Theories and Techniques for a Real-Time Monitoring Microwave Ablation System

Li Wang, *Graduate Student Member, IEEE,* and Xiue Bao, *Member, IEEE,*

***Abstract*—Precisely controlling and demarcating ablation zone boundaries during microwave ablation (MWA) procedures remains a persistent clinical challenge. To address this limitation, our preliminary investigation established a proof-of-concept imaging platform that successfully acquired preliminary focused images demonstrating boundary delineation capability. Building upon these findings, we have incorporated a multi-antenna array configuration to enhance spatial sampling efficiency and developed critical system components.**

***Index Terms*—Microwave ablation (MWA), confocal microwave imaging (CMI), ultra-wideband (UWB)**

I. Introduction

Microwave ablation (MWA) technology has attracted increasing attention in the treatment of tumors, such as liver tumors, pelvic bone tumors, and breast tumors, because it is less invasive and has lower risks than traditional surgery. However, currently, it is still challenging to accurately and effectively kill tumors with a minimum effect on the surrounding normal tissue. One reason is limited by the MWA system, whose working performance is expected to change with the variation of temperature and dielectric properties of the surrounding tissue. The other reason is related to the traditional ablation zone boundary detection techniques, including the computed tomography (CT), the magnetic resonance imaging (MRI), and the ultrasound imaging method, but they are either time-consuming or severely disturbed by microbubbles, and consequently not easy for real-time monitoring of the ablation zone. Considering that during the ablation process, the electromagnetic properties of the tumor and the tissue that surrounds the ablation probe will change dramatically due to the increasing temperature and the reducing water content, a real-time microwave image of the ablation zone is expected to be precisely obtained. In this case, a radar-based microwave imaging systems show great potential.

In our previous work, a dual-antenna microwave imaging system based on a commercial oscilloscope and a turntable was proposed as shown in Fig. 1, and its performance was preliminarily verified by a partially hollowed-out acrylic cylinder [1]. According to the preliminary experiments, there are still a lot of improvements required to realize a real-time monitoring platform. On one hand, it is obviously not practical to rotate the patient for real-time monitoring during surgery. On the other hand, the receiver used in the current system is a commercial oscilloscope, which is expensive, bulky, and not accurate enough.

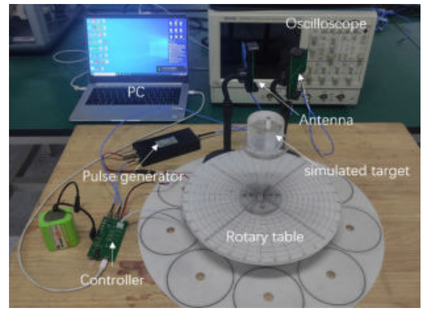

Fig. 1. The experimental time-domain microwave imaging system in our previous work.

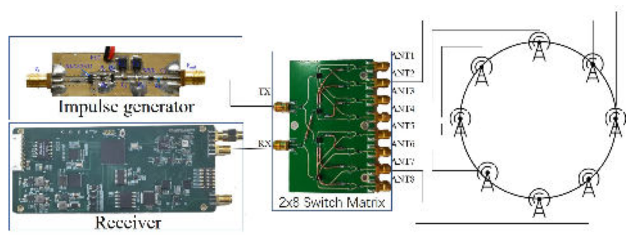

Fig. 2. Top-level block diagram of the real-time monitoring microwave ablation system.

To address these issues, we have redesigned the imaging system to eliminate the need for patient rotation by implementing a stationary multi-antenna array. This configuration allows for continuous real-time monitoring without mechanical movement, enhancing both the practicality and safety of the system during surgical procedures. Additionally, we have replaced the commercial oscilloscope with a custom-built, compact receiver that significantly reduces both the cost and physical footprint of the system. The new receiver also offers improved signal processing capabilities, resulting in higher accuracy and reliability of the microwave imaging results. These advancements collectively contribute to the feasibility of deploying the microwave imaging system as an effective real-time monitoring tool in clinical settings.

II. System Design and Development

A. System Architecture

The system is designed to operate in the 1-4 GHz range, which is a compromise between tissue loss properties, i.e.

L. Wang is with the School of Electronics and Information Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China (e-mail: wangli675@stu.xjtu.edu.cn.

X. Bao is with the Beijing Key Laboratory of Millimeter Wave and Terahertz Techniques, Beijing Institute of Technology, 100081 Beijing, China, and also with the Tangshan Research Institute of BIT, 063000 Tangshan, China.

