Time-Domain Microwave Cancer Screening: Optimized Pulse Shaping Applied to Realistically Shaped Breast Phantoms

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***Abstract* — We compare the tumor detection ability of a time-domain microwave radar system for breast cancer screening fed with two different pulses. We conduct measurements on highly realistic breast phantoms using as inputs to our system both a generic pulse and a pulse reshaped with a synthesized broadband reflector (SBR) designed to have a frequency profile advantageous for tumor detection. We perform measurements with various tumor sizes and locations, as well as antenna positions. Our results in both time-domain and frequency-domain demonstrate that this pulse shaping technique is beneficial in both improving the tumor response and increasing the system efficiency.**

***Index Terms* — cancer detection, microwave imaging, phantoms, pulse shaping methods, radar imaging.**

I. Introduction

Early detection has proven to be a key factor in decreasing breast cancer fatality rates [1]. The traditional detection technique is X-ray mammography, a tool that suffers from high false-positive and false-negative rates and uses harmful ionizing radiation [2]. Microwave methods, based on the inherent contrast in dielectric properties of healthy and malignant breast tissues over the microwave frequency range, are being actively researched as a complementary detection technique. They have the potential to provide comfortable, non-invasive breast scans without ionizing radiation. The majority of microwave breast cancer systems presented in the literature use frequency-domain measurements to record the reflection or transmission coefficients of signals passing through the breast. We elect to use time-domain measurements, with the goal of reducing the hardware complexity with respect to the frequency domain.

This paper reports on improvement of our initial system described in [3]. As will be shown, the frequency spectrum of the impulse used in [3] contains spectral content outside the desirable range, and thus a large portion of power is being transmitted unnecessarily. Thus, we first apply a synthesized broadband reflector (SBR) to a modified microwave breast cancer detection system, with the goal of improving the tumor response by transmitting key frequencies at higher power levels than unwanted frequencies. We aim to operate in the 2-4 GHz range, as, through our experiments, we have observed that this is the range favorable for tumor detection. Frequencies below this range do not aid the detection: they are insufficiently attenuated by the tissue such that numerous reflections occur, thereby clouding the received signals. Frequencies above the noted range experience high attenuation as they propagate through the tissues; hence, any power invested in them is effectively wasted. Our second improvement over previous work is to use phantoms that are realistic in their shape and size, instead of hemispherical breast phantoms [3], for system testing. Further, the mimicked tumors are also improved in terms of realistic representation of their shape and size.

II. Experimental System

In order to compare the effect of pulse shaping on our system's tumor detection ability, we operate the system in two unique modes. In the first mode, a 25 MHz clock triggers an impulse from an off-the-shelf generator. This impulse is fed directly to a transmitting antenna, held in a slot on the exterior of a bowl-shaped radome. The transmitted wave travels through the radome and into the breast phantom, scattering at all tissue interfaces. A receiving antenna picks up the scattered response; then, an oscilloscope records the data.

In the second mode we use an SBR, an easily manufactured, low-cost, planar microstrip line, to reshape the pulse generated by the impulse generator [4]. The SBR is designed to shape the pulse so that its main frequency content is in the 2-4 GHz range. To offset the losses induced by the SBR structure, we also insert a broadband amplifier (35 dB gain over 2-8 GHz) in the signal path before the transmitter. A plot of the frequency spectrum for each pulse fed into the transmitting antenna is shown in Fig. 1. We note that the low frequency content below 2 GHz is strongly attenuated in the band-limited (SBR generated) pulse as compared to the generic impulse.

The phantoms we use here are composed of skin-, fat- and tumor-mimicking tissues, each with dielectric properties matched to those of actual tissues. We construct these phantoms according to the recipes and procedure referred to in [3]. In these tests, we use a breast phantom that has approximately 2 mm thick skin, filled with fat. It is of appropriate size, measuring 17.5 x 16.5 x 8 cm^3. The complete phantom, shown in Fig. 2, is designed to be very similar in shape and geometry to a real human breast. In this particular study, we elect not to embed glands within the fat, in order to more easily observe the advantages and identify any possible difficulties associated with using the SBR structure.

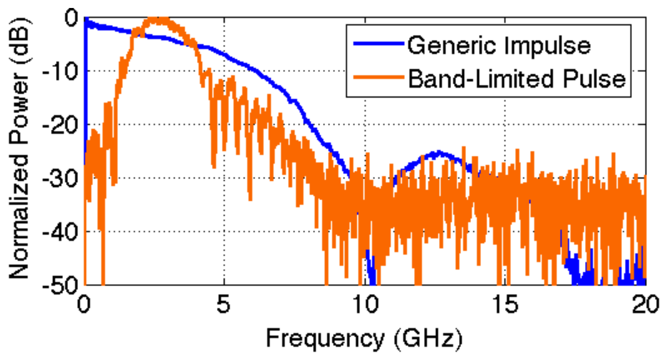

Fig. 1. Frequency spectrum of the generic and SBR-shaped input pulses.

