35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

A CMOS UWB Transmitter for Possible Use for Medical and Biological Imaging Based on Radio-Wave Induced Ultrasound*

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Abstract— **Medical and biological imaging based on radio-wave induced ultrasound with a single source capable of irradiating multiple signals of different frequencies simultaneously can be implemented using ultra-wideband (UWB) technique. Development of a low-cost miniature UWB CMOS transmitter that can be used for this medical application is presented. The UWB transmitter designed using a 0.25-µm CMOS process can generate and transmit both monocycle pulses from 140 to 350 ps and impulses from 100 to 300 ps which contain many concurrent frequencies such as 3.1-10.6 GHz of the UWB spectrum.**

I. INTRODUCTION

Medical and biological imaging based on radio waves is convenient due to the fact that it can be conducted without making physical contacts, can penetrate well into the human body and/or biological tissues, and have relatively good imaging contrast between the tissue being imaged and the surrounding. Radio-wave medical and biological imaging, however, is typically done in a narrow bandwidth in the low microwave frequency range such as 3 GHz. Consequently, it has problems of low depth and spatial resolutions. On the other hand, ultrasound medical and biological imaging provides fine resolution even when operating at a much lower frequency than radio waves, but suffers from poor imaging contrast. A logical development to exploit advantages of both radio wave and ultrasound techniques would be to combine radio and ultrasound waves for imaging purposes.

Acoustic wave, which is the basic wave used in constructing images in ultrasound technique, in the heads of animals and humans can be generated from an illuminating pulsed radio wave [1]. Using radio waves to generate acoustic waves for imaging of biological tissues was reported [2]. Fine imaging of biological tissues using radio wave-induced ultrasound technique has been achieved using a single frequency of 3 GHz [3]-[5], demonstrating its usefulness for medical and biological imaging applications. Radio-wave-induced ultrasound technique, combining radio and ultrasound waves, possesses unique features of non-contact (between antenna and object), relatively deep penetration, fine imaging contrast, and good spatial resolution. It also has similar imaging speed as that of the conventional ultrasound technique since the ultrasound is excited almost instantaneously as the radio wave is incident upon the biological tissue. This is due to the facts that the speed of radio wave is much faster than that of ultrasound and the radio wave absorption and heat conversion occur within a very short time.

It is noted from the radio wave theory that different materials, such as different biological tissues, have different properties and respond differently to irradiating signals at different frequencies. It is then expected that different biological tissues may give optimum images at different frequencies and, hence, using a single frequency for all different tissues may not provide an optimum image. Using a single radio source operating over a large bandwidth, e.g., 3-5 GHz, or multiple sources operating at different frequencies would optimally excite different tissues, which may produce more tissue information and hence possibly better visible and more accurate image. Furthermore, the dielectric property of soft tissue varies substantially versus frequency, possibly leading to further enhancement of imaging contrast when different frequencies are used simultaneously.

Ultra-wideband (UWB) has received significant interests, particularly after the FCC's Notice of Inquiry in 1998 [6] and Report and Order in 2002 [7] for unlicensed uses of UWB devices within the 3.1-10.6 GHz frequency band. UWB systems transmit and receive information using millions of narrow pulses each second with extremely low-power spectral densities across an ultra-wide-band spectrum. This effectively produces extremely small interference to other radio signals while maintains excellent immunity to interference from these signals. UWB devices can therefore work within frequencies already allocated for other radio services, thus helping to maximize this dwindling resource. Additionally, UWB techniques have lower power requirements, less multi-path problems, and enhanced resolution and locating precision, as compared to more conventional continuous wave (CW) approaches. The advantages of the UWB technique make it attractive for medical and biological applications – particularly in generating multiple signals at different frequencies simultaneously using a single source for radio-wave-induced ultrasound technique.

Silicon-based CMOS radio frequency integrated circuits (RFICs) and systems have advanced significantly and can perform at very high frequencies. CMOS RFICs have lower cost and better abilities for direct integration with digital ICs (and hence better potential for complete system-on-a-chip). CMOS RFICs are also small and low-power, making them suitable for battery-operated medical sensors.

