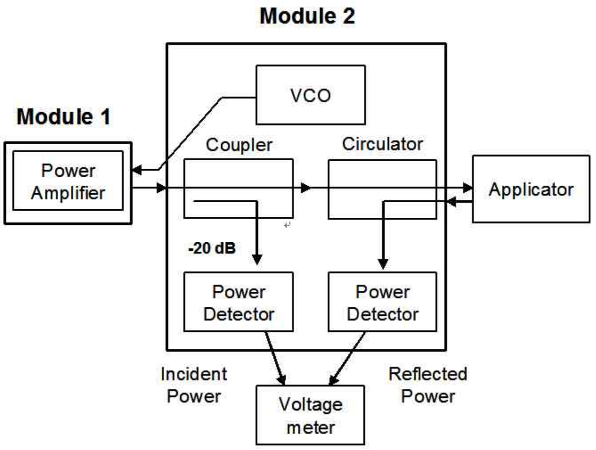


Fig. 1. A block diagram of the miniaturized microwave hyperthermia system.

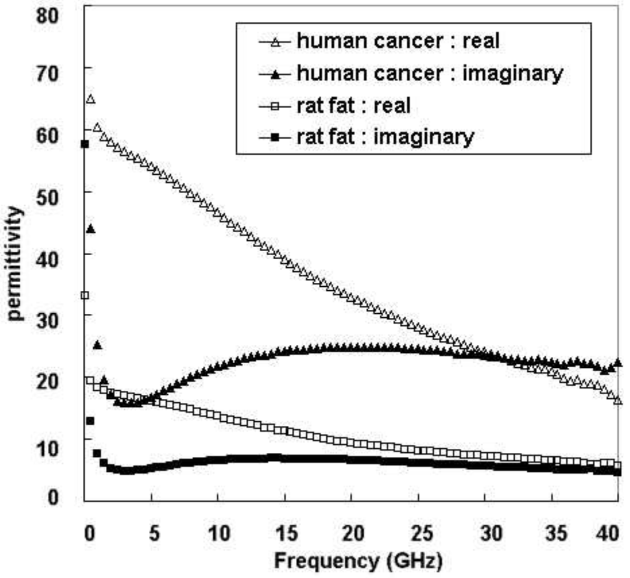


Fig. 2. Measured complex permittivities of human cancer xenografted onto the nude mice and fat extracted from rat thigh.

generated by PAM and prevent the performance degradation of modules from the high heat of the PAM. Except for the high-power amplifier MMIC and the chip circulator, each circuit was fabricated on the Duroid 5,880 substrate(dielectric permittivity=2.2±0.02, dielectric thickness=254 μm, metal thickness=8 μm).

A voltage-controlled oscillator with a buffer amplifier generated an oscillation signal at 17.97 GHz with source feedback topology. The output power was 19 dBm(including connector loss) using bare-chip GaAs transistors of 4×75 μm and the result is shown in Fig. 3. The resolution and the video bandwidths are 100 kHz. The oscillation frequency can be varied with bias control from 17.7 to 18.2 GHz.

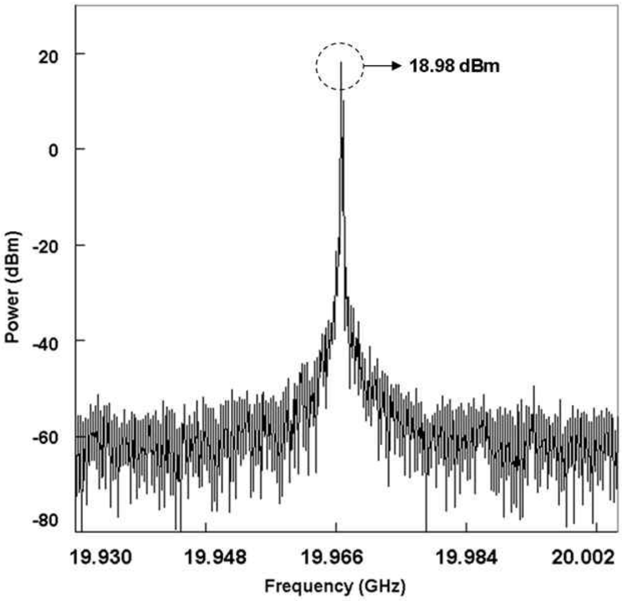


Fig. 3. The measured spectrum of the designed 18 GHz VCO.