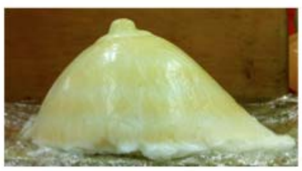

Fig. 2. Photograph of a realistically shaped breast phantom.

III. Methodology

The measurements are performed as follows: we place the breast phantom under test into the radome, surrounded by a fat-like matching medium to avoid lossy air gaps between the skin and radome. Two antennas (one to transmit, one to receive) are positioned in slots on the exterior of the radome. First, we record a healthy baseline signal.[1] Then, we place a tumor of desired size and shape into the phantom at a chosen position and rerecord the signal scattered off of the breast.

In this set of measurements, the end-fire antennas are stacked one on top of the other, on the same side of the phantom. This configuration is chosen because we previously found it to be an antenna arrangement for which our system generates strong tumor response signals [3]. We test two positions for the stacked antennas: Position A1 has the stack centered at the halfway-point between the chest wall and the nipple, while Position A2 places the stack between the halfway point and the chest wall.

To test the system's behavior, we use two spherical tumors, with radii of 0.5 cm ('small') and 1 cm ('large'). We choose spherical because tumors are approximately this shape when they first begin to develop, before they grow out into surrounding tissue [5]. It is at this stage which detection is the most desirable, as a patient's survival rate is still very favorable. Further, we cut a small hole in the tissue in which to place the tumors in, instead of just pushing them into the phantom and allowing the surrounding tissue to compress. This is also based on [5], which indicates that breast tumors infiltrate and destroy surrounding tissue and do not typically grow by pushing the healthy tissue out of the way. The tumors are located in the breast at a depth approximately 1 cm from the chest wall. We use three tumor sites: one halfway between the radome center and radome wall holding the antennas (Site T1), and the other two halfway between the radome center and the radome wall, 45° on either side of the antennas (left of antennas, Site T2; right, Site T3). For each antenna position, we measure the received signal with each of the tumors put in turn into each of the tumor locations.

[1] The baseline measurement is for experimental purposes only, to assess whether tumor reflections generate detectable signals. A real system will instead use detection algorithms.

IV. Measurement Results

In this section, we present parameters to assess the ability of our system in detecting the presence of tumors within a breast phantom. Specifically, we provide a comparison between the measurements with two different incident pulse shapes. We refer to the two systems as the original (without pulse shaping) and the SBR-system.

Fig. 3 compares the signal recorded at the receiving antenna for both experimental systems, with the antennas located in Position A2. The received signal amplitude is vastly improved using the SBR-system; furthermore, the signal shape is now compact and symmetric, whereas the signal recorded using the original system contains low frequency content, which causes a ringing tail. Minor reflections can be observed in the received signal for the SBR-system; these low-power reflections arise from imperfect matching at some of the connections within the experimental system. We note also that time zero in the figures does not correspond to the time at which the pulse was transmitted.

We calculate the tumor response signal, a key metric in determining whether or not the tumor was successfully detected, as the difference between the received signal with tumor present and the healthy baseline. Table I presents the maximum tumor response, in millivolts, for each antenna position, for all tumor sizes and locations under consideration. We include in parentheses the tumor size, denoted by 'S' for small and 'L' for large, as well as the tumor sites, denoted by T1, T2 and T3.

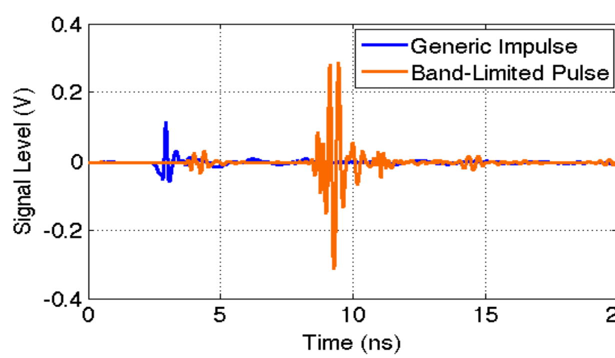

Fig. 3. Comparison of the received signal for both input pulses with antennas in Position A2.