In this paper, we discuss possible use of radio-wave-induced ultrasound technique with multi-frequency source

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*Research supported by the National Science Foundation.

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978-1-4577-0216-7/13/$26.00 ©2013 IEEE

for medical and biological imaging. We report the development of a low-cost miniature CMOS RFIC UWB transmitter for this application. The transmitter can simultaneously generate signals at multiple frequencies and are thus attractive for enhanced radio-wave-induced ultrasound technique.

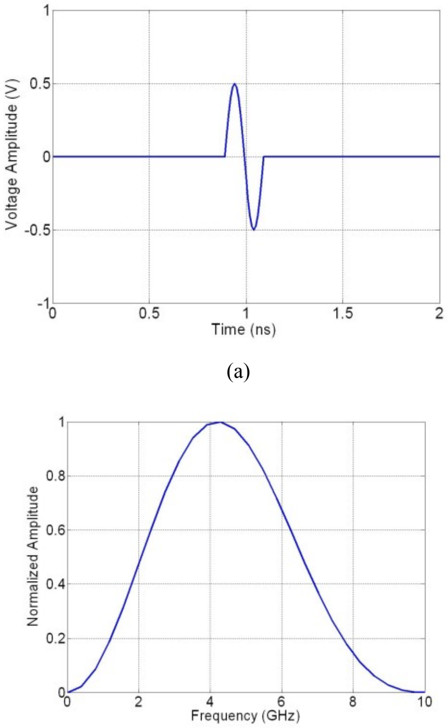
II. RADIO-WAVE INDUCED THERMO-ACOUSTIC IMAGING

A. General Concept

Radio-wave pulse illuminating biological tissue generates heat in the tissue, similar to heat produced in objects, such as meat, illuminated by a radio signal in microwave ovens. This heat due to the absorption of radio-wave energy, results in thermal expansion in the tissue which in turn creates acoustic (or ultrasonic) waves known as the thermo-acoustic effect. The characteristics of these induced acoustic waves depend on the frequency and amplitude of the radio wave and the dielectric property of the tissue being irradiated. The dielectric property is closely related to the physiology and pathology of the tissue and thus can be used to determine the tissue's characteristics [8], [9]. The radio wave induced thermo-acoustic concept is essentially the same as that in the ultrasound technique, except that the acoustic wave is generated indirectly from a radio wave upon incident to the tissue, rather than being sent directly from an ultrasound device. Since the image is formed using generated ultrasound rather than radio wave, the spatial resolution is expected to be as good as that obtained in the conventional ultrasound imaging technique. It is this unique characteristic that makes the technique potentially more attractive than either radio-wave or ultrasound imaging technique alone. A single frequency such as 3 GHz is typically used [3]-[5]. For optimum imaging, multiple frequencies instead of a single frequency should be used. Moreover, multiple frequencies that can be generated concurrently from a single source are more attractive for medical sensing implementation due to small size and low cost.

B. Multi-Frequency Transmitter for Radio-Wave Induced Thermo-Acoustic Imaging

As indicated earlier, a single-frequency source or transmitter may only give optimal response or image for a particular biological tissue. For a complete image of biological tissues, particularly when examining a patient's body, multiple frequencies may be needed. One possible way to obtain multiple frequencies is to combine multiple separate single-frequency sources. This, however, not only complicates the system design but also increases the cost and size of the system. It is possible to use a single source that can generate different frequencies successively with a short delay between different frequencies. This, however, also encounters similar problems of using multiple sources. A better way of achieving multiple signals operating at different frequencies simultaneously is using a carrier-less UWB pulse signal. This kind of pulse signal is very different from the pulsed signal implemented in [3]-[5]. The pulsed signal used in [3]-[5] is a carrier-based signal that operates periodically over different time windows and contains only a single-frequency signal known as "carrier" (e.g., 3 GHz). On the other hand, the pulse signal we propose, although also operating periodically over time windows, does not have a carrier (i.e, carrier-less) and has multiple simultaneous frequencies (e.g., 0-5 GHz). Using such a single source that can generate multiple frequencies concurrently simplifies the system design and reduces the system's cost and size. These advantages are particularly useful for realizing portable low-cost medical imaging systems. As the depth resolution of imaging is inversely proportional to the pulse width, we also propose to use a narrow pulse width (e.g., 0.2 ns) to enhance the resolution. Fig. 1 shows a carrier-less mono-cycle pulse signal having simultaneous multiple frequencies as seen in its frequency spectrum.