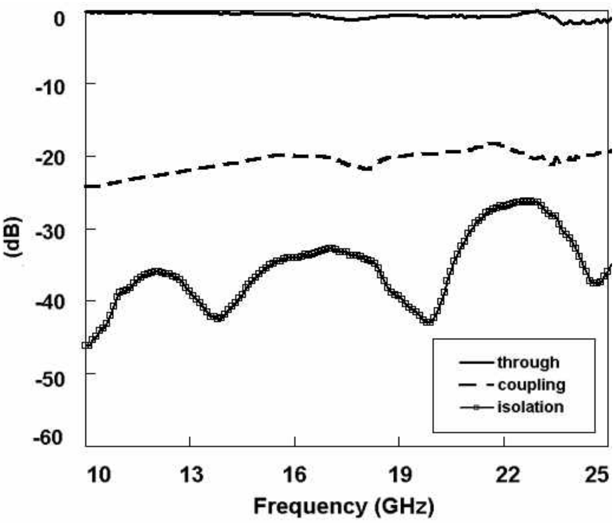


Fig. 4. Measured S-parameters of the designed coupled-line coupler.

A coupled-line coupler was designed and fabricated to monitor the incident power of the hyperthermia system with a 20 dB coupling factor at the designed frequency of 18 GHz. The coupler was designed using two 50 Ohm(770 μm) microstrip lines with a gap of 100 μm and an overlap length of 1,800 μm. The insertion loss (through), coupling and isolation of the coupler were 1.3, 21.7, 34.2 dB, respectively(including connector loss). Fig. 4 shows measured S-parameters of the fabricated 20 dB coupled-line coupler.

A commercial microstrip circulator(RADITEK, RADC-

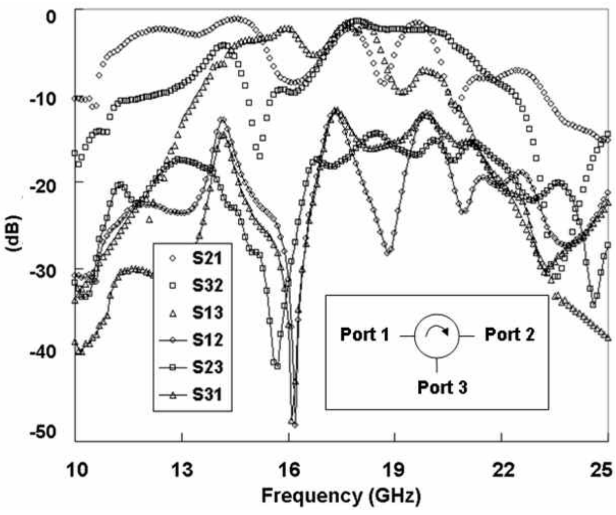


Fig. 5. Measured S-parameters of the circulator.

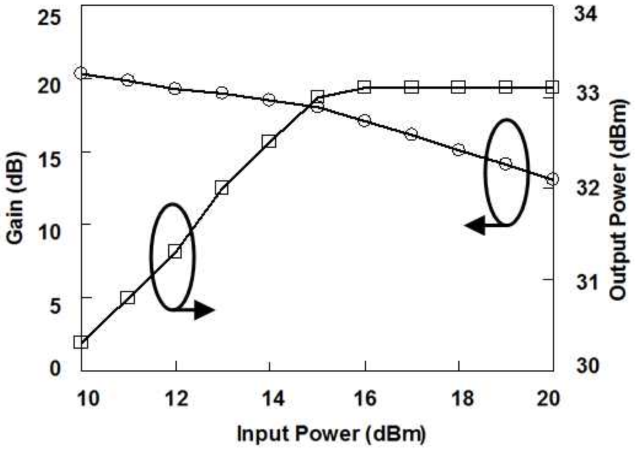


Fig. 6. The measured output power and the power gain of the amplifier.

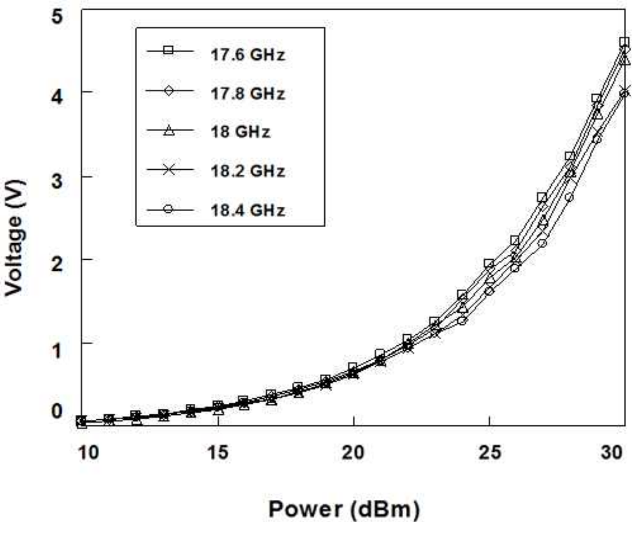


Fig. 7. Measured voltages of the power detector for various frequencies.

