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Impedance matching network for high frequency ultrasonic transducer for cellular applications

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ABSTRACT

An approach for the design of an impedance matching network (IMN) for high frequency ultrasonic transducers with large apertures based on impedance analysis for cellular applications is presented in this paper. The main objectives were to maximize energy transmission from the excitation source to the ultrasonic transducers for cell manipulation and to achieve low input parameters for the safe operation of an ultrasonic transducer because the piezoelectric material in high frequency ultrasonic transducers is prone to breakage due to its being extremely thin. Two ultrasonic transducers, which were made of lithium niobate single crystal with the thickness of 15 μm, having apertures of 4.3 mm ($f_{\text{number}} = 1.23$) and 2.6 mm ($f_{\text{number}} = 0.75$) were tested. L-type IMN was selected for high sensitivity and compact design of the ultrasonic transducers. The target center frequency was chosen as the frequency where the electrical admittance ($|Y|$) and phase angle (θ_z) from impedance analysis was maximal and zero, respectively. The reference center frequency and reference echo magnitude were selected as the center frequency and echo magnitude, measured by pulse-echo testing, of the ultrasonic transducer without IMN. Initial component values and topology of IMN were determined using the Smith chart, and pulse-echo testing was analyzed to verify the performance of the ultrasonic transducers with and without IMN. After several iterations between changing component values and topology of IMN, and pulse-echo measurement of the ultrasonic transducer with IMN, optimized component values and topology of IMN were chosen when the measured center frequency from pulse-echo testing was comparable to the target frequency, and the measured echo magnitude was at least 30% larger than the reference echo magnitude. Performance of an ultrasonic transducer with and without IMN was tested by observing a tangible dent on the surface of a plastic petridish and single cell response after an acoustic pulse was applied on a target cell.

1. Introduction

An ultrasonic transducer/array is a crucial component of an ultrasonic scanner such as those widely used in clinical diagnosis [1–7]. There has been a growing interest in transducers in the frequency range higher than 100 MHz for applications in single cell analysis, acoustic trapping, and studying mechanotransduction with improved lateral resolution [8–12]. In these applications, a highly focused acoustic beam is required [13]. When making highly focused ultrasonic transducers, those having a large aperture are much easier to press-focus. A transducer with a large aperture also generates a stronger pressure field under the same input parameters, such as voltage and pulse duration. Therefore, to generate the same acoustic pressure field, a transducer with a large aperture is safer and more effective than a transducer with a small aperture because lower input voltage and shorter pulse duration are needed.

The advantages of a transducer with a large aperture are true only when the electrical impedance between the ultrasonic transducer and auxiliary components are matched. As the operating frequency approaches the resonance frequency of the piezoelectric material, the magnitude of the acoustic pulse becomes larger because the energy transfer condition is optimized [14]. In other words, at the resonance, the magnitude of the electrical impedance of the ultrasonic transducer becomes optimized allowing maximal energy conversion. Energy conversion optimization depends upon the input electrical impedance of the transducer which in turn depends upon the dielectric constant of the piezoelectric material [15]. Electrical impedance mismatch between the ultrasonic transducer and excitation source leads to a large energy reflection

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between them thereby wasting energy, which results in excessive power consumption when trying to achieve the same acoustic pressure field. [16–19]. Therefore, an impedance matching network (IMN) is essential for the optimization of power transfer and efficiency by minimizing reflections between the ultrasonic transducer and the excitation source. This is particularly acute in applying large aperture high frequency transducers, which have extremely low electrical impedance at the resonance frequency, to a number of cellular applications [8–13] given that popular and highly sensitive piezoelectric materials typically have fairly high dielectric constants, which are unfavorable for the design of large aperture devices.

Various schemes of broadband IMN have been adopted for ultrasound imaging applications so as to obtain wide bandwidth because it helps to improve axial resolution [20–24]. Broadband IMN produces a spectral response that has a wide bandwidth with a gradual peak and echo signal energy distributed over a broad range of frequencies [25]. Therefore, broadband IMN may not be appropriate in applications where maximum intensity at the resonance frequency is required [26].

The commercially available transducer simulation software, PiezoCAD (Sonic Concepts, Bothell, WA), has been widely used in transducer design, however, it is very challenging to fabricate transducers in the frequency range above 100 MHz based on PiezoCAD modeling. Because PiezoCAD modeling does not take into account the effects of variations in thickness of the piezoelectric material at higher frequency and the electromechanical effects resulting from press-focusing, PiezoCAD modeling is not likely to show good agreement in terms of magnitude of admittance ($|Y|$), phase angle (θ_z), the real (R) and the imaginary (X) values compared with impedance analysis based on the real fabricated transducer [16,27–29]. For low frequency transducers, PiezoCAD modeling agrees well with impedance analysis based on the real fabricated transducer because the thickness variations and other aspects of the transducer design process have a more negligible impact on the characteristics of the transducers. For high frequency transducers, however, small variations have a direct influence on the characteristics of the transducers. We therefore chose a design method for the impedance matching network (IMN) using impedance analysis based on the real fabricated transducer and the Smith chart to determine the appropriate component values and topology of IMN instead of a design method based on PiezoCAD modeling.