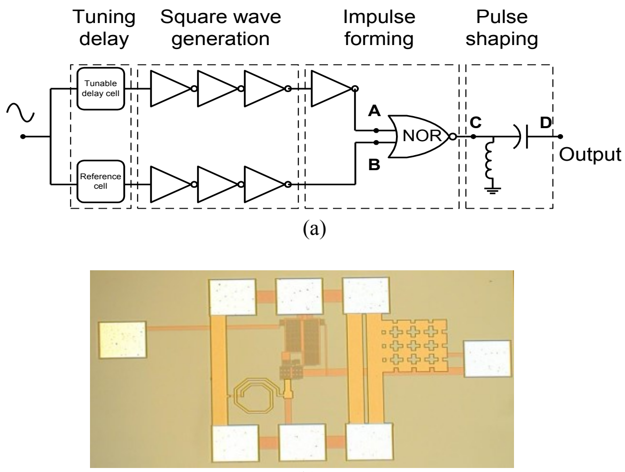
(a)

(b)

Figure 1. Carrier-less mono-cycle pulse signal with 1-V amplitude and 0.2-ns pulse-width (a) and its frequency spectrum (b).

III. CMOS UWB MULTI-FREQUENCY TRANSMITTER

Figure 2 shows the CMOS tunable multi-frequency monocycle pulse generator chip fabricated using a 0.25-μm CMOS process. It integrates a tuning delay circuit, a square-wave generator, an impulse-forming circuit, and a pulse-shaping circuit in a single chip. The measured tunable impulse and monocycle-pulse signals are shown in Fig. 3. Impulse signals having 0.5 – 1.3 V peak-to-peak voltage with 100 – 300 ps tunable pulse duration and monocycle pulses with 0.3–0.6 V peak-to-peak voltage and 140–350 ps duration were measured. These pulses contain concurrent multi-frequency signals, including those across the entire UWB spectrum of 3.1-10.6 GHz. It is noted that the tunable narrow impulse generated at node C consists of three parts: rising edge, tuning delay, and falling edge. For pulses with very narrow width, only part of the rising and falling edges is involved, resulting in impulse with much smaller amplitudes. Consequently, a tunable monocycle pulse is achieved at node D.



(a)

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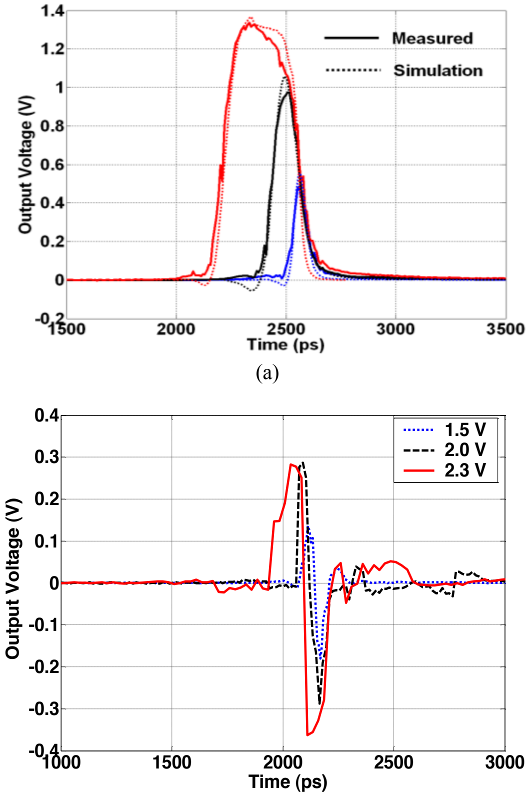
Figure 2. Schematic (a) and photograph (b) of the CMOS UWB tunable multi-frequency monocycle pulse generator.



(a)

(b)

Figure 3. Impulse (a) and monocycle pulse (b) signals with tunable pulse duration.