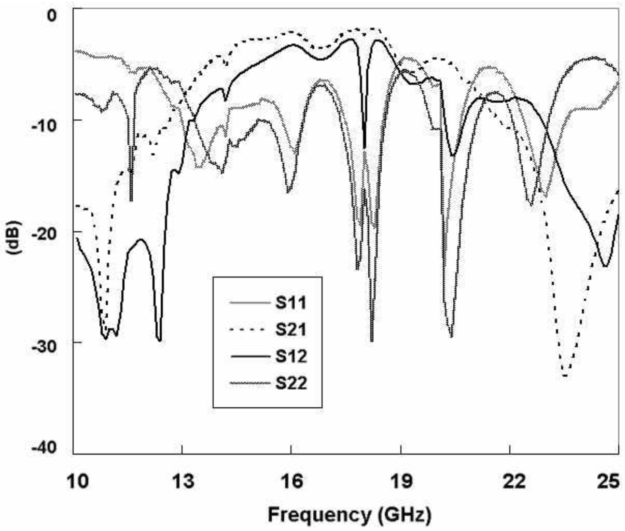
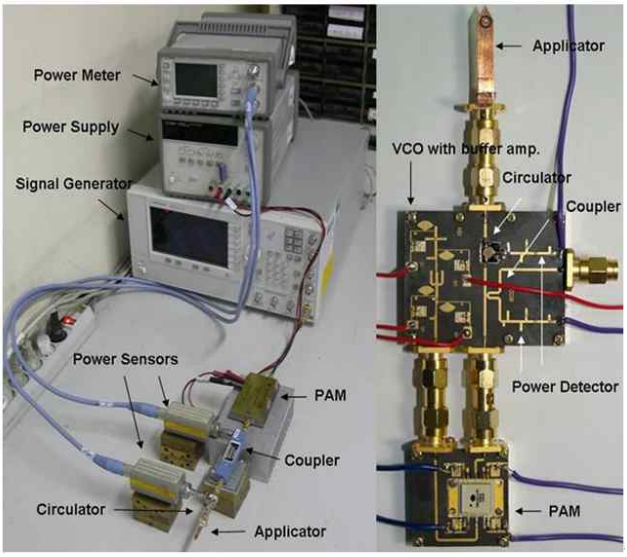


Fig. 8. Measured S-parameters of the second module.

17.2-18.7-MS31-2WR) was used to measure the reflected power with isolation of 20 dB. The power from the signal source passes through a coupler and a circulator, the incident power can be monitored from a 20-dB coupled port of the coupler and the reflected power can be monitored from the circulator. Measured S-parameters of the circulator are shown in Fig. 5. The average values of the insertion loss and isolation are 1.6 and 20.7 dB(including connector loss) from 17.6 to 18.4 GHz, respectively.

A commercial high-power and high-gain amplifier (TriQuint Semiconductor, TGA2514-FL) was used to amplify the signal from the VCO after a buffer amplifier. Since an output power of at least 1 W is needed to perform microwave hyperthermia, a high-power and high-gain amplifier is one of the most important components of the hyperthermia system. The saturated output power of the amplifier is 33.2 dBm and the power gain is 13.4 dB. Considering losses from signal paths, over 1 W of power can be emitted from the system output. The measured power and the gain of the power amplifier are shown in Fig. 6. Because the heat from the operating amplifier affects overall performances of the Power Amplifier Module and other circuits, a separate module block(Module 2 in Fig. 1) has been dedicated to PAM. Heat-sinking fin was attached to the power amplifier block.

A power detector was designed and fabricated with two bare-chip GaAs transistors of 2×20 μm. The drain and sources of the transistors were combined with wire bonds to function as diodes. Fig. 7 shows measured voltages for various frequencies. As shown in Fig. 7 the bandwidth of the power detector is about 0.8 GHz. Fig. 8 shows measured S-parameters of Module 2(in Fig. 1).



(a) Components-based systems (b) Miniaturized system

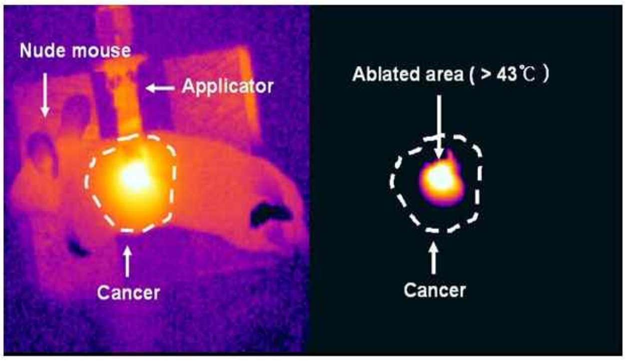
Fig. 9. The components-based (a) and the miniaturized (b) microwave hyperthermia systems.