In this paper, we developed an L-type IMN for a large aperture high frequency transducer, which achieved a much sharper peak at the resonance frequency by sacrificing bandwidth [30], allowing a greater acoustic pulse at the resonant frequency to be generated than that generated by an ultrasonic transducer without IMN. The L-type IMN could be easy to tune the matching network with a reliable performance using the combination of inductor and capacitor in the frequency range from kHz to GHz depending on ultrasonic transducers' electrical impedance compared to transmission line IMN [20]. A detailed description of the design process for the optimization of an impedance matching network (IMN) for a large aperture high frequency transducer is presented. The IMN design process follows five steps; (1) measuring maximum magnitude of admittance ($|Y|$) and zero phase angle (θ_z) from impedance analysis and estimating the resonance frequency that would be termed as the target center frequency of the ultrasonic transducer; (2) determining the appropriate component values and topology of IMN using the Smith chart based on the real (R) and the imaginary (X) values obtained from the impedance analysis; (3) performance verification of the ultrasonic transducer with and without IMN by pulse-echo measurement; (4) optimizing component values and topology of IMN by trial and error after comparing the target center frequency and measured center frequency from pulse-echo measurement; (5) determined component values and topology implemented on a printed circuit board (PCB), and integrated with the ultrasonic transducer. The optimized center frequency was set to a value similar to the target center frequency, measured from impedance analysis. At the same time, the optimized echo magnitude was set to a value at least 30% larger than the reference echo magnitude obtained by pulse-echo testing of the same ultrasonic transducer without IMN. Under the same input parameters, such as peak-to-peak voltage (V_{pp}) and treatment time (T_t), cell response and the effects on the surface of a plastic petridish by the acoustic pressure field, generated by ultrasonic transducers with and without IMN, were observed by microscope.

2. Materials and methods

2.1. Ultrasonic transducers, impedance analyzer, pulse-echo and insertion loss measurement system

Two ultrasonic transducers were fabricated and tested. Single element lithium niobate ($LiNbO_3$) ultrasonic transducers were fabricated with conventional approaches [28]. The aperture sizes of the first (TR1) and the second (TR2) ultrasonic transducers were 4.3 mm and 2.6 mm, respectively. The f_{number} of TR1 and TR2 were 1.23 and 0.75, respectively. The designed center frequencies of TR1 and TR2 were 110 MHz and 150 MHz, respectively. The characteristics of the ultrasonic transducer were measured by an impedance analyzer (Agilent E4991, Agilent Technologies, Santa Clara, CA), which has an operating frequency range from 1 MHz to 3 GHz. The magnitude of electrical impedance ($|Z|$) and admittance ($|Y|$), phase angle (θ_z), real (R) and imaginary (X) values of the electrical characteristics were measured.

To verify the performance of the impedance matching network (IMN), pulse-echo and insertion loss (IL) measurement of the ultrasonic transducers with and without IMN was conducted [31]. For the pulse-echo measurement, an imaging system was developed as shown in Fig. 1(a). It was comprised of a pulser/receiver (5900PR, Olympus NDT Inc., Waltham, MA), 12-bit analog to digital converter (ADC) with up to 2 GS/s sampling (CS122G1, Dynamics Signals LLC., Lockport, IL), a 3D linear translation/rotation stage (ILS100HA, Newport, Irvine, CA), motion controller (ESP301-3N, Newport, Irvine, CA), and a custom-built MATLAB (MathWorks Inc., Natick, MA) program. An ultrasonic transducer with or without IMN was excited by the pulser/receiver with 200 Hz pulse repetition frequency. The measurements were performed in the degassed/deionized water and the focal depth was aligned using a 3D linear translation/rotation stage with a motion controller and a custom-built MATLAB program. The reflected echo signals from a quartz target, placed at the focal point, were amplified by the pulser/receiver. Received signals were digitized with ADC at 1 GHz sampling rate. Digitized signals were transferred to the custom-built MATLAB program to visualize pulse-echo responses.

For the insertion loss (IL) measurement as presented in Fig. 1(b), a sine burst 5 V signal of 30 cycles generated from a function generator (AFG 3251, Tektronix, Beaverton, Oregon) was used to excite ultrasonic transducers with and without IMN, and the reflected echo signal from a quartz target placed at the focal distance was recorded in an oscilloscope (TDS 5052, Tektronix, Beaverton, Oregon) set to 1 MΩ coupling. IL was measured by voltage ratio of the echo signal to the sine burst signal, expressed in decibels (dB) over a range of −6 dB bandwidth (BW). The measured value was then compensated for the attenuation in water (0.0002 dB/mm/MHz^2) [29] and reflection from the quartz target (1.9 dB).

2.2. Design of impedance matching network

An impedance matching network (IMN) was used to transform the real value and cancel the imaginary value of the input electrical

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