Figure 4 shows the CMOS tunable monocycle pulse generator chip mounted directly onto the edge of the UWB antenna without a feed line. The area occupied by the antenna aperture is only 1.2 in x 1.4 in. A quasi-microstrip antenna operating from 0.2 to more than 20 GHz is used as the receiving antenna for pulse transmission measurement of the UWB transmit module. Figure 5 shows the signals received from the tunable impulse and monocycle pulse signals, shown in Fig. 3, transmitted by the UWB transmit module. The pulse-duration tunability is clearly visible in the received pulses. All the received signals have shape similar to the first derivative of the transmitted pulses, as expected from the designed antenna. Both the measured impulse and monocycle-pulse transmission results clearly demonstrate the workability of the developed CMOS tunable multi-frequency UWB transmit module, which can be used as the irradiating source for medical imaging sensors based on the radio-wave-induced ultrasound technique.

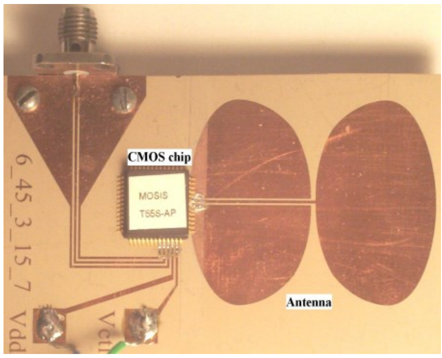
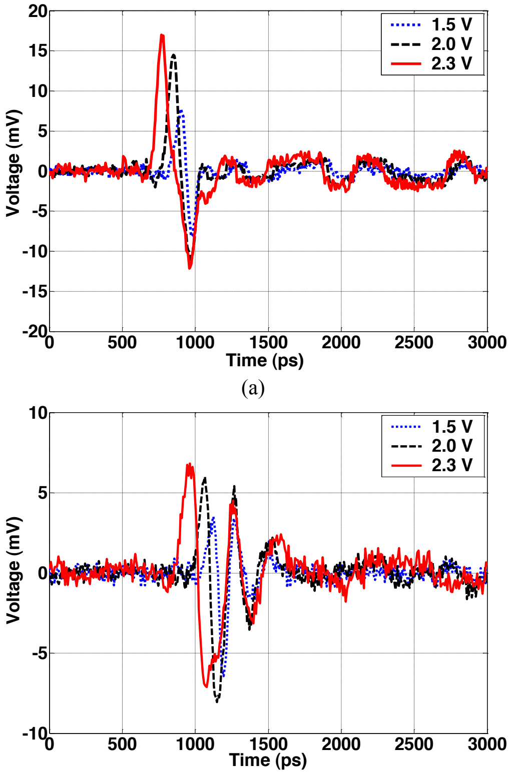


Figure 4. Photograph of the UWB transmitter-antenna module.



(a)

(b)

Figure 5. Received signals of the impulses (a) and monocycle pulses (b) transmitted by the UWB transmit module.

IV. POSSIBLE USE OF THE UWB TRANSMITTER FOR RADIO-WAVE INDUCED ULTRASOUND

Current radio-wave induced ultrasound technique is based on a single frequency, which may limit possible imaging. The ability of generating tunable pulses of various durations in a very small CMOS chip as reported here makes possible implementation of the radio-wave induced ultrasound excited by multiple concurrent sources for compact biological and medical imaging sensors. For instance, systems for two possible applications can be envisioned: one for imaging mastectomy specimens or other biological samples and another one for imaging the human body. In these systems, a carrier-less radio-wave pulse, generated by the developed UWB transmitter, is transmitted toward a biological sample or an area in the human body to be imaged. Since the pulse contains multiple frequencies, the irradiation is effectively formed from multiple radio waves operating at different frequencies simultaneously. Parts of these radio waves are absorbed by the tissues which are converted into heat and then acoustic waves. These acoustic waves are captured and converted into electrical signals by ultrasonic transducers located at various locations and angles at they propagate away from the irradiated area. The converted electrical signals are amplified, filtered through different channels (one for each transducer), and processed to generate image of the illuminated area. For imaging the human body, the transducers can be placed directly onto the body with gels in between to facilitate the coupling of the acoustic waves to the transducers (as used in the conventional ultrasound imaging technique). Another possible system, that allows simultaneous imaging of several samples or body locations to be made quickly, can also be implemented using multiple antennas with each antenna fed by a carrier-less radio pulse signal having multiple frequencies generated from the developed TX. It is expected that the development of these systems requires substantial cross-disciplinary collaboration efforts between different disciplines such as medicine, biomedical engineering and electrical engineering. With sufficient collaborations, such systems can be developed within a reasonable time for clinical applications.