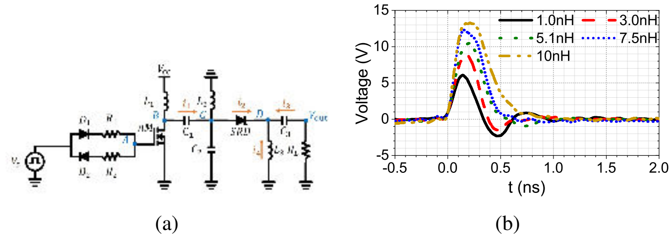

Fig. 3. (a) The circuit of the proposed sub-nanosecond pulse transmitter. The waveform of the fabricated sub-nanosecond pulse transmitter with (b) different value of L_3.

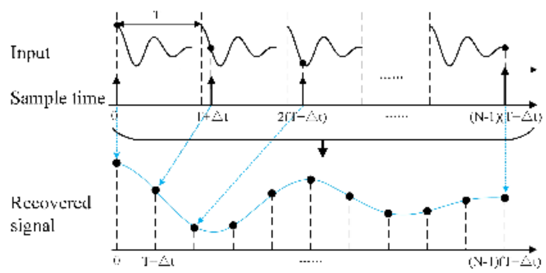

Fig. 4. equivalent time-sampling timing diagram.

detection depth and detection resolution. A top-level block diagram of the system is shown in Fig. 2. An impulse generator was designed to provide $12.6\,\mathrm{V}$ quasi-Gaussian impulses of $300\,\mathrm{ps}$ full-width at half-maximum (FWHM) [2]. An ultra-wideband receiver based on equivalent sampling technology is designed to achieve distortion-free sampling of echo signals. Therefore, an analog input bandwidth of more than $18\,\mathrm{GHz}$ and an equivalent sampling rate of up to $1\,\mathrm{TSPS}$ are obtained at a very low cost. Each antenna is designed to operate as both a receiver and a transmitter, enabling the collection of data from multiple angles with a minimal number of antennas. Therefore, a 2×8 switch matrix is carefully designed so that the system can obtain 64 data sets through 8 antennas. The program will automatically manage device control and data collection, while the computer will draw the boundary of the ablation zone in real time.

B. Impluse Generator

An SRD-based compact sub-nanosecond impluse generator is proposed as shown in Fig. 3(a). Working as a charge switch, the SRD can cut off the current of an inductor, generating a sub-nanosecond pulse. Fig. 3(b) presents the generated sub-nanosecond pulses for different L_3 values by using the designed transmitter. Generally, a larger L_3 results in a larger pulse amplitude but a worse FWHM. As a compromise, the value of L_3 is set to $7.5\,\mathrm{nH}$ in this system.

C. Receiver

Typical ultra-wideband pulse receivers rely on high-performance ADCs, which usually means complex circuit design, high power consumption, and high cost. To address these challenges, a receiver based on equivalent sampling techniques [3] has been developed. As shown in Fig. 4, the period of the signal to be sampled is T, and the period of the sampling clock is $T + \Delta t$, slightly larger than T. In each cycle of the signal, only one point is sampled. Through this technique, when Δt is set to $1\,\mathrm{ps}$, the receiver obtains an equivalent sampling rate of $1\,\mathrm{TSPS}$ at the true sampling rate of $1/T$ SPS. Therefore, a cheap ADC is used in the receiver. In addition, a sample-and-hold chip, HMC661, is used to extend the analog input bandwidth of the ADC to $18\,\mathrm{GHz}$. The slight delay, Δt, is achieved through a specialized delay chip.

D. Switch Matrix

A 2×8 switch matrix forms any desired transmit–receive pair. The prototype is made using a four-layer mixed printed circuit board (PCB). The switch chips are placed in the top layer. The second layer serves as a reference, while the third and fourth layers are dedicated to power supply and control signal transmission, respectively. For some conflicting RF paths, semi-steel coaxial cables with an outer diameter of $0.86\,\mathrm{mm}$ are used as jumpers. The test results indicate that the insertion loss is better than $6\,\mathrm{dB}$ within $2\,\mathrm{GHz}$, and the loss is better than $12\,\mathrm{dB}$ within $6\,\mathrm{GHz}$.

III. Conclusion

To facilitate clinical translation of the proposed microwave imaging system, we have optimized the hardware architecture by implementing a novel multi-antenna configuration. Critical system components including an ultra-wideband pulse generator, receivers, and a programmable switch matrix were specifically developed to meet clinical requirements. Due to time constraints, system integration will be completed in future research.

IV. Scholarship Impact and Career Plan

I would like to express my gratitude to IEEE MTT-S for recognizing my contributions and awarding me the graduate scholarship. This scholarship has given me the confidence to continue exploring the mysteries of microwave technology, as well as providing me with more opportunities in other areas. Unfortunately, due to the visa processing timeline, I regret that I am unable to attend IMS2024. After completing my PhD, I plan to stay at the university to continue my research on microwave ablation and microwave imaging.

References

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