TABLE I
MAXIMUM TUMOR RESPONSE (MV) FOR ORIGINAL AND SBR-SYSTEMS (CORRESPONDING TUMOR SIZE, LOCATION)

	Original System	**SBR-System**
Position A1	29.1 (L, T2)	51.0 (L, T1)
Position A2	26.9 (S, T3)	100.8 (S, T1)

We observe that, regardless of the antenna position, the reshaped pulse provides an improvement in tumor response signal. Table I demonstrates that a large tumor does not always produce the largest tumor response signal, a trend that was also noticed and explained in [3]. Furthermore, it is impossible to conclude from this data whether a specific tumor location will enable easier detection; however, we can conclude that both sized tumors are detectable at all three locations. The minimum tumor response signal across measurements is 6.2 mV and 14.7 mV, respectively, for the original and SBR-system, well above the noise floor (2 mV).

We define the relative tumor response parameter as

$$T = 20\log\left(\frac{\max|Tumor\ Response|}{\max|Input\ Signal|}\right); \qquad (1)$$

a metric which provides information about the tumor response signal relative to the input signal. This metric is of primary interest here since the two systems have differing input signal levels; thus the T parameter provides an unbiased report on the level of the tumor response. Table II presents the best value for T for each antenna position. As per Table I, we include in parentheses the tumor size and location for which the measurement occurred. Using the SBR-system results in improved tumor detection capabilities for both antenna positions.

We contrast representative spectrograms of the tumor response for the original and SBR-systems in Figs. 4 and 5, respectively. We observe from Fig. 5 that the peak power in the SBR-system tumor response signal is much higher, and is sharply focused in the 2–4 GHz range at a specific point in time. This image is in stark contrast to the spectrogram with the generic impulse as the input. The power of the tumor response signal, as seen in Fig. 4, is spread out amongst a wide range of frequencies, with the majority below 2 GHz. This low frequency content explains the long time duration of the tumor response signal. Further, the time lag between the two tumor response signals in Figs. 3, 4, and 5, is caused by the extra components in the SBR-system chain, which introduce additional delay.

V. CONCLUSION

This work compared the performance of a microwave time-domain breast cancer detection system operated with a generic pulse and one shaped using a synthesized broadband reflector. Tests were performed on a realistically shaped breast phantom with two tumor sizes, three tumor positions and two antenna arrangements. The tumor was easily detected in all scenarios. More importantly, the use of the SBR improves both the magnitude of the tumor response and the level of the tumor response relative to the input. Further, pulse shaping with the SBR provides a clean, short-duration pulse with well-concentrated frequency content relative to the generic pulse.

TABLE II
RELATIVE TUMOR RESPONSE PARAMETER (DB) WITH CORRESPONDING TUMOR SIZE, LOCATION IN PARENTHESES

	Original System	**SBR-System**
Position A1	-46.7 (L, T2)	-43.7 (L, T1)
Position A2	-47.4 (S, T3)	-37.8 (S, T1)

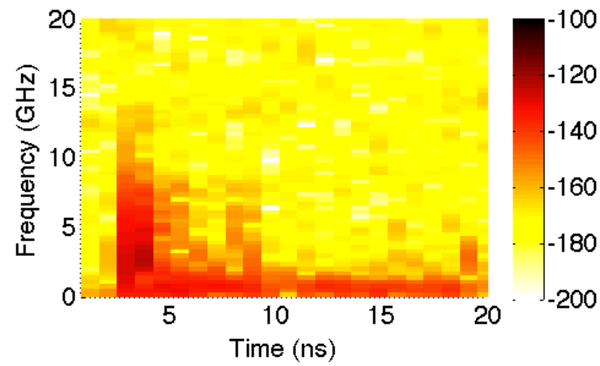

Fig. 4. Spectrogram of the tumor response signal with the original system using the generic impulse.

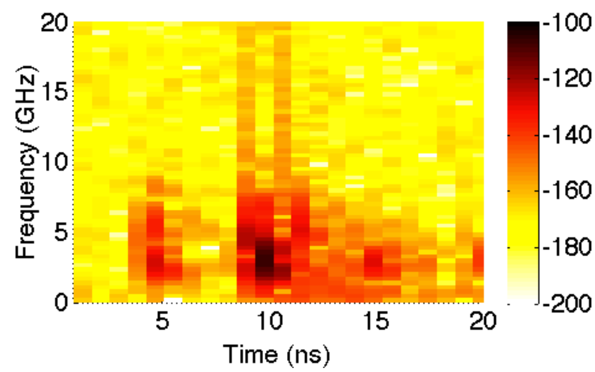

Fig. 5. Spectrogram of tumor response signal with SBR-system.

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