V. CONCLUSION

Radio-wave-induced ultrasound technique employing a single source or transmitter that can generate multiple signals of different frequencies is attractive for enhancing medical and biological imaging. The single transmitter uses UWB carrier-less radio pulses as the irradiating pulses. The use of carrier-less radio pulses with many frequencies may enable optimal excitation of different biological tissues concurrently, possibly leading to high-quality images of samples or human body quickly without increasing cost. A miniature low-cost CMOS tunable UWB transmitter that can produce these concurrent signals across different frequency ranges including the UWB spectrum of 3.1-10.6 GHz has been developed which can find applications in enhanced radio-wave-induced ultrasound method. Possible medical and biological imaging systems based on the radio-wave-induced ultrasound technique can employ such UWB transmitters in conjunction with a single antenna or multiple antennas, and multiple acoustic transducers. The multiple antennas and acoustic transducers can be spatially located at different locations and angles to allow large imaging coverage, increased information reception, and enhance sensitivity. Thinking forward, it is envisioned that subsequent development may include small low-cost portable imaging sensors, such as hand-held flashlight-like units, which should be extremely useful for various medical practices such as dermatology. Possible development of endoscopic ultrasound imaging techniques based on radio waves, in which radio waves are used to generate acoustic waves, is also envisioned. This may improve minimally invasive diagnostic medical procedures, which may potentially lead to new medical discoveries and treatments – for example, possibly providing deeper tissue penetration, while maintaining fine resolutions as compared to the currently used endoscopic ultrasound technique, for examination of interior surfaces of organs for possible cancer.

REFERENCES

[1] J. C. Lin, "On Microwave-Induced Hearing Sensation," IEEE Trans. on Microwave Theory and Techniques, vol. 25, July 1977, pp. 605-613.

[2] J. C. Lin and K. H. Chan, "Microwave Thermoelastic Tissue Imaging System Design," IEEE Trans. on Microwave Theory and Techniques, vol. 32, Aug. 1984, pp. 854-860.

[3] M. Xu, G. Ku and L. V. Wang, "Microwave-Induced Thermoacoustic Tomography Using Multi-Sector Scanning," Medical Physics, vol. 28, Sep. 2001, pp. 1958-1963.

[4] G. Ku et al., "Thermoacoustic and Photoacoustic Tomography of Thick Biological Tissues Toward Breast Imaging," Technology in Cancer Research & Treatment, vol. 4, May 2005, pp. 1-7.

[5] G. Ku and L. V. Wang, "Scanning Thermoacoustic Tomography in Biological Tissue," Medical Physics, vol. 27, May 2000, pp. 1195-1202.

[6] "Revision of part 15 of the commission's rules regarding ultra-wideband transmission systems." [Online]. FCC Notice of Inquiry, adopted August 20, 1998, released September 1, 1998. Available: http://www.fcc.gov/oet/dockets/et98-153.

[7] "Revision of part 15 of the commission's rules regarding ultra-wideband transmission systems," FCC Report and Order, Adopted February 14, 2002, Released July 15, 2002.

[8] S. Chaudhary, R. Mishra R, A. Swarup A, and J. Thomas, " Dielectric Properties of Normal and Malignant Human Breast Tissues at Radiowave and Microwave Frequencies," Indian Journal of Biochemistry Biophysics, vol. 21, Feb. 1984, pp. 76-79.

[9] W. Joines, Y. Zhang Y, C. Li, and R. Jirtle, "The Measured Electrical Properties of Normal and Malignant Human Tissues from 50-900 MHz," Medical Physics, vol. 21, Apr. 1994, pp. 547-550.