The insertion loss through a 20 dB coupler and a circulator is 1.9 dB at 18 GHz and return losses are over 10 dB from 17.5 to 18.4 GHz. The total output power of the hyperthermia system was 1.35 W at 18 GHz.

Ⅲ. Measurements

Fig. 9 shows a photographic comparison of the components-based and the miniaturized microwave hyperthermia systems. In the miniaturized system, the size of the PAM is 3×3 cm^3 and that of the second module is 3×5 cm^3. The total size of the miniaturized system including two connectors is 10×6.5 cm^3(excluding applicator). The planar coaxial applicator at the output of the miniaturized system was also fabricated on Duroid 5880 substrate, which was the same substrate used to build the hyperthermia system. The details of the planar coaxial applicator can be found in our previous work[8]. The loss of the applicator including connector loss was 1.2 dB at 18 GHz. Thus, the output power of the system including the applicator was 1.1 W.

The hyperthermia system was tested on xenografted nude mice. Fig. 10 shows IR(Infra Red) images of a nude mouse with a cancer after 5 minutes of ablation. The first one is an IR image of a normal view with an inserted applicator on a nude mouse and the second one is a rescaled IR image of the first one over 43 ℃. The area of the surface of which the temperature was above 43 ℃ was defined as the "ablated area" of the surface[1]. The average value of the ablated area calculated from five experiments was 41 % of the total area of a cancer. The area can be broader as the power becomes higher.



(a) An IR image of a normal view (b) The rescaled(over 43 ℃) same IR image of(a)

Fig. 10. IR images of a normal view (a) and an over 43 ℃ view (b) after 5 minutes of a hyperthermia.

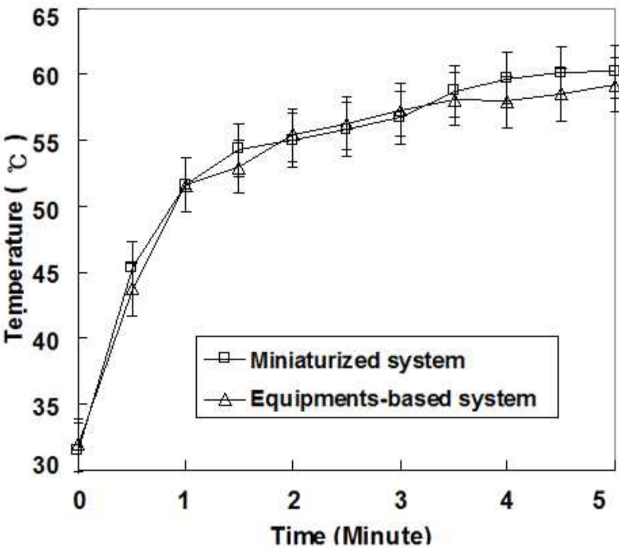


Fig. 11. Measured ablation results of cancer on nude mice with the components-based and the miniaturized systems.

Fig. 11 shows measured ablation results of nude mice with cancer, compared with those of the components-based system under the same experimental conditions with power of 1.1 W for 5 minutes. Each set of data consists of values averaged over five times. As shown in the figure, the temperature difference between the components-based and the miniaturized systems is within the error-bars. During the ablation, most of data are almost the same with a maximum temperature difference of 1.8 ℃ at 4 minutes(59.7 and 57.9 ℃ in the components-based and the miniaturized systems, respectively). The above results indicate that the miniaturized microwave hyperthermia system can successfully replace the massive components-based one without performance degradation.

Ⅳ. Conclusion

A miniaturized hyperthermia system was developed using high-frequency microwaves. The system could be divided into two modules. The first one was a PAM (Power Amplifier Module) and the second one was made of integrated circuits consisting of a VCO with a buffer amplifier, a 20-dB-coupled line coupler, a chip circulator and two power detectors. As a signal source, a VCO integrated with a buffer amplifier generated an output power of 19 dBm at 17.97 GHz. Following the VCO, a PAM having a 2 W of output power was employed. The 20-dB-coupled line coupler and a power detector with a bandwidth of over 1 GHz were used to monitor the incident power. The circulator and the other power detector were also used to monitor the reflected power. The integrated modules had small insertion loss, maintaining over 1 W of output power for the entire system. In order to verify the miniaturized system, ablations were performed on nude mice xenografted with human breast cancer. From ablated results of both systems, it could be seen that the massive and expensive system could successfully be replaced by a small and low-cost planar system. This method can be a promising approach to implement a low-cost and practical microwave ablation system in clinical environments.

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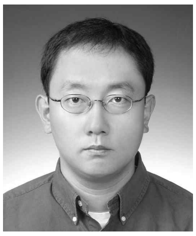

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